Geographical Information Management and Applications

Site Suitability Analysis for Different Indigenous Rainwater Harvesting Systems – A Case Study of Sana'a Water Basin, Republic of Yemen

Master's Thesis

Student: Muhammed Dahan Abdulrahman Al-Komaim

muhammed.alkomaim@gmail.com

Supervisor(s): Prof. Dr. Ir. Charlotte De Fraiture.

PhD Fellow. Musaed Aklan

Responsible Prof.: Dr. Ir. Ron van Lammeren

Place of research: Wageningen University & Research.
September 2017 – March 2018

Universiteit Utrecht

UNIVERSITY OF TWENTE.

TU Delft

WAGENINGEN UR

Site Suitability Analysis for Different Indigenous Rainwater Harvesting Systems – A Case Study of Sana'a Water Basin, Republic of Yemen

Author MSc Thesis:

Muhammed Dahan Al-Komaim

Date:

28 February, 2018

Preamble

I present to you gladly the final result of my research in the domain of water management (rainwater harvesting). A research field which got my attention after getting acquainted with the significant water shortages in Yemen during my work in Sana'a Water & Sanitation Local Corporation (SWSLC). I have always been interested in finding solutions for this problem and therefore would like to make a small contribution to mitigate the water problems in my country.

This is all made possible because of the wonderful guidance and support of my supervisors, Prof. Dr. Ir. Charlotte De Fraiture and PhD Fellow Musaed Aklan. I would like to thank them for investing their time, energy and knowledge during the supervision process. I also would like to thank Dr. Ir. Ron van Lammeren who safeguarded the scientific process of this thesis in his role as professor. In addition, I would like to express my deep gratitude to the local experts for their contribution to this research.

Finally, I hope this research can make a contribution to the enhancement of the water resources availability in Yemen generally and in Sana'a water basin particularly. I also hope that I can deepen my knowledge in this field in the future.

Enjoy your reading.

Wageningen, 28 February, 2018, Muhammed Al-Komaim

Summary

Nowadays, the management of water resources in Sana'a Water Basin is a complex issue due to limited data, rapid population growth, aridity and complex physiographic environment. Groundwater is the main water resource in the basin for domestic, agricultural and industrial uses, in which the agricultural sector consumes about 90% of this resource. As a result, the groundwater level is declining rapidly.

Rainwater harvesting systems (RWH) are a prominent solution to deal with water scarcity by conserving available water resources and the energy needed to deliver water to the water supply systems. The impact of climate change on water resources can also be reduced by rainwater harvesting. Accordingly, RWH is becoming an important part of the sustainable water management around the world.

The identification of suitable sites for RWH is an important step to maximize the water availability, land productivity, and groundwater conservation in arid and semi-arid areas. This study aims to select the optimum sites for different indigenous RWH systems in Sana'a water basin through the use of modern techniques such as Geographic Information Systems (GIS), Remote Sensing (RS) and Multi-criteria Analysis (MCA). The selection criteria in this study is based on five biophysical factors as well as socio-economic parameters. These criteria were identified based on intensive literature review. Some local experts (five experts) are asked to evaluate and determine the relative importance of each criterion to each other. Then, the consistency ratio between the experts' opinions was evaluated using the pairwise comparison method and a final weight was computed for each criterion. In addition, the local experts were asked about their views on the proper locations within Sana'a basin for each RWH system and this information is used later on to validate the results of the final suitability maps.

Based on the literature review, discussions with supervisors and the questionnaire results, four RWH systems are selected in this study, namely, Terraces, Check-dams, Ponds, and Spate Irrigation. Therefore, each RWH system is analysed individually and has its own suitability map. The Weighted Linear Combination (WLC) technique was applied in combination of the Boolean technique to generate the final suitability maps for RWH systems in Sana'a basin.

The results of the suitability maps indicated that a sufficient area of high and very high suitability are existed in the study area for the four RWH systems, particularly terraces, check dams, ponds, and spate irrigation, which are 33%, 35%, 33%, and 32% respectively. Accordingly, Sana'a water basin is in general well suited for the implementation of RWH systems.

Arising from the validation of the results, the applications used in this study show that they work effectively to identify potential sites for RWH systems. This is confirmed by the local experts proposed locations, literature review, and comparing the results with many existing RWH systems in the study area.

Finally, the results of the sensitivity analysis revealed that developing the suitability maps for potential RWH using relative weights gathered from local experts are more accurate. Furthermore, it is noticeable from the sensitivity analysis that the slope layer is the most sensitive layer among others and inaccuracies in this layer can lead to errors in the identification of the RWH suitable sites.

Table of Contents

Abbreviations

AHP	Analytic Hierarchy Process
ASARs	Arid and Semi-Arid Regions
CR	Consistency Ratio
DEM	Digital Elevation Model
FAO	Food & Agriculture Organisation
GIS	Geographical Information System
HWSD	Harmonized World Soil Database
IIASA	International Institute for Applied Systems Analysis
ISRIC	International Soil Reference and Information Centre
ISSCAS	Institute of Soil Science, Chinese Academy of Science
JRC	Joint Research Centre of the European Commission
MCA	Multi-criteria analysis
MAI	Ministry of Agriculture and Irrigation
MWE	Ministry of Water and Environment
NWRA	National Water Resources Authority
PWCM	Pairwise Comparison Matrices
RS	Remote Sensing
SWSLC	Sanaá Water & Sanitation Local Corporation
USGS	United States Geological Survey
UNDP	United Nations Development Programme
RWH	Rain Water Harvesting
WHO	World Health Organisation
WLC	Weighted Linear Combination

1. Introduction

1.1 Context:

Water is the most valuable vital resource for all life forms on the planet including, food production, domestic, drinking, power generation, industrial and recreational use. Human beings, historically, have employed a variety of techniques to obtain water such as Water Harvesting structures, which play an important role in conserving precious natural resources such as, water and soil, which are depleting at alarming rate (Singh et al., 2009)

In arid and semi-arid countries, where the precipitation is naturally rare and erratic, the risk of crop failure is very high. As a response to this phenomenon of water scarcity, water harvesting has been used for thousands of years. Plant production can be increased significantly in drought prone areas by concentrating the rainfall/runoff in parts of the area using water harvesting structures (Prinz, 1996, Samra et al., 2002). Although many of old WH structures are abandoned and no longer in use, recently, there is a growing interest in reviving WH systems because of its environmentally sound and the easiness of integrating it with indigenous and traditional knowledge (Samra et al., 2002).

Constructing suitable water harvesting structures or applying changes in land management can reduce surface runoff, conserve water, and increase infiltration rate. Appropriate sites and structures of WH help in flood control in lower catchment, avoid excessive runoff, improving soil moisture availability and increase the water table (Singh et al., 2009).

Yemen has a rich heritage in managing water resources dating back to thousands of years. The great historical Marib dam and its ruins of irrigation structures, which discovered by the recent archaeological excavations of German Team in 1982 and 1984, dating some 4000 years ago (the middle of the third millennium B.C.) (Abdulrahman, et al., 1994 as cited in (Nasr, 1999). Spate irrigation systems in Yemen, diverted enough floodwater to produce agricultural products, dating back to at least 1,000 B.C. (Adato 1987, Eger 1988 as cited in (Prinz, 1996). The unique, spectacular mountain terraces of Yemen validate its long history of water harvesting.

Climate change in Yemen during the last few years has become a real concern (Miyan, 2015; Sieghart, 2009). Yemenis have been struck by severe droughts and depleted water supplies, extreme flooding and sea level rise (Miyan, 2015, Sieghart, 2009). The conditions of the long dry season and the great variability of the annual rainfall pattern, result in major changes of water availability and lead to a significant decrease in rain-fed crop production (Adeel et al., 2008; Falkenmark, 1997; Oweis et al., 2004; UNU-INWEH, 2009).

1.2 Problem Statement:

Water resources management in Sana'a Basin is a complex issue due to limited data, rapid population growth, aridity and complex physiographic environment. Today, groundwater in Sana'a Basin is the main water source for domestic, agricultural and industrial uses. The agricultural sector consumes about 90% of groundwater resources in the basin (WEC, 2004; Alderwish, & Dottridge 1998). However, groundwater is over exploited and levels are declining rapidly.

One of the strategies proposed to increase water use efficiency in Yemen is to improve the use of the great variety of indigenous water harvesting methods, which previous generations have developed and employed for thousands of years (Craig, 2012, Al-Wadaey and Bamatrf, 2010). The process and use of water-related data are currently low in Yemen due to the lack of using modern techniques in data collection and analysis (Craig, 2012). GIS and remote sensing tools are very useful techniques used to improve managing water resources (Craig, 2012). More reliable estimates of water resources can be provided by remote sensing data from satellites (Moore & Fisher, 2012). Since 60's there are significant researches and development works in term of water harvesting structures, however, few of these studies were carried out for selecting suitable sites for water harvesting structures in the watershed using modern information technologies such as RS And GIS (Singh et al., 2009).

To conclude, Sana'a Basin has limited data and all previous studies conducted in the Basin, concerning selection or evaluation of water harvesting sites and structures, were mainly focused on small parts of the basin vis.: (Alderwish, 2010; Noman, 2004; WEC, 2016; Alderwish & Dottridge, 1998). There is no single study used GIS and Remote Sensing as techniques to tackle the water harvesting research for the entire basin. Accordingly, this study aims to identify the suitable water harvesting sites and systems for the whole basin using modern techniques of GIS and RS.

1.3 Research Objectives

1.3.1 General Research Objective

The aim of this research is to identify suitable sites for indigenous rainwater harvesting systems in Sana'a Water Basin, Republic of Yemen, using Geographical Information Systems (GIS) and Remote Sensing (RS). The main outputs of this research will be a suitability map of water harvesting sites based on different criteria and a proven methodology for developing this map in places with limited data. The information generated will help decision makers in formulating policies and targeted investments in water management and soil moisture conservation in the Sana'a Basin.

1.3.2 Specific Research Objectives

The specific and immediate objectives of this research are:

1) Identify the appropriate application to study and map the suitable RWH sites and systems.
2) Distinguish a number of suitable techniques of RWH systems to be used.
3) Formulate criteria of suitability for the different systems.
4) Apply the formulated criteria to find suitable locations by using the accessible geodata.
5) Propose several indigenous water harvesting structures with relatively high suitability.
6) Assessing the quality of the results using sensitivity analysis and/or other validation techniques (if time allows).

1.4 Research Questions

In order to reach the mentioned objectives several research questions are drafted. The main research question is: *What are the suitable locations for different indigenous rainwater harvesting systems in Sanaá Basin when considering environmental factors?*

The main research question is subdivided into several sub-questions:

1) What is the appropriate application that can be used for the study and selection process of sites and systems of RWH?
2) What are the promising indigenous rainwater harvesting structures which can be used in the study area?
3) What are the criteria for determining suitability of different RWH sites?
4) Where are the suitable locations for different RWH systems in the basin?
5) What is the quality of the results (robustness)?

1.5 Related Work and Innovation

Many studies have been conducted in Sana'a basin. They include, but are not limited to water scarcity, assessment of water resources and recharge components. A research about how can water retention, recharge and reuse used in integrated natural resources management was conducted for Al Sayla, as the main wadi in Sanaá Basin (WEC 2016). Another study was carried out about the designs and tender documentations of Bahman check dams project in Sanaá (Stanley Consultant INC. 2006). In addition, a study concerning indigenous knowledge for using and managing water harvesting techniques in Yemen was conducted (Noman, 2004). From a regional perspective, many of the studies use GIS and RS for the selection of potential sites for water harvesting such as (Al-shabeeb, 2016; Al-Adamat et. al., 2010; Singh et al., 2009; Bakir & Xingnan 2008; El-Awar et al., 2000).

The innovativeness of this work is to further develop the methodology of suitability mapping for water harvesting using GIS and remote sensing and apply it in Sana'a Basin, Yemen with limited data. In Yemen there is lack in using GIS techniques and/or remote sensing in this kind of studies, and this study will use these advanced techniques to tackle the research problem.

In addition, local experts' opinions about the weight of different criterion and the required criteria will be conducted using a key informant analytical questionnaire.

1.6 Research Scope

To keep the research doable there is a need to define the research scope. In the previous paragraphs it has been discussed what will be researched, this paragraph will shortly address what will not be included in the research. The boundaries of the research will not exceed Sana'a Water Basin borders.

The study is not primarily about comparing different techniques used to better select water harvesting sites. Rather those techniques will be discussed in the theoretical framework and based on the literature review, only one of those techniques will be included in the research methodology.

In addition, all expensive and modern water harvesting structures such as stop dams will not be considered. The focus will be on the indigenous water harvesting structures which have little or no reliance on fossil fuels and are made of local materials. This research will also look for local, cheap and sustainable solutions that farmers can build and manage themselves.

1.7 Research Outline

This research is presented in six chapters as outlined below:

Chapter 1 gives an introduction about the context and the key problem that forms the basis of this research. In addition, the research objectives and questions, related works and innovation, and research scope are highlighted.

Chapter 2 reviews the theoretical framework of this research.

Chapter 3 presents the research approach in which the study area, data, and conceptual framework (methodology) are described. This chapter forms the basis of the following chapters.

Chapter 4 presents the data analysis in which the criteria weights and the suitability analysis are explained.

Chapter 5 discusses the results in which the results of the suitability maps are explained and validated. Besides, the sensitivity analysis is discussed.

Chapter 6 outlines the conclusions and recommendations arising from the research and also explaining the limitations and constraints faced in this research.

2. Theoretical Framework

2.1 Rainwater Harvesting Concepts

RWH is the practice of making water accessible by concentration of rainwater or runoff water diversion for the beneficial use, or it is the method of collecting runoff water generated from rainwater in larger areas and using it beneficially in smaller areas (Goins, 2002; Oweis et al., 2001; Beckers et al., 2013). Ancient civilizations used different WH structures to collect, store, and/or increases the availability of intermittent rainwater and surface runoff to irrigate crops and to supply water for animal and human uses (Beckers et al., 2013,). Traditional WH techniques have been practiced for millennia and led to the flourishment of those civilizations in many dry and semi-arid regions (Prinz, 1996; Edmunds & Cardona, 2006; Harb, 2015).

According to Kahinda et al. (2007) RWH has the opportunity to contribute to equal, efficient and sustainable use of water resources by mitigating spatial and temporal water scarcity, leading to water availability beyond the basic human needs, and hence facilitate small-scale productive activities. When planning and implementing RWH projects, more emphasis is made on the importance of economic, social, and environmental considerations to ensure sustainability (Pacey & Cullis, 1986).

RWH systems are flexible and can be adapted to local circumstances and should therefore be constructed according to the ecological characteristics of a specific region or study area (Mati et al., 2006).

2.2 Applications used for identifying suitable sites for RWH

The different criteria of the selection of suitable sites for RWH can be integrated into a tool using variety of applications. Adham et al. (2016) have categorized the applications that have been used to identify suitable site for RWH in arid and semi-arid regions (ASARs) in the last thirty years into four main groups: 1) GIS and RS, 2) hydrological modelling (HM) with GIS and RS, 3) multi-criteria analysis (MCA) integrated with HM and GIS/RS, 4) MCA integrated with a GIS. However, there are specific requirements with advantages and drawbacks for each method.

2.2.1 GIS and RS

GIS packages supported by RS data provide cost-effective and time-saving methods for identification of the suitable sites for RWH. This tool has advanced significantly in recent decades because of the computer technology development. Accurate information with high spatial and temporal resolution can be derived from RS before it is processed and analysed in GIS environments (Adham et al., 2016). GIS is considered to be a very useful tool to extract information especially in areas with limited data, which is often the case in most developing countries (Mahmoud, 2014). According to Adham et al. (2016) GIS and RS provide a data-reviewing capability which supports both errors identification and quality control. This method also produces easy-to-read/use information via maps and also offers a good opportunity to acquire a better understanding of any patterns. Although this application is cost-effective compared to other applications mentioned in the previous paragraph, it requires field surveys before implementing RWH systems to verify suitable sites. Furthermore, the quality (spatial and temporal resolution) and availability of the data affect the accuracy of GIS/RS method.

2.2.2 Hydrological modelling with GIS and RS

Runoff information is an important data for the identification of RWH suitable sites. HM has several methods to simulate the runoff such as the Soil Conservation Service (SCS), SCS with Curve Number (CN), and the Thornthwaite and Mather (TM) models. According to Adham et al. (2016) HM with GIS/RS methods provides a time-efficient and cost-effective technique for identifying suitable RWH sites and offers a rational means to facilitate decision-making.

There are advantages and disadvantages for each hydrological model and the model complexity, users, and data availability play an important role in the accuracy of the results. Applying HM method, particularly SCS approach, requires more detailed data because RWH is highly location-specific and this will lead to more difficulties when applying it for large areas. Moreover, some of the hydrological models are not available for free and require therefore a purchased license (Adham et al., 2016).

2.2.3 MCA integrated with HM & GIS/RS

MCA is a method of analysis which combines data of several criteria. Estimating a relative weight for each criterion, rather than assuming equal weight for all criteria, is one of the main rules of MCA. In addition, MCA compares two or more alternatives resulting in suggesting the suitable alternative (Banai-Kashani, 1989).

The integration of those techniques namely MCA, HM, and GIS results in a good tool for the identification of RWH suitable sites. This method is widely applied in several studies in ASARs, taking advantage of all techniques strengths. This integrated method has high flexibility in dealing with both qualitative and quantitative factors, yet it is recommended for data-rich regions (Adham et al., 2016).

2.2.4 MCA integrated with GIS and RS

In this method for selecting suitable sites for RWH, MCA is integrated with GIS without involving HM. This method is highly flexible in different regions with different area sizes, and the criteria can be easily changed or updated. MCA - GIS application is an effective tool to predict suitable sites for RWH in ASARs especially in data-poor regions (Adham et al2016). In addition, Tumbo et al. (2014) compared the resulted suitability map which generated by MCA - GIS method with the existing RWH technologies which obtained based on the indigenous knowledge of the farmers. The results indicated that high percentage of indigenous RWH technologies were located in the very high suitability levels. Strong matched of this method’s results and farmers' indigenous experiences makes it a powerful method (Tumbo et al. 2014).

2.3 Indigenous RWH systems

WH was more practiced in the past than it is now. Traditional WH techniques have been practiced for millennia in many arid and semi-arid zones as a key activity in helping poorer communities in rural areas to achieve water security and promoting their livelihoods (Prinz, 1996; Edmunds & Cardona, 2006).

The remains of WH structures in Yemen such as dams, reservoirs, ancient water storage and delivery systems confirm how ancient Yemen's people employed a wide variety of WH systems throughout the country's various agro-ecological zones. Archaeological missions have excavated several flood-control structures in Yemen; at Juban (Albeida), Raiboon (Hadhramout), and Aljanad (Taiz). These systems were in use between 800 BC and AD 300. These structures have served as flood-breakers, sediment traps, and water stores (water supply source) (Bamatraf, 1994; Oweis et al., 2004). The domestic water supply system in Aden, called *saharij,* is one of the oldest WH techniques dating back to the 1st millennium BC and discovered in the 19th century (Bamatraf, 1994). On the other hand the historical Marib dam and its irrigation system located in the historical city of Marib is a fine example of controlled irrigation (Francaviglia, 2000). It continued in operation for thousands of years before it is collapsed around the year 610AD (Bamatraf, 1994; Weiss and Gerlach, 2009).

In ancient times, people used RTRWH systems. Different types and sizes of underground cisterns to store water were used. In Yemen *Seqayat (s. seqayah)* are well-known underground tanks used for both drinking and irrigation purposes. *Khazzanat (s. khazan)*, modern structures typically constructed in a rectangular shape, are also widely used in Yemen with large capacities that exceed 2,800,000 cubic feet (Oweis et al., 2004; Oweis et al., 2012). In Istanbul, Turkey, the ancient Basilica Cistern with a capacity of 80000 m^3 is proposed to be the largest in the Mediterranean region (Bamatraf, 1994).

It is believed that the earliest WH structures for supplying drinking water for people and animals were built 9000 years ago in Edom Mountains in Jordan (Prinz, 1996). In the Ur area of Iraq[1], simple WH methods for domestic and agricultural use were practiced over 6500 years ago. Runoff farming systems were used in Negev 4000 years ago (Oweis et al., 2012). In Negev desert, a number of ruinous settlements, stone walls, cisterns, check dams and terraces along the hillsides were linked by artificial canals to wadis, where there are the remains of thousands of farms dating from the Nabatean period (Guttmann-Bond, 2010).

In the coastal area in the Libyan pre-desert, where the rainfall is variable with an annual mean volume of less than 50mm, hundreds of kilometres of runoff irrigation systems were excavated by the UNESCO Libyan Valleys team. This system lasted over 400 years until Roman times. The system served wealthy, densely populated communities where the level of agricultural

[1] Ur was an important Sumerian city-state in ancient Mesopotamia, located at the site of modern Tell el-Muqayyar in south Iraq's Dhi Qar Governorate

production was enough to generate a surplus of different crops and livestock (Prinz, 1996). Some WH techniques are still in practice today but not as much as in the past, when different WH systems played significant roles (Prinz, 1996). Different indigenous RWH techniques practiced in Yemen are given in bellow sections.

2.3.1 Check Dams

A Check dam can be a temporary or permanent structure in which the local available materials are used in its construction. Preventing the soil and water removal from the watershed is the main purpose of the check dam and it also stores water which can be used for groundwater recharge. Moreover, check dams reduce water flow velocity (flood control). It also can be used to convert runoff into canals or farms. One of the advantages of the check dams is the low cost because the local material and traditional knowledge are used. On the other hands, however, those structures can last about 2-5 years (Sivanappan, 1997).

2.3.2 Terracing

Terraces are defined according to Balci et al., (1989) as "*a series of level or virtually level strips running across the slope at vertical interval, supported by steep banks or risers*". They are used to reduce the velocity of the runoff, minimizing soil erosion, conserving soil moisture and fertility, facilitating modern cropping operations, promoting intensive land use on slopes, and reducing shifting cultivation.

Till 50 years ago, people in the highland areas were rely heavily on rainfed agriculture in stunning mountain terraces that give Yemen its unique landscape (Adeel et al., 2008; UNU-INWEH, 2009). The rich soil obtained from volcanic laves and pyroclastics in Yemen mountain land and the spring and summer rains of the semi-arid climate were an asset for locals. As a result, millions of terraced fields were constructed by old settlers on steep, rugged mountain slopes (Bamatraf, 1994). In the terraces, rainwater is collected and soaked into the shallow soil. Runoff is prevented from flowing down to the next terrace by walls at the edge of the terraces except during heavy rainfall events. Stones are the materials used to build the walls of the terraces, while the soil is not eroded because of the voids between the stones which allow water to move down to sequential terraces. In order to channel flow from one terrace to the next one, subsurface drainage is required in these areas. The design and construction of the terraces is made in a way to allow the runoff passage through sheet flow, and as a result, damages to the terraces due to runoff concentrating at certain points are prevented. It is important to construct the terraces in the upper parts of the wadis to make this method more effective (Fingure 1) (Noman, 2004).

Figure (1): Terraces on mountain slopes in the Yemen Highlands. Source: Noman (2004)

2.3.3 Ponds

Ponds are storage structures constructed for the purpose of storing and collecting water essentially from surface runoff. Ponds are useful for irrigation, and livestock (Noman, 2004; Sivanappan, 1997). In Yemen there are different type of indigenous ponds including; Bariks[2],

[2] Birak (singular birkah) are another roofless WH system, usually underground and smaller than the kuruf ponds.

Siqyat[3], Niqab[4], Kuruf[5], Mawajel[6], Khazzan[7]. The type, shape and size of the pond depend on many factors, such as water use, type of soil and local construction materials.

2.3.4 Spate Irrigation

Spate irrigation is the simplest type of water harvesting, known also as 'large catchment water harvesting'. According to Food & Agriculture Organisation FAO and the United Nations Development Programme UNDP (1987), spate irrigation is defined as "an ancient irrigation practice that involves the diversion of flashy spate floods running off from mountainous catchments where flood flows, usually flowing for only a few hours with appreciable discharges" (Cited in Steenbergen et. al., 2010).

Traditionally, spate irrigation is practiced in Yemen along the wadi courses and coastal plains of Tihama and south and eastern parts of the country. As a result, this technique covers a large portion of the cultivated area in Yemen (Noman, 2004).

It is believed that spate irrigation started in Yemen, when the Neolithic period became more arid. It has been practised for around 5000 years (Lawrence & Van Steenbergen, 2005).

2.4 Factors affecting the identification of potential RWH systems

2.4.1 Precipitation

Some of the key factors that should be evaluated in choosing RWH systems are the quantity, timing and variability of rain which occurs throughout a season or year. Precipitation also helps to determine the available soil moisture. At least 15- 20 years of rainfall data are needed in arid lands. Generally, microcatchments or contour strips is suitable when the annual rainfall is no more than 150 mm. Farming systems can be constructed in areas with annual rainfall more than 250 mm. However, RWH will probably never be feasible from an economical perspective in areas with an average annual rainfall less than 50 – 80 mm (Thames, 1989).

[3] Siqyat (singular siqaya) are roofed techniques. They are commonly built partly below ground with the roof showing above ground.
[4] Niqab (singular Noqbah) are underground, roofed and handmade cisterns.
[5] Kuruf / karifis (s. karif) are big ponds or roofless man-made cisterns. This pond-type of storage structure is generally formed by damming a simple low-land area and diverting runoff into it from the surrounding areas.
[6] Majel (plural mawajel) is the common name given, in the northwestern areas of the highland zone of Yemen -sad (dam).
[7] A khazzan (plural khazzanat) is a roofless modern storage system.

2.4.2 Slope

Slope is an important key factor to assess the method of surface RWH technique since it influences the recharge and infiltration of the targeted area because of the runoff (Prinz et al., 1998; Critchley & Siegert, 1991). Thus different systems of RWH depend on the slope degree of a given area. Water harvesting for some kind of RWH techniques is not recommended for areas with slopes greater than 5% because the distribution of the runoff is uneven and the requirement of large quantities of earthwork which consider as inefficient from an economical perspective (Critchley & Siegert, 1991).

2.4.3 Land Use/Land Cover

Land use/cover (LU/LC) is an important factor and plays several roles in the selection of RWH sites. The effects of rainfall are modified by the land use/cover of the study area and it also influences soil erosion (Adinarayana et al., 1995). In addition, Land use/cover type has an effect on the runoff and soil erosion (Nunes et al. 2011). Some land use/cover types such as shrub cover can increase the rainfall infiltration capacity and decrease the rate of soil erosion of an area.

2.4.4 Soil

Soil in the catchment area ideally should be with a high runoff coefficient, whereas in the cultivated area the soil should be a deep, fertile loam. Soil characteristics in most cases for rainwater harvesting must be similar to those for irrigation. The depth of soil in areas where RWH systems are proposed is specifically important. The capacity to store the harvested runoff is high in deep soils and they also provide nutrients for plant growth. It is not recommended to establish RWH systems in area with soils of less than one meter deep, unless it is a storing system. Ideally, two meters or more is the best, yet barely found in practice (Critchley & Siegert, 1991).Several important soil characteristics are influenced by the soil texture in terms of infiltration rate and available water capacity. There are three broad classifications for soil texture, namely sandy soils, loamy soils, and clayey soils (Critchley & Siegert, 1991). According to the department of geography of Michigan State University (MSU), Sandy loam and loamy soil are best for most plant growth because they are rich in nutrients and they allow the movement of water, air and nutrients to plants. As a result, Sandy loam and loam soil are suitable for RWH systems which are used for agricultural purposes such as terraces and spate irrigation fields.

2.4.5 Socio-Economic

In 2003, FAO listed socio-economic factors as one of the main criteria for the selection of RWH sites (Kahinda et al., 2007). After 2000, many studies conducted to identify the suitable sites for RWH began emphasizing the importance of the socio-economic parameters beside the biophysical criteria and it was concluded that socio-economic parameters are needed to enhance the selection of optimum sites (Adham et al., 2016).

2.5 Criteria used for selecting suitable RWH sites

Suitability selection for RWH sites relies on several criteria. Biophysical and socio-economic are considered to be the two main groups of criteria. Pre 2000 studies focused only on biophysical criteria, such as rainfall, drainage network, soil type, slope and land use/cover. However, later studies have tried to combine socio-economic criteria with the biophysical components, in which the later are considered also as main criteria for the selection of RWH sites (Adham et al., 2016).

In the Saudi Arabia case, five criteria were chosen to select the best in-situ system locations; rainfall, runoff, slope, soil type and land use/cover (Mahmoud & Alazba, 2014). Another study (Mahmoud, 2014) carried out in Saudi Arabia to identify the suitable sites for groundwater recharge zones used almost the same five parameters. Moges (2009) conducted a suitability analysis for some of the RWH systems, namely ponds and in-situ, where rainfall, slope, soil type, soil depth and Land use/Cover criteria were used. In Tanzania, suitable locations for ndiva (storage reservoir), terrace and boda (in-situ) were identified using six criteria; rainfall, slope, soil type, soil depth, land use/cover, and drainage network (Tumbo et al., 2014). In Syria (Pauw et al., 2008) , only five criteria were chosen to locate the suitable sites for micro and macro catchments, in which rainfall, slope, soil type, soil depth, and land use/cover are used. All the aforementioned studies however did not apply/consider the socio-economic criteria for the selection process of RWH sites.

On the other hand, several studies in ASARs have used socio-economic parameters combined with the main biophysical criteria. For instance, in Malaysia, Yusof et al. (2000) identified the suitable locations for RWH reservoirs using slope, soil type, and land use/cover as a biophysical criteria and distance to settlements and roads as a socio-economic criteria. In the Basalt Aquifer/NE Jordan, four categories of criteria and six sub criteria are considered as most important attributes for locating the ponds sites in the study area (Al-Adamat, 2008). Rainfall, slope, soil type, land use/cover, distance to (settlements, streamflow, borders, roads, and agricultural area), and infrastructures were involved (Al-Adamat, 2008). Another two studies conducted in Jordan to select suitable sites for two different RWH systems, namely ponds and reservoirs used the same biophysical criteria (rainfall, slope and soil type). However, they did not use the same socio-economic criteria. The study of the ponds (Al-Adamat et al., 2010) used only two socio-economic criteria, namely distance to settlements and distance to streamflow. Whereas, the study of the reservoirs (Al-Adamat et al., 2012) involved more socio-economic criteria, such as distance to (settlements, streamflow, borders, and agricultural area). Moreover, Al-shabeeb (2016) identified the suitable locations for RWH systems in Azraq Basin-Jordan using the two groups of criteria, in which rainfall, slope, soil clay contents, lineament density, geology, drainage density, international borders, wadis, roads, urban, wells, and farms were involved in the analysis.

It is not easy to define a certain number of criteria for RWH site selection as the objectives of decision makers can vary depending on the need and the usage of RWH systems. At the same time, a general datasets of criteria for RWH site selection faces difficulties due to the specific local conditions, in both environment and human society, and decision makers' inclinations between sustainable development and fast development. There are however some criteria related to RWH systems safety and fundamental requirements which are substantial for the construction of RWH systems, such as rainfall, slope, Soil and Land Cover/Use (Dia, 2016).

2.6 Weights and classifications of the criteria

There are several studies have been carried out to identify suitable sites for RWH systems using different criteria's weights and classifications. Table (1) summarises the weights and classifications of the criteria used in 4 different studies conducted for the purpose of selecting process of suitable sites for RWH.

Table (1): Summary of weights and classifications of the criteria used in different studies.

Study	Al-Shabeeb, 2016 (RWH in General)			Dai, 2016 (RWH Dams)			Krois & Schulte, 2014 (RWH Terraces & bunds)			Moges, 2009 (RWH Ponds)			Moges, 2009 (RWH In-situ)		
Criteria	Weight	Classification	Preference value	Weight	Classification	Preference value	Weight	Classification	Preference value	Weight	Classification	Preference value	Weight	Classification	Preference value
Rainfall	0.245	≥500	4	0.343	500 – 639mm	5	0.04	400-600mm	9	0.198	> 300	5	0.178	> 300	5
		500>R≥300	3		400 – 500	4		200-400&600-800	7		225 - 300	4		225 - 300	4
		300>R≥100	2		300 – 400	3		800-1000	5		150 - 225	3		150 - 225	3
		<100	1		200 – 300	2		100-200 &1000-1200	3		75 - 150	2		75 - 150	2
					112 - 200	1		0-100	2		< 75	1		< 75	1
Slope	0.202	<3%	4	0.254	0-1 (°)	5	0.39	Terraces ° / Bunds °		0.072	< 2	3	0.085	< 2	5
		5>S≥3	3		1 – 2	4		18-30 / <2 – 5	9		2 – 8	5		2 – 8	4
		10>S≥5	2		2 – 3	3		10-18>30 / 5 – 10	7		8 – 15	4		8 – 15	3
		>10	1		3 – 4	2		5 – 10 / 10 – 18	5		15 – 30	2		15 – 30	2
					4 – 5	1		2 – 5 / 18 – 30	3		> 30	1		> 30	1
					Higher than 5	0		0-2 / >30	1						
Soil Texture	0.15	≥35% clay	4	0.116	Clay Loam	4	0.15	15-35 % Clay	9	0.432	Fine	5	0.426	Fine	2
		35>C≥18	3		Loam	3		6 – 15	7		Fine and medium	4		Fine and medium	3
		18>C≥10	2		Sandy Loam	2		35 – 55	5		Medium	3		Medium	5
		<10	1		Sand	1		0 – 6	3		Medium and coarse	2		Medium and coarse	4
								>55	1		Coarse	1		Coarse	2
Soil Depth	-	-	-	-	-	-	0.14	>1.0	9	0.136	>1.5	5	0.262	>1.5	5
								0.5 – 1.0	7		1.0- 1.5	2		1.0- 1.5	5
								0.3 – 0.5	5		0.50 - 1.0	1		0.50 - 1.0	5
								0.2 – 0.3	3		0.25 - 0.5	1		0.25 - 0.5	3
								< 0.2	1		< 0.25	1		< 0.25	1
Land Use/Cover	-	-	-	0.07	Bare Land	4	0.14	Agriculture	9	0.046	Intensively cultivated	5	0.049	Intensively cultivated	5
					Shrub and Herb	3		Meadows, Shrub, Scarce Agriculture	7		Moderately cultivated	5		Moderately cultivated	5
					Forest	2		Grassland	5		Forest, exposed surface	2		Forest, exposed surface	1
					Farmland	1		Forest	3		Mountain	2		Mountain	1
					Water	0		-	1		Water body, urban area	restricted		Water body, urban area	restricted
					Settlement	0		Infrastructure, Water	0						

Study / Criteria	Al-Shabeeb, 2016 (RWH in General)			Dai, 2016 (RWH Dams)			Krois & Schulte, 2014 (RWH Terraces & bunds)			Moges, 2009 (RWH Ponds)			Moges, 2009 (RWH In-situ)		
	Weight	Classification	Preference value	Weight	Classification	Preference value	Weight	Classification	Preference value	Weight	Classification	Preference value	Weight	Classification	Preference value
Lineament Density	0.142	0<L≤1.5	4	-	-	-	-	-	-	-	-	-	-	-	-
		1.5<L≤2.5	3												
		2.5<L≤3.5	2												
		>3.5	1												
Geology	0.128	Chalky marl,Marl, Limestone	4	0.177	High Resistance	4	-	-	-	-	-	-	-	-	-
		Limestone, dolomitic limestone	3		Moderate Resist.	3									
		Limestone, Chalk, Chert	2		Slightly Low Resi.	2									
		Basalt	1		Low Resistance	1									
Drainage	0.133	>2.55(km/sq.km)	4	0.04	5 order	5	-	-	-	-	-	-	-	-	-
		2.55>D≥1.5	3		4	4									
		1.5>D≥0.75	2		3	3									
		<0.75	1		2	2									
					1	1									
Runoff coefficient	-	-	-	-	-	-	0.14	> 0.9	9						
								0.6 – 0.9	7						
								0.3 – 0.6	5						
								0 – 0.3	3						
								-	1						
Groundwater Depth	-	-	-	-	-	-	-			0.115	< 40 m	2			
											40 - 120 m	4			
											high relief area	5			

3. Research Approach

3.1 Study Area

Sanaá water basin is located in the central highland of Yemen. Figure 2 shows Sana'a basin and its sub-basins as in Japan International Cooperation Agency (JICA) study 2007. The area of the basin is 3200 km^2 and the average elevation is 2200 m above sea level. The capital city of Yemen, Sanaá city, is included within the basin boundaries. It has grown during the last three decades to be the largest urban centre in the country. The population of the city has raised due to rapid urbanization to about 2 million capita. Sanaá Basin is mostly an intermountain plain which is surrounded from the west, south and east by highlands (Al-Sakkaf, 2006). Different landscape forms are marking the topography of the basin. The topography is defined by four major physiographic units, namely plateau, terraced hillslopes, peneplains and wadis. The basin has a low precipitation and an erratic pattern. Distinguished spatial and temporal variations in precipitation are witnessed in the area. Average annual temperature is approximately 19 ^oC and the average annual precipitation is about 220 mm. Therefore, the basin is classified as semi-arid area based on these climate characteristics (Al-Sakkaf, 2006).

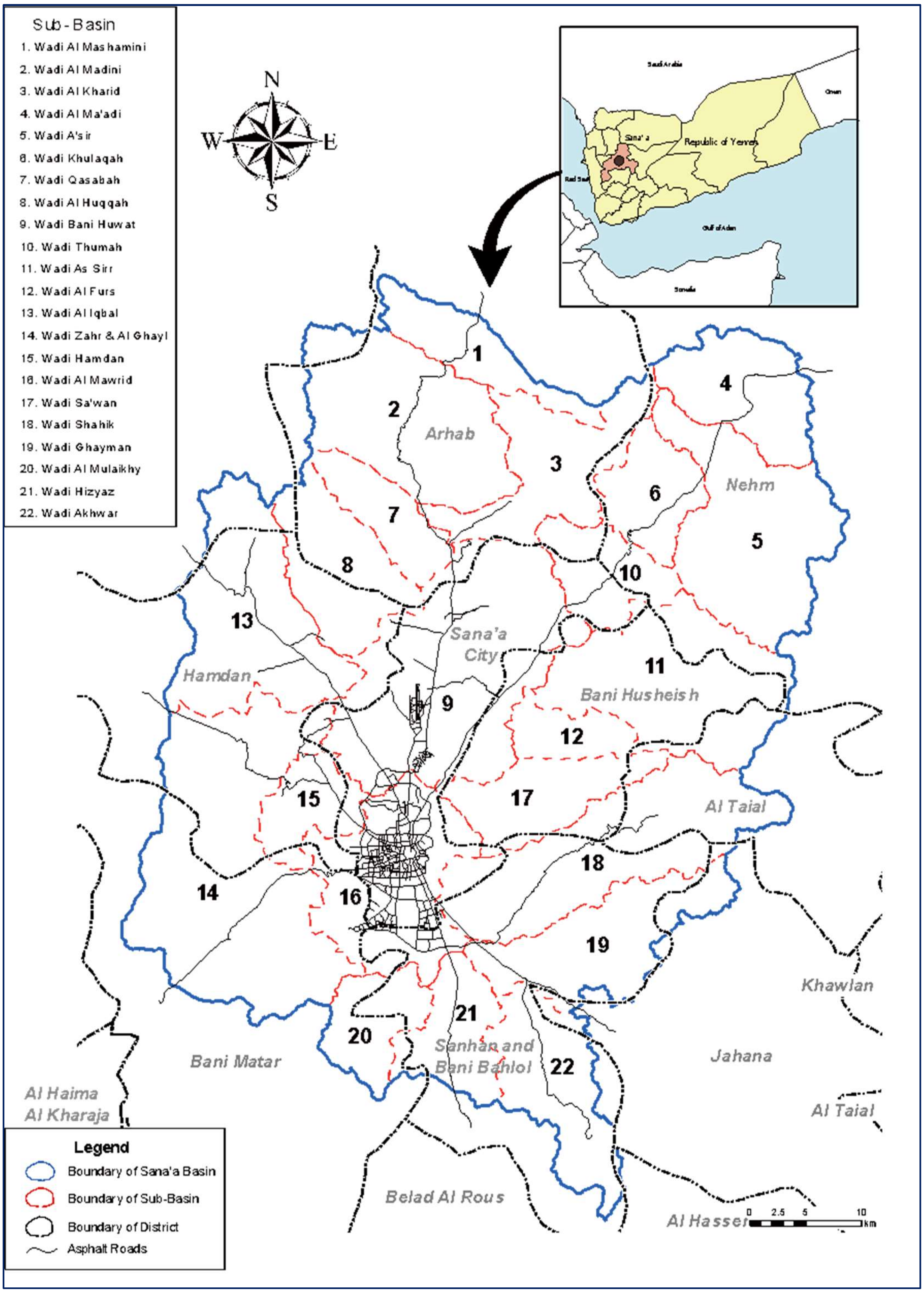


Figure (2): Sana'a Basin and its Sub-basins.

Source: JICA, (2007)

3.2 Data

3.2.1 Digital Elevation Model (DEM)

The DEM used in this study is the Shuttle Radar Topography Mission (SRTM) Global Digital Elevation Model (GDEM) which is an international project spearheaded by the US National Geospatial-Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA). This is the third version of the GDEM which was generated in 2015 with resolution of 1 arc second (30 m) (Figure 3). According to Elkhrachy (2017) the 30m SRTM elevations data presented a better absolute vertical accuracy than the absolute vertical accuracy of the ASTER version 2.

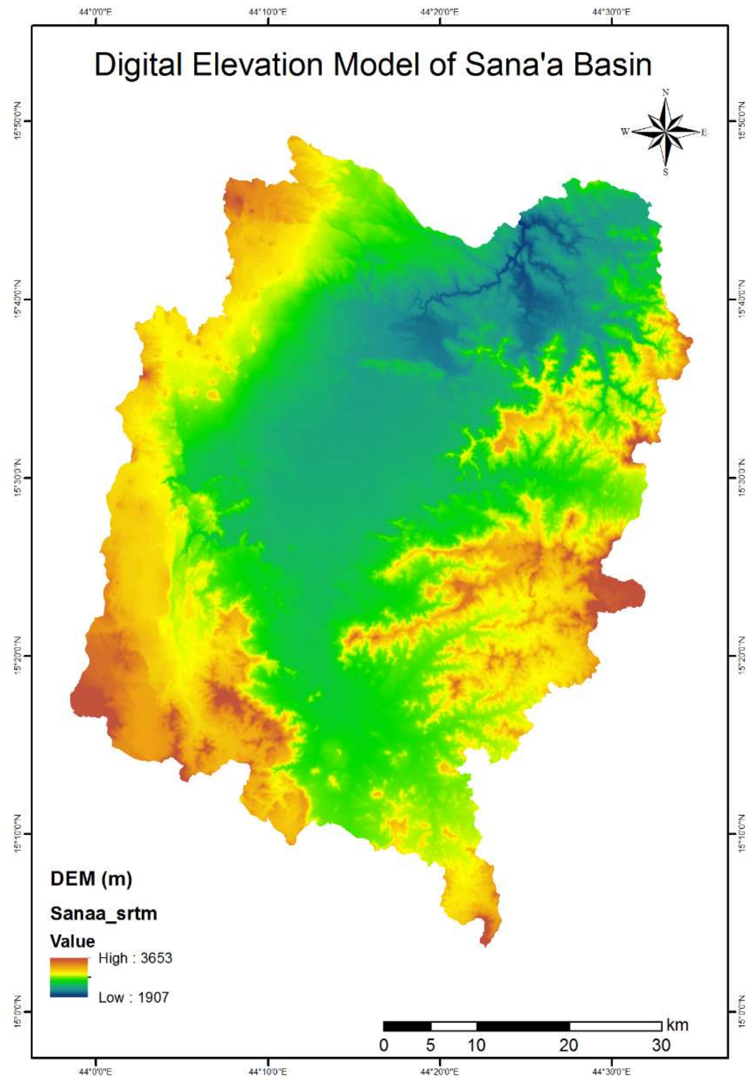


Figure (3): Digital Elevation Model of Sanaá Basin.

3.2.2 Rainfall Data

According to the summary report of Sanaá Basin Water Management Project (SBWMP) (2010), Sanaá basin has about 24 rainfall stations which have been installed since 1970. A number of 15 stations were installed within the basin while the rest were installed outside in a close distance to the basin's boundary. Unfortunately, none of these stations has continuous data for the entire period. The range of the records in most stations is between two to seven years. Based on the available data, rainfall in Sana'a is ranged between 110 – 350 mm/year with some years having much higher rainfall amounts above 350 mm (flood events) (CES & BRGM, 2010, Taher, 2016, Al-ameri et al., 2014). The maximum annual rainfall of about 430 mm occurred in 1996 while the lowest annual rainfall of 106 mm occurred during the year 1991.

The spatial distribution of the rainfall however is not indicated in this data which makes it difficult to be used in the analysis. Therefore, precipitation data with a spatial distribution derived from the WorldClim- Global Climate Data version 2 will be used for this study. The average monthly rainfall data for the years from 1970-2000 is available with high spatial resolution of 30 seconds (~1 km) (Figure 4).

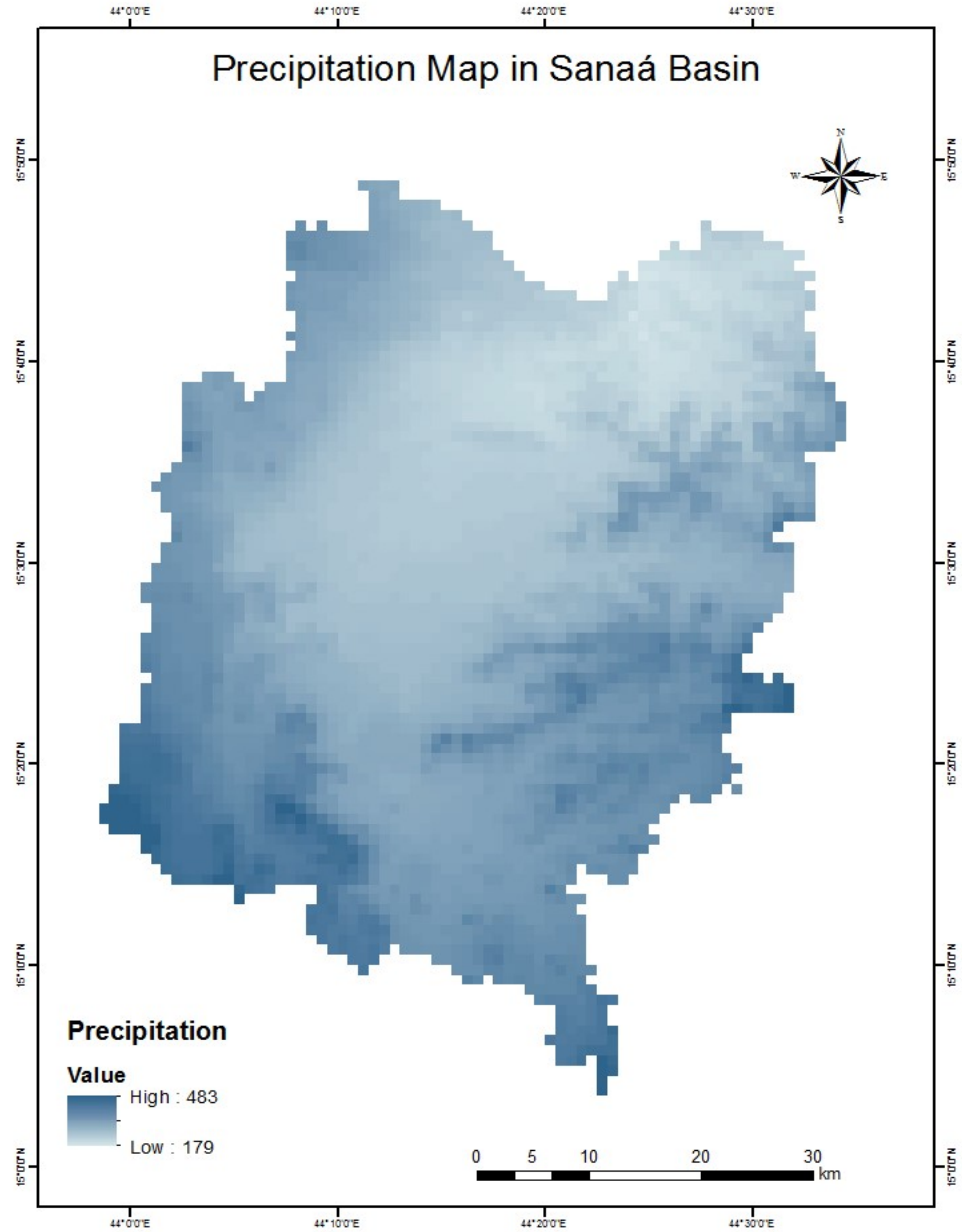


Figure (4): Precipitation Map in Sanaá Basin.

3.2.3 Soil Data

The soil data used in this study is The Harmonized World Soil Database (HWSD). HWSD version 1.2 is the result of collaboration between many organisations, namely FAO with International Institute for Applied Systems Analysis IIASA, ISRIC-World Soil Information, Institute of Soil Science, Chinese Academy of Sciences (ISSCAS), and the Joint Research Centre of the European Commission (JRC). This database was generated in 2012 with spatial resolution of 30 seconds (~1 km) (Figure 5)[8].

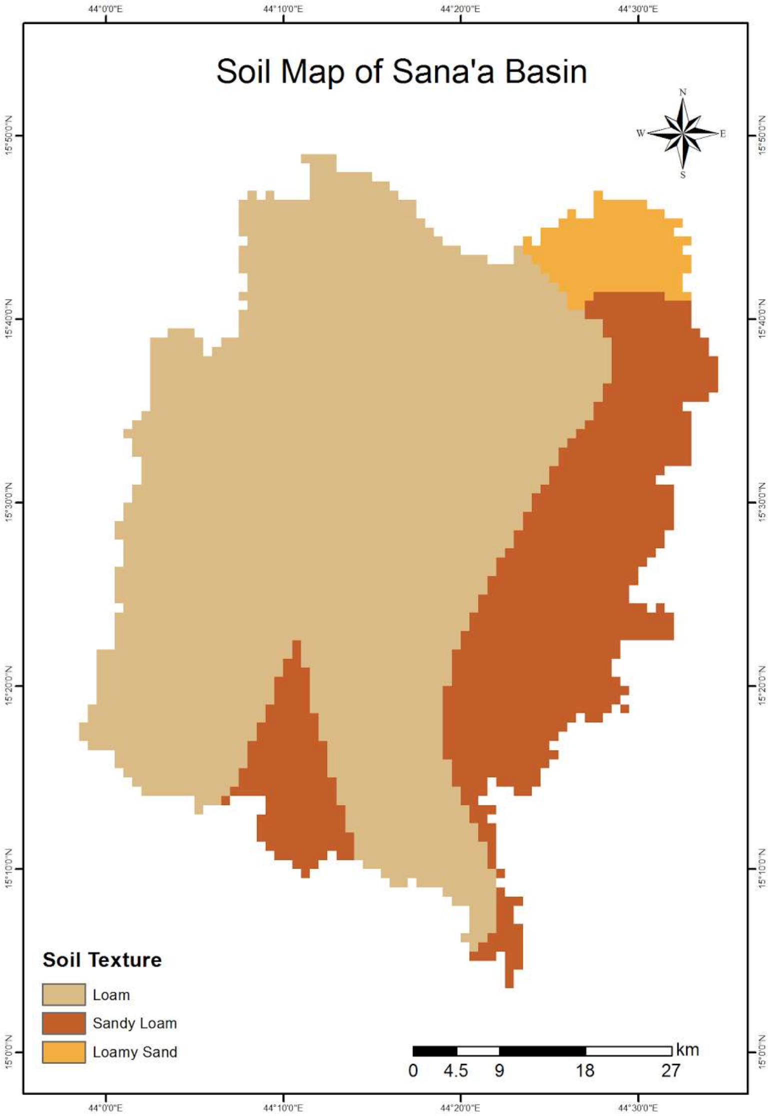


Figure (5): Soil Map of Sanaá Basin.

[8] This dataset is acquired from http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/.

3.2.4 Land Cover/ Land Use Data

Land cover/ land use data (BaseVue 2013) used in this study is owned by ESRI and is developed by MacDonald, Dettwiler and Associates Ltd. (MDAUS). This data was created in 2015 with spatial resolution of 30 m. This dataset is acquired from ArcGIS Online.

According to the Land cover data shown in Figure (6), most of the area of Sana'a Basin are covered by barren/minimal vegetation located in the north and general agriculture located in the middle and southern parts of the basin. Shrub/Scrub areas are covering a large areas and spread in almost the whole areas of the basin. Low, medium and high density of urban areas (The Capital City) are located in the south part of the basin.

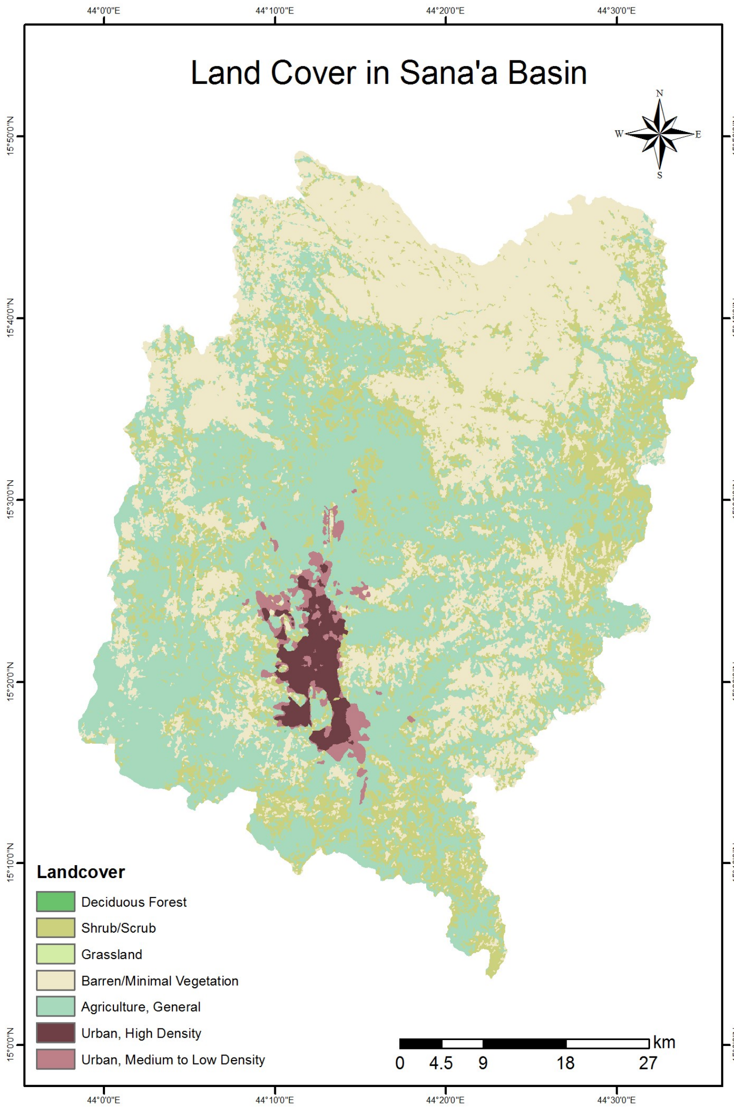


Figure (6): Land Cover/Land Use in Sanaá Basin.

3.2.5 Socio-Economic Data

3.2.5.1 Urban Area

Figure (7) illustrate the urban area in Sana'a water basin. This data is extracted from the Land use/cover map of the study area and was created in 2015.

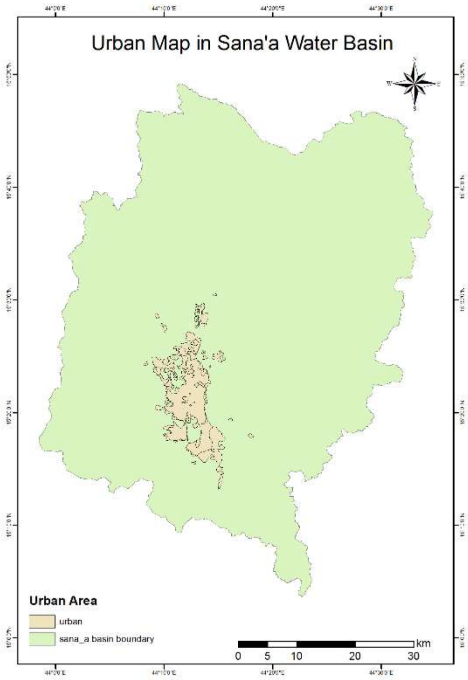


Figure (7): Urban map

3.2.5.2 Roads

Figure (8) shows the asphalt roads in the basin. This data was collected in 2007 and obtained from the General Authority of Lands Surveying and Urban Planning.

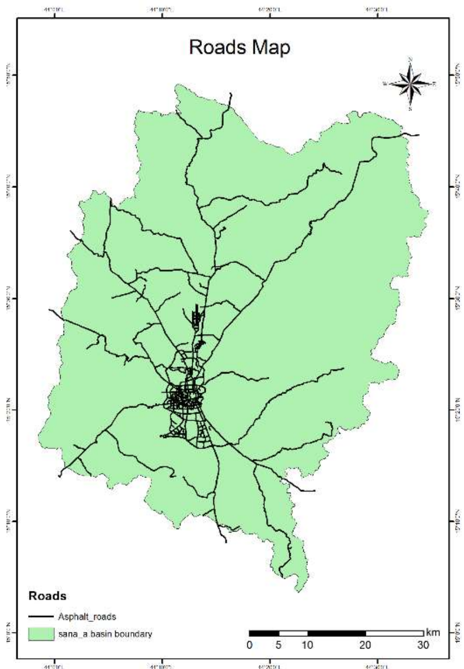


Figure (8): Roads map

3.2.5.3 Wells

Figure (9) shows the water wells in the basin. This data is obtained from the Water and Environment Centre (WEC). The wells' inventory in 2004 includes all existing wells at that time despite their status. Therefore, this data was cleaned in order to exclude all dry and abandoned water wells.

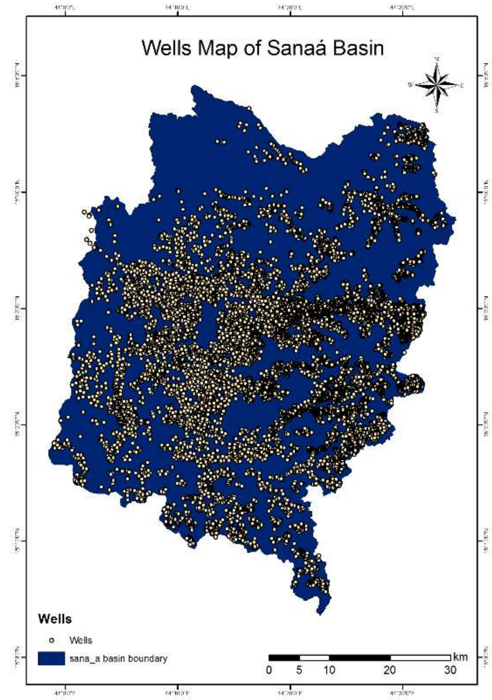


Figure (9): Water wells map

3.2.5.4 Dams

Figure (10) shows the dams in the basin. This data is was gathered in 2007 and obtained from the National Water Resources Authority (NWRA) – Sana'a Branch.

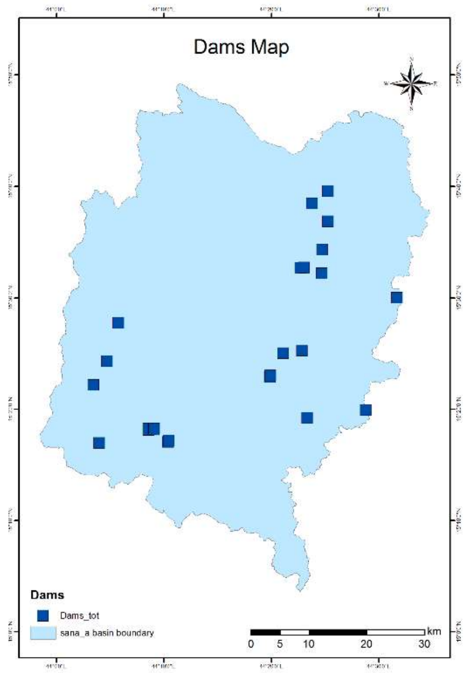


Figure (10): Dams map

3.2.5.5 Wadis

Figure (11) shows the wadis in the basin. This data was generated in 2007 and obtained from the Water and Environment Center (WEC).

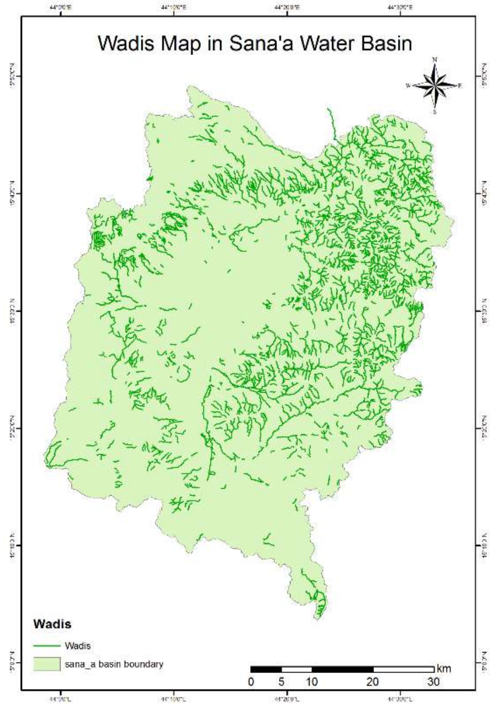


Figure (11): Wadis map

3.2.5.6 Sewage Passage

Figure (12) shows the open sewage passage in the basin. This data was collected in 2007and obtained from Sana’a Water & Sanitation Local Corporation (SWSLC).

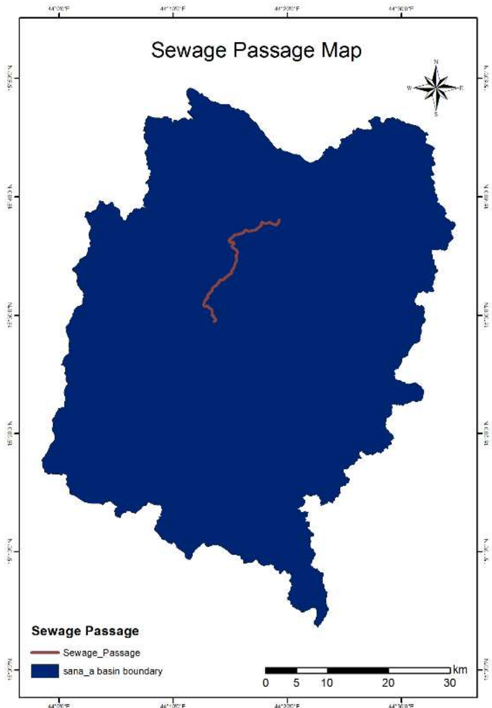


Figure (12): Sewage Passage map

3.3 Methodology

This research will identify suitable sites for indigenous rainwater harvesting systems using GIS and RS techniques. The diagram (Figure 13) and Table (2) illustrate the workflow of the research and the used applications. The methodology of this research is based on several studies carried out to tackle the RWH suitability analysis problem such as (Dai, 2016; Al-shabeeb, 2016; Mosate, 2016; Al-Adamat et. al, 2010).

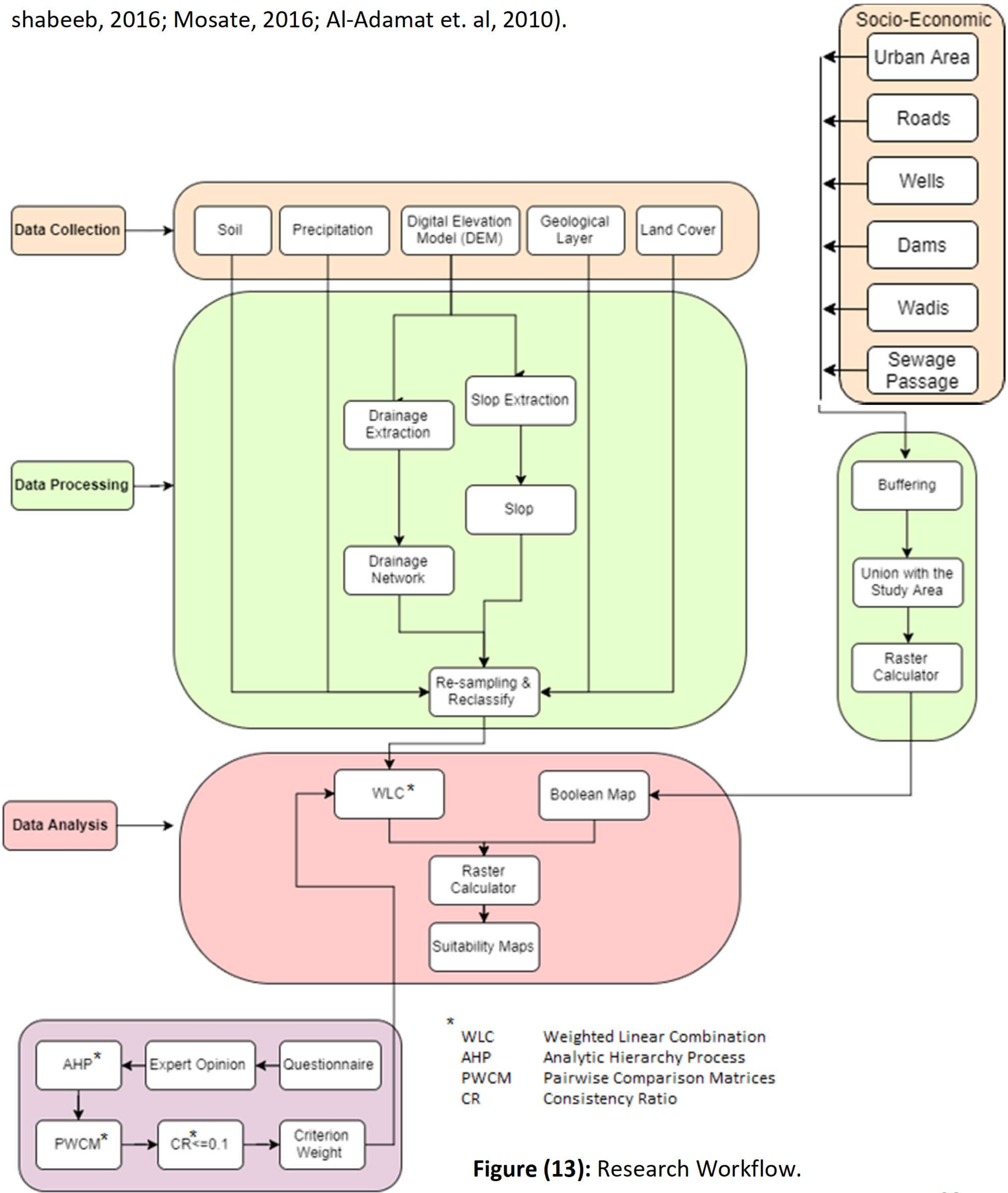


Figure (13): Research Workflow.

Table 2: Summary of the methods used to address each research question

#	Research questions	Outline of methodology
1	What is the appropriate Application that can be used for selection process of sites and systems of RWH?	Literature review
2	What are the promising indigenous rainwater harvesting structures which can be used in the study area?	Literature review & Designed questionnaire
3	What are the criteria for determining suitability of different RWH sites? (Environmental factors and the weight of each factor)	- Designed questionnaire & literature review. - AHP & PWCMs
4	Where are the suitable locations for RWH systems in the basin?	MCA & GIS
5	What is the quality of the results (Robustness)?	Sensitivity analysis and/or results validation

3.3.1 Adapted method for identifying suitable sites for RWH

The application of MCA integrated with GIS will be used to determine the suitable sites of RWH systems in the study area (see section 2.2.4)This method is an effective tool to predict suitable sites for RWH in data-poor regions. In addition, the validation of the results of this method based on the indigenous knowledge of farmers, have proved its robust (Tumbo et al., 2014). The study area of this research has limited data and it is considered to be a semi-arid region.

3.3.1.1 Multi-criteria analysis

The purpose of this process is to find the most suitable locations for RWH systems within the study-area. This process will be done by the means of MCA which allows to combine several relevant criteria into one final outcome. A MCA is a very common method in GIS-based decision making that based on different criteria. However, the decision can be based on factors or constraints. Factors enhance the suitability of an area and constraints limit the suitability (Eastman et al., 1995). After selecting factors and constraints, the criteria need to be standardized in order to be able to make a useful overlay. This process converts the values and the most suitable areas are reclassified with the highest value (mostly 10) and the least suitable areas with the lowest value (0). After the standardization the criteria can be weighted based on their importance. This allows making more important criteria more influential on the result. Overlaying the standardized and weighted criteria leads to a suitability map which shows which areas are more suitable and which are not suitable (Heywood et al., 2011).

3.3.1.2 Analytical Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP), is an effective method for handling complex decision making. It helps to capture both subjective and objective aspects of a decision by reducing complexity of decisions to a series of pairwise comparisons followed by a combination of results. This method was initially developed by Saaty (1980). AHP is implemented in GIS as a method of MCA to define weight for each evaluation criterion based on the pairwise comparisons of the criteria. Criterion with higher weight is more important than the others. This technique also has the ability to check the consistency of the judgments, thus decreasing the bias in the process of decision making. Using AHP, both tangible and intangible criteria can be measured with accurate scales (Saaty, 2013). Several studies have been carried out for the determination of most suitable sites for RWH using AHP such as (Al-shabeeb, 2016; Munyao, 2010; Oberle, 2004). A typical AHP hierarchy is shown in figure (14).

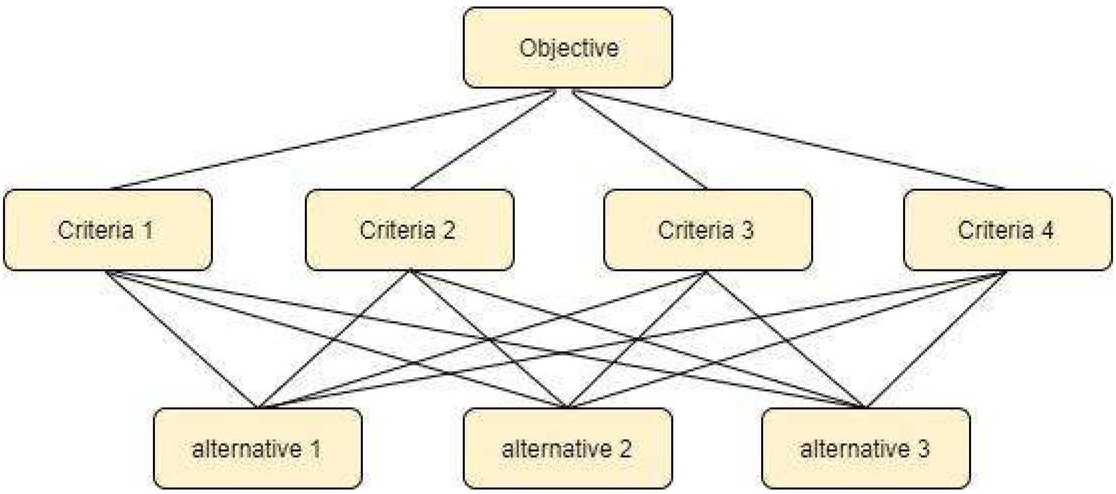


Figure (14): Typical AHP Hierarchy.

3.3.1.3 Pairwise Comparison Matrices (PWCMs)

The pairwise Comparison Matrices PWCMs is used to compare all possible pairs of criteria to define which criterion has higher priority. The AHP approach is based on a series of PWCMs, which compares all the criteria to each other. A scale from 1 to 9 is suggested by Saaty (1980) for PWCMs elements. In this scale, the factors with equal importance are indicated with a value of 1 and factors with extreme importance over another factor are indicated with a value of 9. Table (3) shows the scales for the pairwise comparisons method with brief explanation.

Table 3: Scales for the pairwise comparisons method, adapted from Saaty (2008).

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Equal to moderate importance	
3	Moderate importance	Experience and judgement slightly favor one activity over another
4	Moderate to strong importance	
5	Strong importance	Experience and judgement strongly favor one activity over another
6	Strong to very strong importance	
7	Very strong importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very strong to extremely strong importance	
9	Extremely strong importance	The evidence favoring one activity over another is of the highest possible order to affirmation
Reciprocals of above	If activity *i* has one of the above non-zero numbers assigned to it when compared with activity *j*, the *j* has the reciprocal value when compared with *i*	

3.3.1.4 Evaluation of matrix consistency

The value generated from the PWCM depends on subjective judgement which might lead to errors in the results. Thus, an evaluation is required. A consistency check therefore is applied to the PWCM to identify the judgement errors and to calculate a consistency ratio (CR). The CR indicates the ratio of the Consistency Index (CI) to the average random consistency Index (RI) (Saaty, 1980). A table of the value of RI according to the number of criteria as shown in Table (4) was developed by Saaty (1980). The assessment of the consistency to assign the CR involves the following operations:

1) Computing the Principal Eigenvalue (λmax).
2) Calculating the Consistency Index.
3) Selecting the appropriate value of RI.
4) Calculate CR. The maximum value of the CR for an acceptable PWCM is 0.1 (Saaty, 1980).

Table 4: Values of Random Index (Saaty 1980)

Number of criteria	2	3	4	5	6	7	8
Random Index	0	0.52	0.9	1.12	1.24	1.32	1.41

3.3.1.5 Boolean Technique

Boolean technique is based on the variables which has only two possible values; True or False. This technique overlay using operators such as AND operator (pessimistic hypotheses) and OR operator (for both optimistic and the pessimistic hypotheses). The use of Boolean method for identifying the suitable sites for water harvesting systems have been addressed in many studies such as (Al-shabeeb, 2016; Al-Adamat et. al, 2010). This method will be used in the analysis of the socio-economic data of the study area.

3.3.1.6 Weighted Linear Combination (WLC)

The weighted linear combination (WLC) technique is a modified version of the index overlay technique (Eastman, 1997). Malczewski (2004) indicate that WLC includes standardization of suitability maps by assigning weights of relative importance to the criteria, and then integrating the weights and standardized maps to get an overall suitability map. This method is flexible in selecting the optimum sites and therefore provides better site selection. In addition, this technique has been adopted in several researches such as (Al-shabeeb, 2016; Mosate, 2016; Al-Adamat et. al, 2010).

3.3.2 Adopted Selection Criteria

Based on the specific characteristics of Sanaá Basin, literature review of previous studies, and the available data, six criteria are chosen for this study including: Precipitation, slope, soil type, land use/cover, and drainage network. Besides, seven socio-economic parameters will be included in the analysis, namely urban areas, roads, wells, dams, wadis, and sewerage passage to select the optimum sites for water harvesting in the study area.

3.3.3 Selection of the Local Experts

The criteria obtained from the literature review, for the purpose of selecting suitable sites of RWH in Sana'a Basin, is sent to the local experts in order to determine the relative importance of different criterion to each other. Besides, the local experts have been asked to determine the most important traditional RWH techniques that can be used with an indication of suitable locations from their perspectives. The proposed locations for the RWH techniques is used for the validation of the final suitability maps. Appendix (1) shows the list of questionnaires, which has been already discussed, verified and pre-tested by two local experts. The five targeted local experts are from Sanaá University, Water and Environment Centre (WEC) and other public and local institutions that are relevant to the water harvesting. They are with different background and experiences related to water, soil, RWH and socio-economics. Those experts are selected based on their knowledge of the study area in particular and the water issue in Yemen in general.

3.3.4 Data Processing

3.3.4.1 DEM Mosaicking

Sana'a water basin is covered by 2 pieces of SRTM DEM. Raster mosaic is implemented to make these 2 individual DEM into one in order to have a more efficient analysis.

3.3.4.2 Projection & Reshape & Uniform Resolution

In this part of the processing, it is required to adjust all the used data into one particular coordinate system and with the same spatial resolution. The projections of the data in this research are different. To change the projections into one unified coordinate system, re-projection is applied. The selected projection coordinate system is WGS_1984_UTM_Zone_38N, which is the one used officially in Yemen. All the datasets gathered are reshaped from a national or global scale into the scale of the study area. To facilitate the implementation of raster calculation in the analysis, all datasets are adjusted into a uniformed spatial resolution (30m) which is the resolution of the DEM.

3.3.4.3 Precipitation

The acquired precipitation data from the WorldClim- Global Climate Data version 2 for the years from 1970-2000 is in a monthly based. Therefore, a raster data aggregation is applied to generate one raster map including the annual rainfall in the basin. According to the map (Figure 15), the mean annual rainfall in Sana'a Basin ranges between 179 mm in the north-eastern areas to 483 mm towards West and Southwestern areas. A re-classification is carried out to convert the continuous data into discrete data and to make individual values into categories related to preferential level of constructing RWH systems on. The classes illustrate the annual precipitation in the level of *<179 mm, 179 mm – 200 mm, 200mm – 300mm, 300 mm – 400 mm, and 400 mm – 483 mm* (Figure 15). Table (5) indicates the preference value for different rainfall classes for each RWH system in which the intervals between the classes are after Dai, (2016).

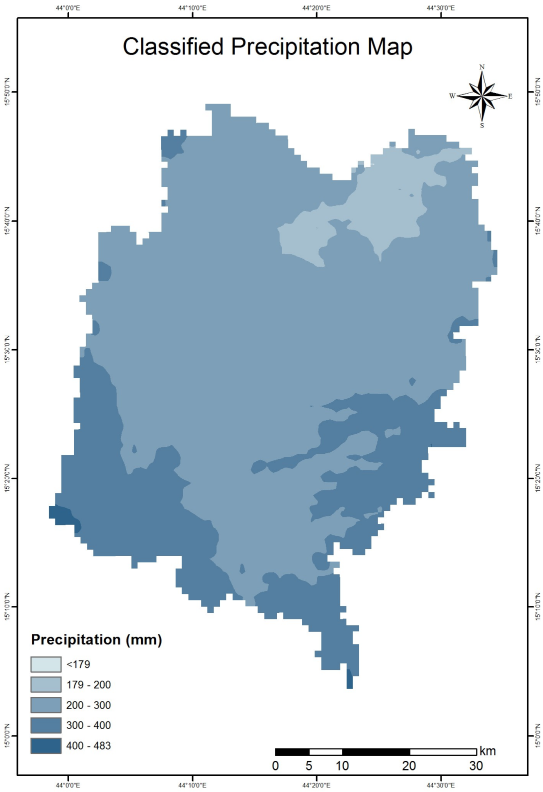


Figure (15): Classified Precipitation map

Table (5): Precipitation's preference value for each RWH system (Classes intervals after Dai, 2016)

Precipitation (mm)	Preference Value			
	Terraces	**Check dams**	**Ponds**	**Spate Irrigation**
<179 mm	1	1	1	1
179 mm – 200 mm	2	2	2	2
200mm – 300mm	3	3	3	3
300 mm – 400 mm	4	4	4	4
400 mm – 483 mm	5	5	5	5

3.3.4.4 Soil

The soil characteristics of Sana'a basin is derived from the HWSD version 1.2 of 2012. There are 12 classes of soil properties in the USDA Textural Soil Classification through which the percentage mass of components, such as sand, silt, clay and loam, can be defined. After clipping the data of the study area from the global database, 3 classes are defined for soil types in Sana'a basin, namely loam, loamy sand, and sandy loam. For the identification of RWH systems, sandy loam has been chosen to be the suitable soil type for terraces in previous studies, such as (Mbiliniy et al., 2007). Concerning the spate irrigation system, there is a lack in using it as RWH system in the previous studies which identified the suitable site for RWH. Therefore, the classification for the spate irrigation is based on the suitability of soil for agriculture which is similar to terraces RWH. Accordingly, the preference values for different RWH systems are assigned to soil types which can be found in table (6). According to the reclassified soil texture map in figure 16, loamy soil is distributed in most of the study area. Whereas, loamy sand is covering a small part of the basin in the northeast.

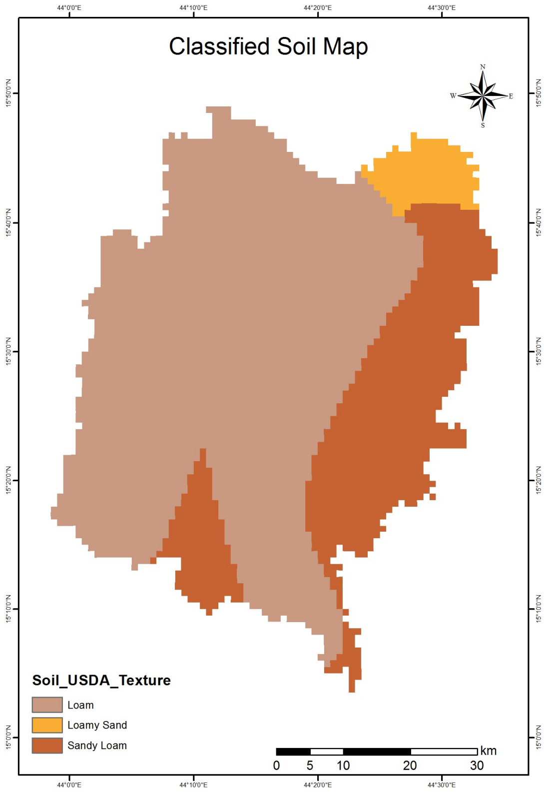


Figure (16): Classified Soil Texture map

Table (6): Precipitation's preference value for each RWH system (After Mbiliniy et al., 2007; Dai, 2016)

Soil Texture	Preference Value			
	Terraces	Check dams	Ponds	Spate Irrigation
Loam	4	5	5	4
Loamy Sand	3	3	3	3
Sandy Loam	5	4	4	5

3.3.4.5 Slope

Slope can be calculated in two different ways, namely degree of slope and percentage slope. The second way is the one used in this study, which indicates the percentage ratio of elevation change on horizontal distance change. Slope can be generated according to an elevation dataset, such as a DEM, in which the maximum rate of change in elevation over distance between each cell and its eight neighbours is calculated. As a result, the lower the slope, the flatter the terrain and the higher the slope, the steeper the terrain.

For the identification of RWH systems, different slope thresholds have been chosen in previous studies, such as less than 10 percent for dams (Singh et al. 2009; Dai, 2016) and 2 – 8 percent for ponds (Moges, 2009; Isioye, 2012). On the other hand, the steep slope, such as 30 degree which equals to 57.74 percent is suitable for terraces (Mbiliniy et al., 2007; Krois & Schulte, 2014). Accordingly, the preference values for different RWH systems are assigned to each slope class which can be found in table (7) for the terraces and in table (8) for the check dams, ponds, and spate irrigation. The reclassified slope maps in figures (17 & 18) show the location of steep and flat terrains in the study area.

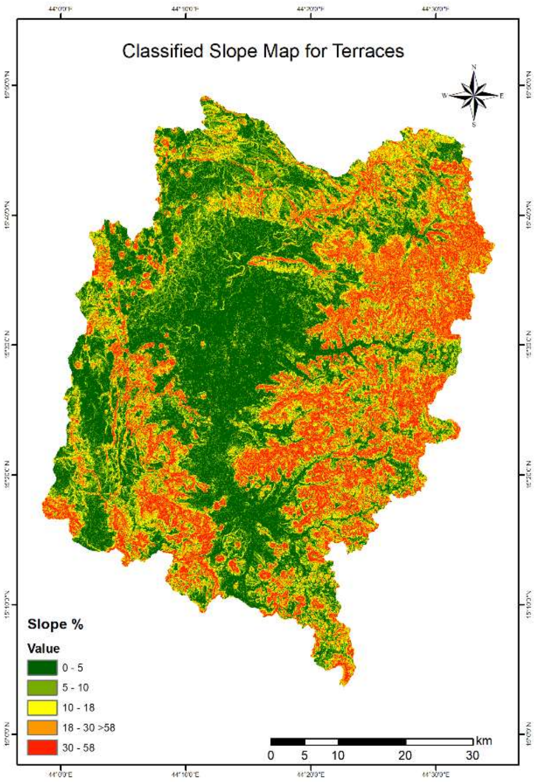


Figure (17): Classified Slope Map (Terraces)

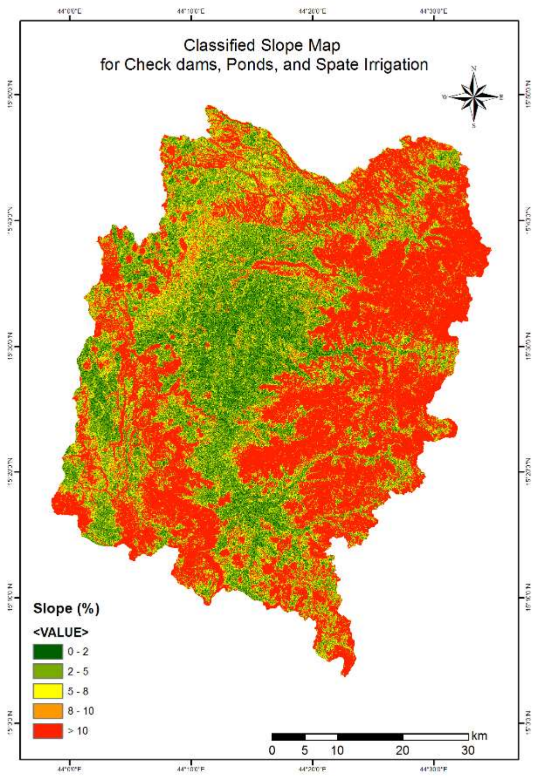


Figure (18): Classified Slope Map (Check-dams, Ponds & Spate Irrigation)

Table (7): Slope preference value for Terraces. (After Krois & Schulte, 2014)

Slope (%)	Preference Value
	Terraces
0 – 5	1
5 – 10	2
10 – 18	3
18 – 30 >58	4
30 - 58	5

Table (8): Slope preference value for check-dams, ponds & spate irrigation (After Dai, 2016; Moges, 2009; Isioye, 2012).

Slope (%)	Preference Value		
	Check dams	Ponds	Spate Irrigation*
0 – 2	5	5	5
2 – 5	4	4	4
5 – 8	3	3	3
8 – 10	2	2	2
>10	1	1	1

***** Spate irrigation is not used in many studies in the literature. Therefore, the slope of the check dams is consider as suitable for the spate irrigation because those two systems are practiced in the same places in the study area.

3.3.4.6 Land Cover/ Land Use

In this study, land use/cover is reclassified from 7 classes into 5 classes, where the Urban, High Density and Urban, Medium to Low Density are combined into one class and restricted in order to exclude RWH site on urban areas. For terraces and spate irrigation, the agricultural areas are considered to be with very high suitability as in (Krois & Schalte, 2014). Whereas, the urban areas are considered as a very low suitability for all RWH systems as shown in figure (19). The preference values of land use/cover classes for each RWH system are shown in table (9).

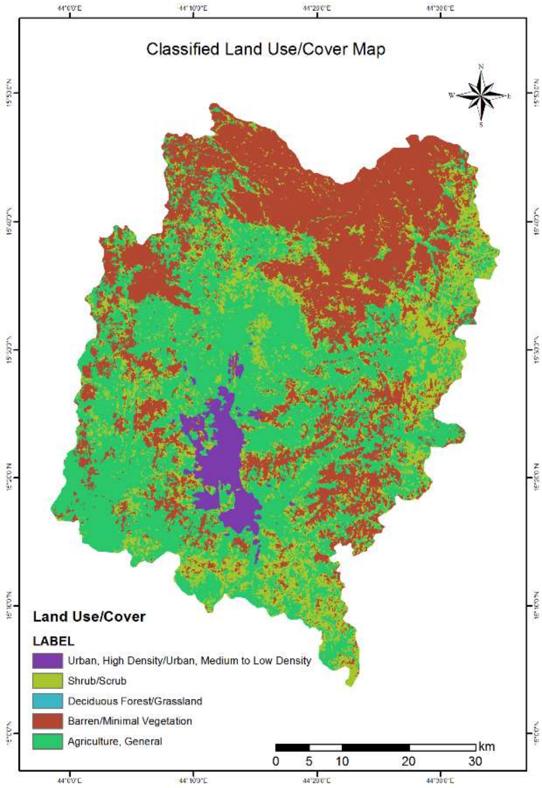


Figure (19): Classified Land use/cover map

Table (9): Land use/cover preference value for each RWH system (After Moges, 2009; Isioye, 2012; Mbilinyi et al., 2007; Krois & Schult, 2014).

<table>
<tr><th rowspan="2">Land Cover/Use</th><th colspan="4">Preference Value</th></tr>
<tr><th>Terraces</th><th>Check dams</th><th>Ponds</th><th>Spate Irrigation*</th></tr>
<tr><td>Forest</td><td>1</td><td rowspan="2">1</td><td rowspan="2">1</td><td>1</td></tr>
<tr><td>Grassland</td><td rowspan="2">3</td><td rowspan="2">3</td></tr>
<tr><td>Shrub/Scrub</td><td>2</td><td>2</td></tr>
<tr><td>Barren/minimal vegetation</td><td>2</td><td>3</td><td>3</td><td>2</td></tr>
<tr><td>Agricultural</td><td>4</td><td>4</td><td>4</td><td>4</td></tr>
<tr><td>Urban, High Density/Urban, Medium to Low Density</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
</table>

***** Spate irrigation is not used in many studies in the literature. Therefore, the land cover/use of the terraces is consider as suitable for the spate irrigation because those two systems are used for the agriculture.

3.3.4.7 Drainage

The drainage network (Stream Network) can be delineated from a DEM raster image. There is however still a possibility of having sunk areas existed in the DEM because of landform like Karst Topography or data error. This error is caused by the resolution limitation of DEM on both vertical and horizontal direction or caused by system errors during the DEM's generation (Hao et al. 2010 as cited in Dai, 2016). As a result of those sinks, unreasonable flow direction may be generated during the calculation, for example, the drainage network will not be continuous. The sink can occur when all neighbouring cells are with a higher elevation than the processing cell or when two cells create a loop, when they flow into each other.

The Arc Hydro Tools, which is an extension of ArcGIS, can be used to extract the drainage network. By using this tool, there are four consecutive steps to extract the drainage network:

1- Fill sink.

2- Flow Direction.

3- Flow Accumulation.

4- Stream Definition.

The process started with filling all sunk areas in the DEM. This step is an iteration progress which stops when all the sinks are filled and no more new sinks can be found. Secondly, the flow direction were calculated based on the filled DEM. The generated flow direction is used as the foundation of flow accumulation. Flow accumulation of a cell is based on how many cells are flowing into this cell. There must be a threshold for the flow accumulation in order to exclude the small flows that more likely to disappear due to natural process like evapotranspiration and infiltration. Some thresholds are tested to generate stream network and then compared with the water features on world topographic map provided by ESRI on ArcGIS Online. After that, a threshold value of 15000 accumulated unit is chosen for the stream definition in this study. All cells with values equal or more than 15000 accumulated units are considered as streams. The stream network is then converted to a vector data in which the flow direction raster is used to show the direction of flow out of each cell.

In this study, the drainage density is used as one of the biophysical criteria. To generate the drainage density map, the stream network vector map is used to calculate the line density in the study area (Figure 20). The preference values of drainage density classes for each RWH system are shown in table (10).

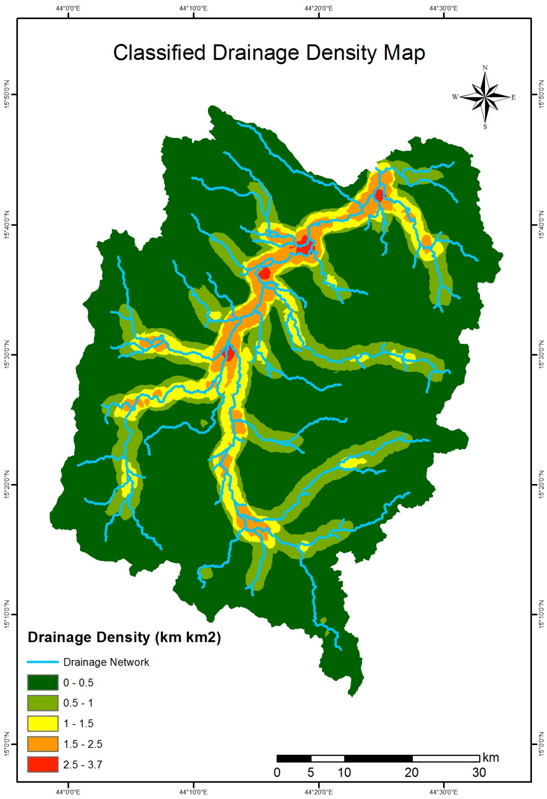


Figure (20): Classified Drainage Density Map

Table (10): Drainage density preference value for each RWH system (Al-Shabeeb, 2016).

Drainage (km km2)	Preference Value			
	Terraces	Check dams	Ponds	Spate Irrigation
0 – 0.5	1	1	1	1
0.5 – 1	2	2	2	2
1 – 1.5	3	3	3	3
1.5 – 2.5	4	4	4	4
2.5 – 3.7	5	5	5	5

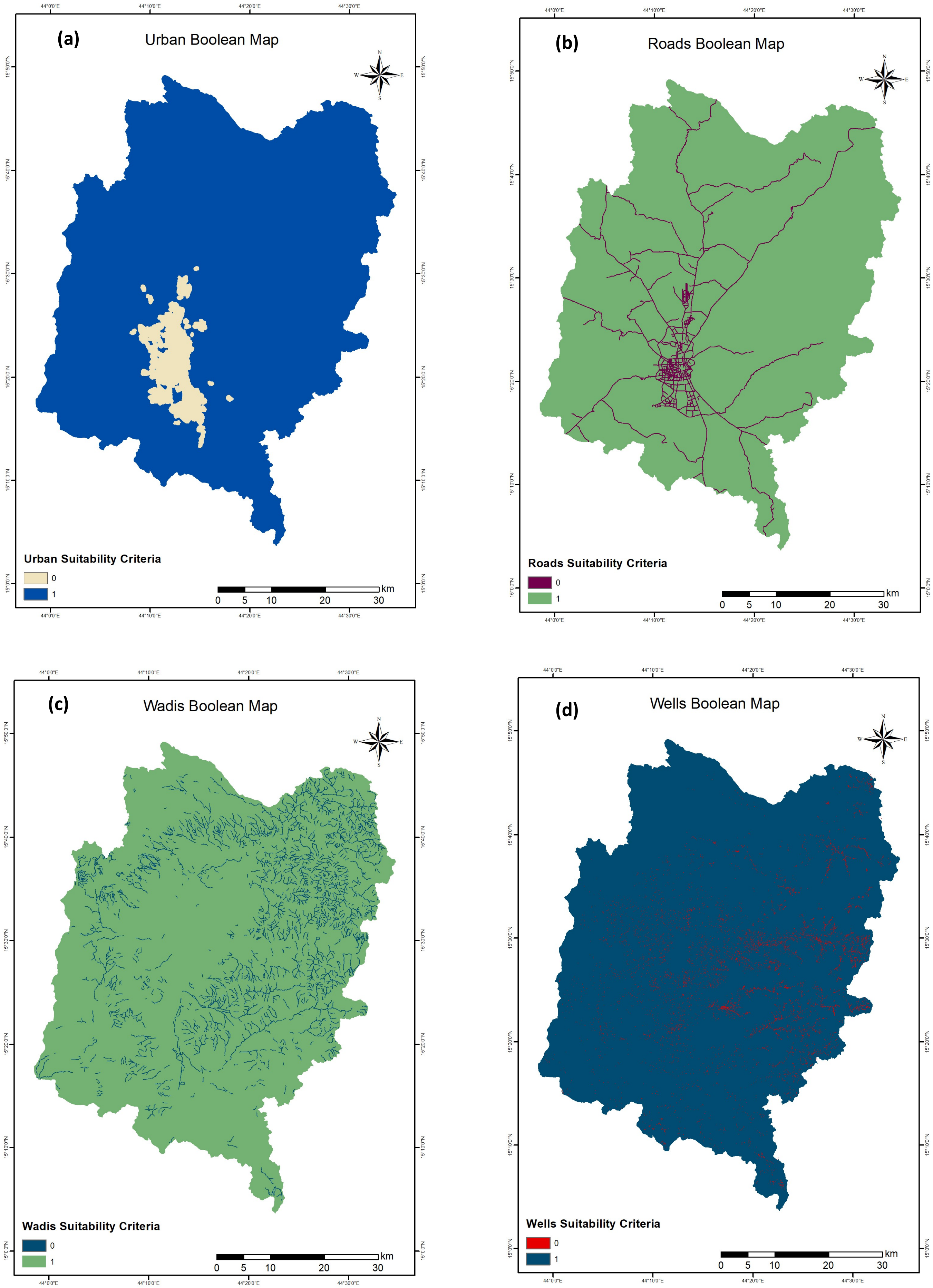
3.3.4.7 Socio-Economic Parameters

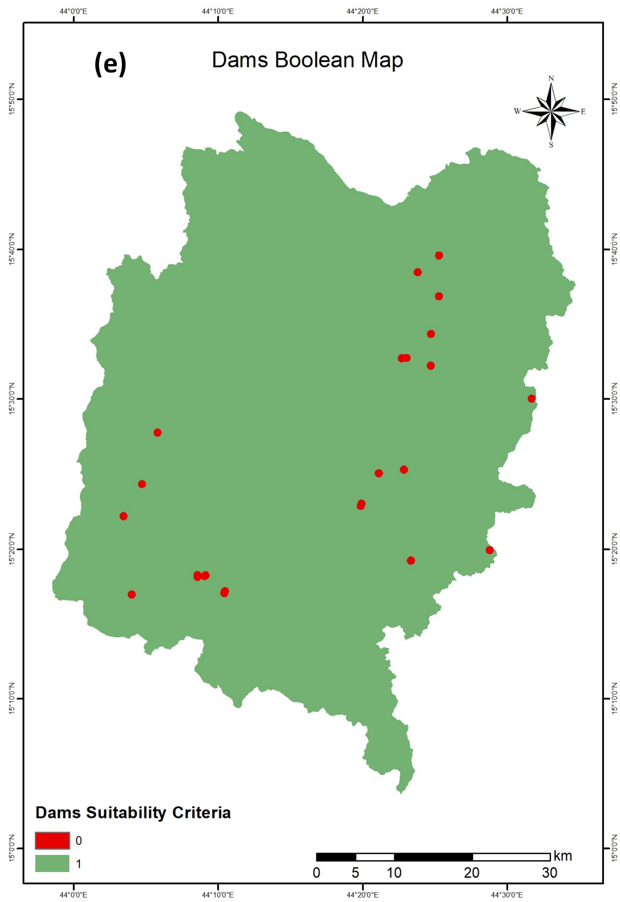
Six socio-economic criteria (parameters) were integrated into the result map shown in Figures (21 a-f). Some spatial data techniques were used for all parameters including buffering, union, and raster reclassification. The buffering zones are applied for each socio-economic criterion based on the appropriate buffer distance listed in Table (11), which are derived from the literature review, such as (Al-shabeeb, 2016; Al-Adamat, 2010), as well as the specific characteristics and situation of the study area. For example, the applied buffer distance to water wells is 50m which is less than the distance (500m) used in the literature review this is due to the huge number of wells in the basin and also it is a common practice in Yemen to cultivate and to harvest water in a close distance to the water wells. The distance applied to the sewage passage is 1000m in order to prevent any pollution. Further to the roads, the given distance is 75m from each side of the road in total 150m and this distance is enough to prevent any future conflict between the constructed RWH systems and the roads development because the widest roads in the study area is only 100m. The buffer zones of each socio-economic criterion was spatially merged with the study area using the union technique to incorporate the areas beyond the buffer zone distances Figures (21 a-f). Then the raster reclassification is applied for all maps based on the values listed in Table (11).

Table 11: Socio-economic parameters with their distances (based on Al-shabeeb, 2016; Al-Adamat, 2010).

No.	Parameters	Condition (m)	Value
1	Urban	>250	1
		≤250	0
2	Roads*	>75	1
		≤75	0
3	Wadis	>50	1
		≤50	0
4	Wells*	>50	1
		≤50	0
5	Dams	>500	1
		≤500	0
6	Sewage Passage*	>1000	1
		≤1000	0

***** The value is identified based on the characteristics of the study area.


(a)
Urban Boolean Map
Urban Suitability Criteria
0
1
km
0 5 10 20 30
(b)
Roads Boolean Map
Roads Suitability Criteria
0
1
km
0 5 10 20 30
(c)
Wadis Boolean Map
Wadis Suitability Criteria
0
1
km
0 5 10 20 30
(d)
Wells Boolean Map
Wells Suitability Criteria
0
1
km
0 5 10 20 30



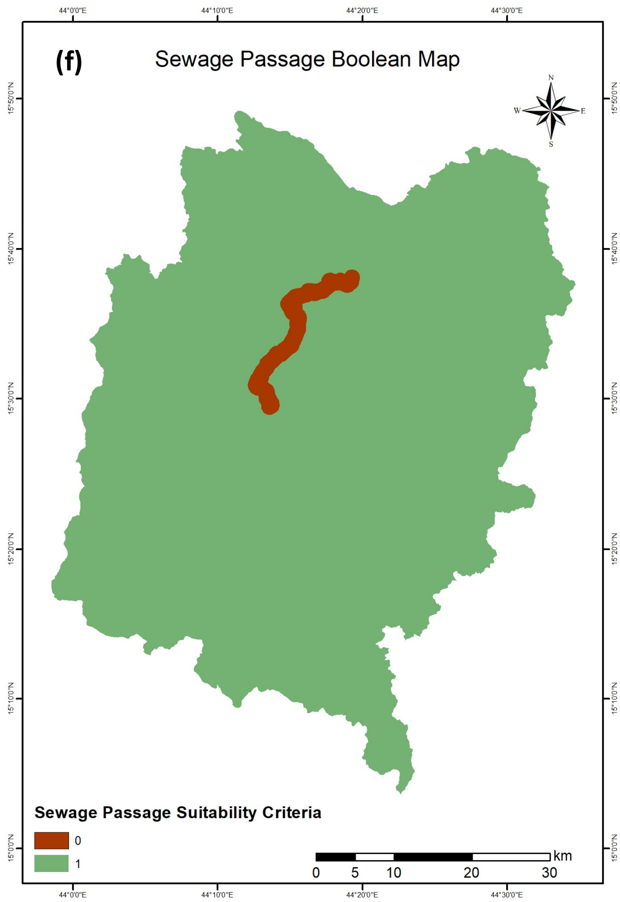


Figure (21): (a) Urban Suitability **(b)** Roads Suitability **(c)** Wadis Suitability **(d)** Wells Suitability **(e)** Dams Suitability **(f)** Sewage Passage Suitability

4. Data Analysis

4.1 Establishing the criteria weights

The criteria used for the identification of potential RWH systems are not equally important. Therefore, different weights are assigned to the criteria. For the development of weights, the PWC within the Analytical Hierarchy Process (AHP), was applied by calculating the Consistency ratio (CR) to assess the consistency between the acquired experts' opinions and then to identify the final weights for each criterion. The results of the conducted questionnaire for the local experts are summarized in Tables (12-15). The experts' opinions are selected based on the scale in Table (2). The experts gave their opinions for four different RWH systems, namely terraces, check dams, ponds, and spate irrigation. Those four systems are indicated, according to the experts' opinions, to be the most important traditional RWH techniques that can be used for Sana'a basin.

The CRs for all the experts' weights for each RWH system were less than 0.1, which is the maximum CR value for an acceptable pairwise comparison. Since the CRs are within the acceptable rate, this indicates that the acquired experts' opinions are consistent, and thus are suitable for the implementation of the AHP analysis. The results of the pairwise comparison matrices (Weights, λmax, RI and CR) are shown in Table (16).

Table 12: Pairwise comparison matrix of local experts' opinion (Terraces)

Factor	**Rainfall**	**Soil**	**Slope**	**Drainage**	**Land use/Cover**
Rainfall	1.00	4.00	1.00	4.00	6.00
Soil	0.25	1.00	0.25	3.00	3.00
Slope	1.00	4.00	1.00	5.00	3.00
Drainage	0.25	0.33	0.20	1.00	1.00
Land use/Cover	0.17	0.33	0.33	1.00	1.00

Table 13: Pairwise comparison matrix of local experts' opinion (Spate Irrigation)

Factor	Rainfall	Soil	Slope	Drainage	Land use/Cover
Rainfall	1.00	4.00	3.00	5.00	5.00
Soil	0.25	1.00	0.50	2.00	2.00
Slope	0.33	2.00	1.00	2.00	4.00
Drainage	0.20	0.50	0.50	1.00	1.00
Land use/Cover	0.20	0.50	0.25	1.00	1.00

Table 14: Pairwise comparison matrix of local experts' opinion (Check-dams)

Factor	Rainfall	Soil	Slope	Drainage	Land use/Cover
Rainfall	1.00	7.00	2.00	4.00	5.00
Soil	0.14	1.00	0.20	0.50	1.00
Slope	0.50	5.00	1.00	4.00	4.00
Drainage	0.25	2.00	0.25	1.00	2.00
Land use/Cover	0.20	1.00	0.25	0.50	1.00

Table 15: Pairwise comparison matrix of local experts' opinion (Ponds)

Factor	Rainfall	Soil	Slope	Drainage	Land use/Cover
Rainfall	1.00	7.00	4.00	5.00	6.00
Soil	0.14	1.00	0.25	0.33	1.00
Slope	0.25	4.00	1.00	2.00	3.00
Drainage	0.20	3.00	0.50	1.00	1.00
Land use/Cover	0.17	1.00	0.33	1.00	1.00

Table16: Weights (percent of Influence), λmax, RI, and CR for each RWH system.

Factors	**Weights (%)**			
	Terraces	**Spate Irrigation**	**Check dams**	**Ponds**
Rainfall	37	47	45	54
Soil	14	14	6	6
Slope	35	22	31	20
Drainage	7	9	11	12
Land use/Cover	7	8	7	8
λmax	5.30	5.12	5.12	5.20
RI	1.12	1.12	1.12	1.12
CR	0.07	0.03	0.03	0.04

4.2 Suitability Analysis

4.2.1 Biophysical Criteria Analysis

Five biophysical criteria were used in the study for the selection of suitable locations for four different RWH systems, namely Rainfall, slope, soil texture, drainage density, and Land use/cover. Weights were given to each individual criterion as shown in table 16. The WLC technique was used to integrate these biophysical factors to obtain the WLC suitability map for each RWH system. This technique includes standardising and assigning weights of relative importance to the suitability maps, then integrating the standardised maps and the weights to obtain a suitability map.

All the thematic maps were combined in ArcGIS® using the Raster Algebra tool. The weight of each criterion was multiplied by the reclassified map, then the WLC suitability maps were computed using the following equation:

*Suitability Index = (Rainfall*Rw)+(Slope*Sw)+(Soil Texture *STw)+(Drainage *Dw)+(LU/LC*LU/LCw)*

Where:

w = the weight of each criterion.

Suitability index = a dimensionless number that identifies the suitable sites for the RWH systems.

After integrating all the thematic layers using the above mentioned equation, the WLC suitability maps for the selected RWH systems were generated and were classified into five classes of suitability in the study area, namely very low suitability, low suitability, moderate suitability, high suitability, and very high suitability. The results of this part of the analysis are shown in figures (22-25) for each RWH system.

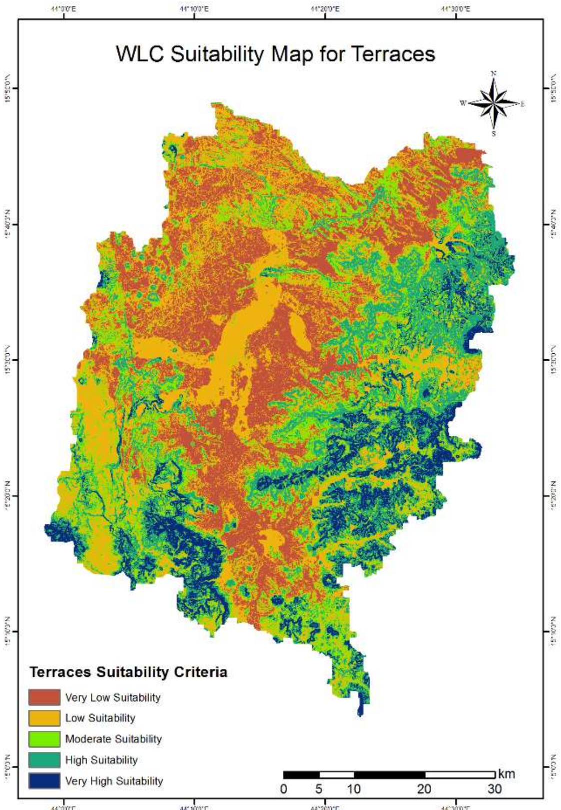


Figure (22): WLC Suitability Map (Terraces)

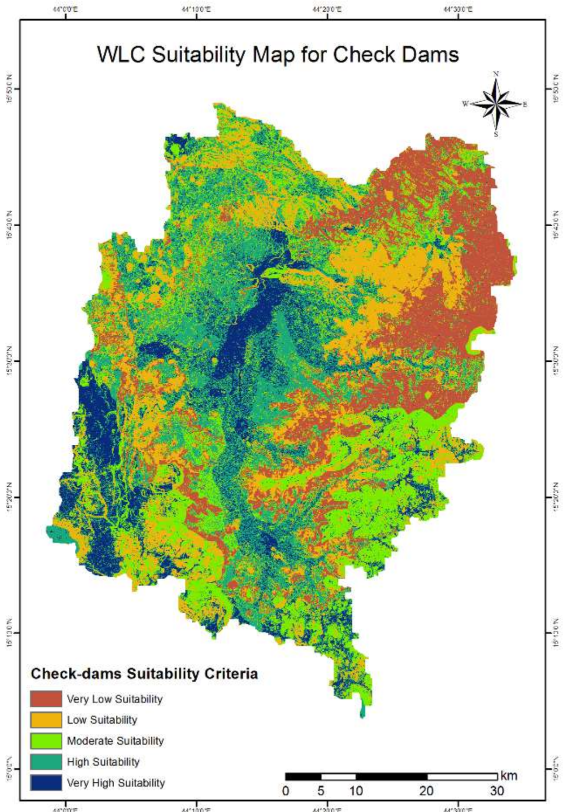


Figure (23): WLC Suitability Map (Check-dams)

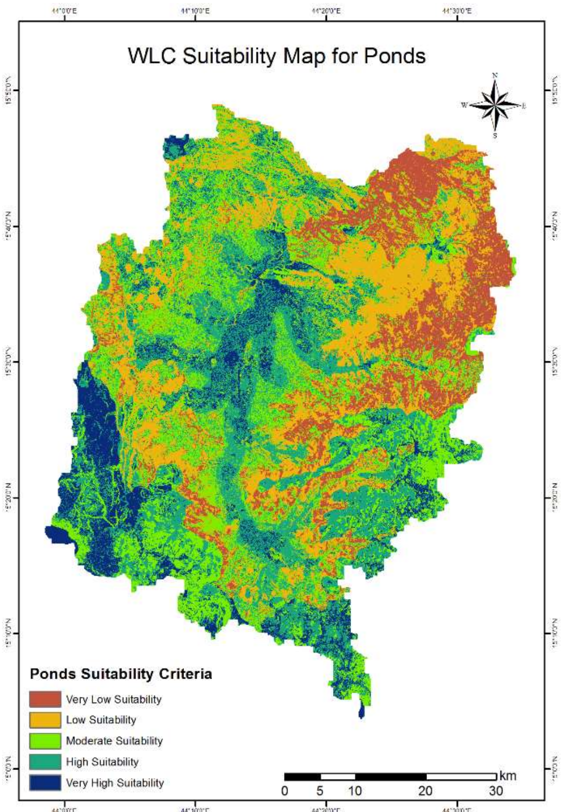


Figure (24): WLC Suitability Map (Ponds)

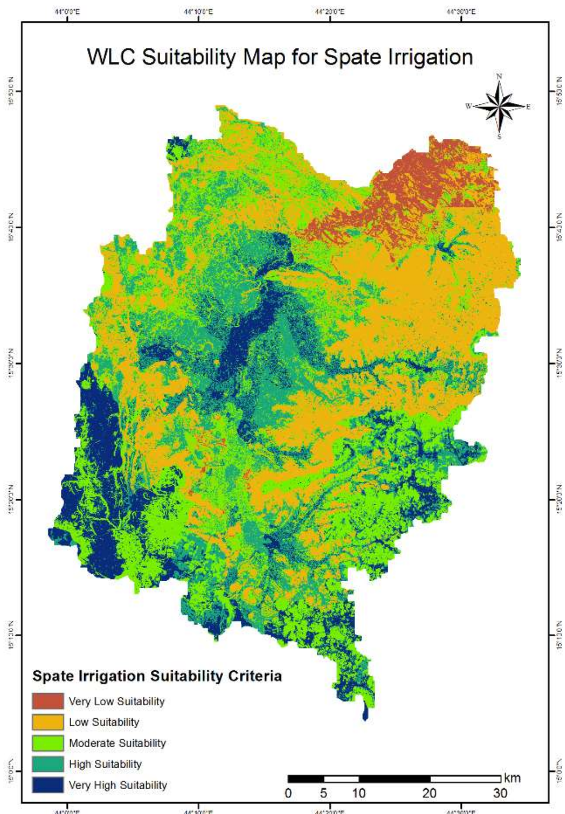


Figure (25): WLC Suitability Map (Spate Irrigation)

4.2.2 Socio-Economic Criteria Analysis

Boolean technique was applied to the socio-economic parameters in order to exclude the sites which cannot be used as locations for RWH systems. Six socio-economic parameters were included for the terraces and ponds RWH. However, only five socio-economic parameters were used for the check dams and spate irrigation RWH. The wadis data were not included for those two systems because the middle of the wadis is considered to be suitable for check dams and spate irrigation as practiced in Yemen. After that, all socio-economic maps were integrated to generate the Boolean maps. As a result, two Boolean suitability maps were generated as shown in figures (26 & 27). In those figures all areas that are not suitable for the four selected RWH systems are illustrated.

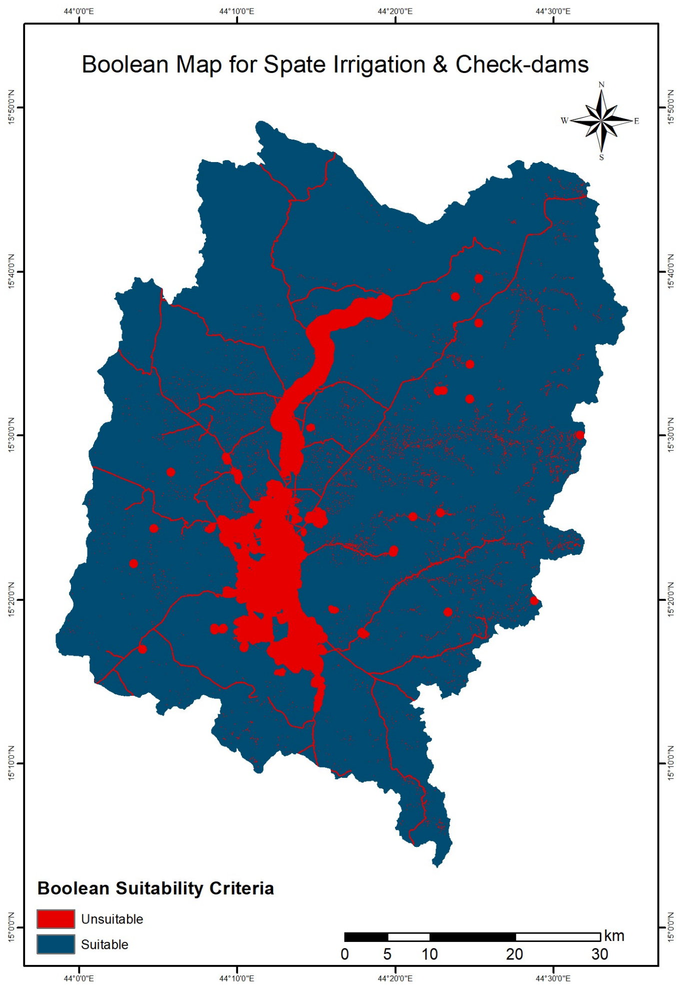


Figure (26): Boolean Suitability Map (Spate Irrigation & Check-dams))

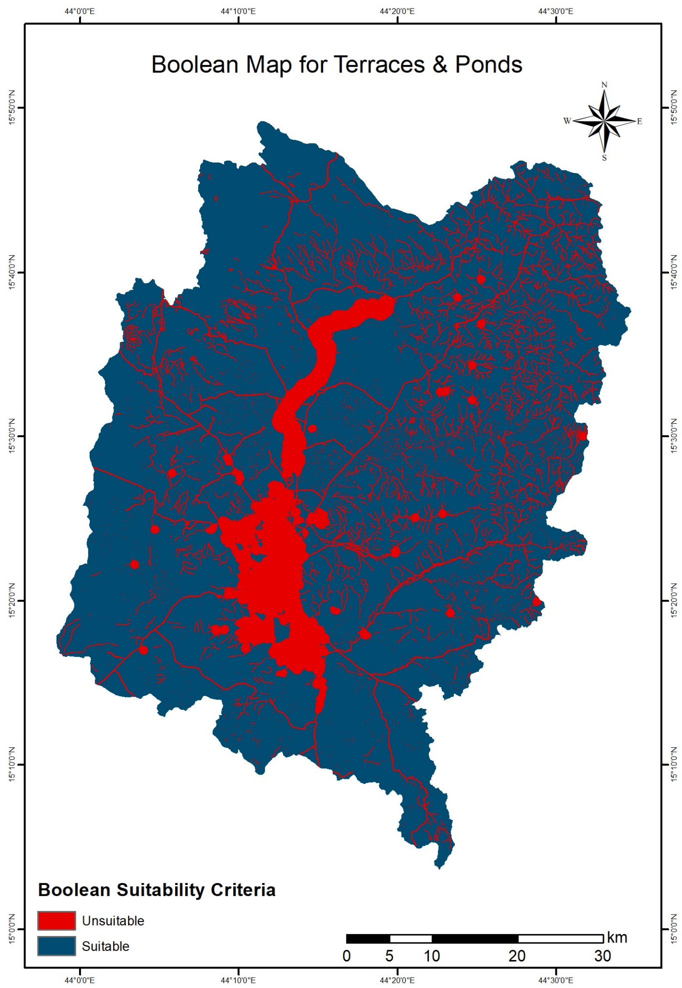


Figure (27): Boolean Suitability Map (Terraces & Ponds)

5. Results & Discussion

5.1 RWH Suitability Maps

Based on the literature review and the questionnaire results, four RWH systems are selected in this study, namely, Terraces, Check-dams, Ponds, and Spate Irrigation which are some of the traditional RWH systems practised in Yemen. Therefore, each RWH system is analysed individually and has its own suitability map. Thus, the results of the WLC and the Boolean techniques were integrated to generate a final suitability map for each RWH system. Those final suitability maps were classified into: not suitability, low suitability, moderate suitability, high suitability, and very high suitability. The potential sites for RWH systems as identified reflect specific suitability levels of parameters and weight of factors applied in the analysis.

5.1.1 Terraces suitability map

A suitability map for constructing terraces in Sana'a basin, illustrated in figure (28), was generated as well as a histogram and a table showing the area and percentage of each suitability level which are shown in figure (29) and table (17).

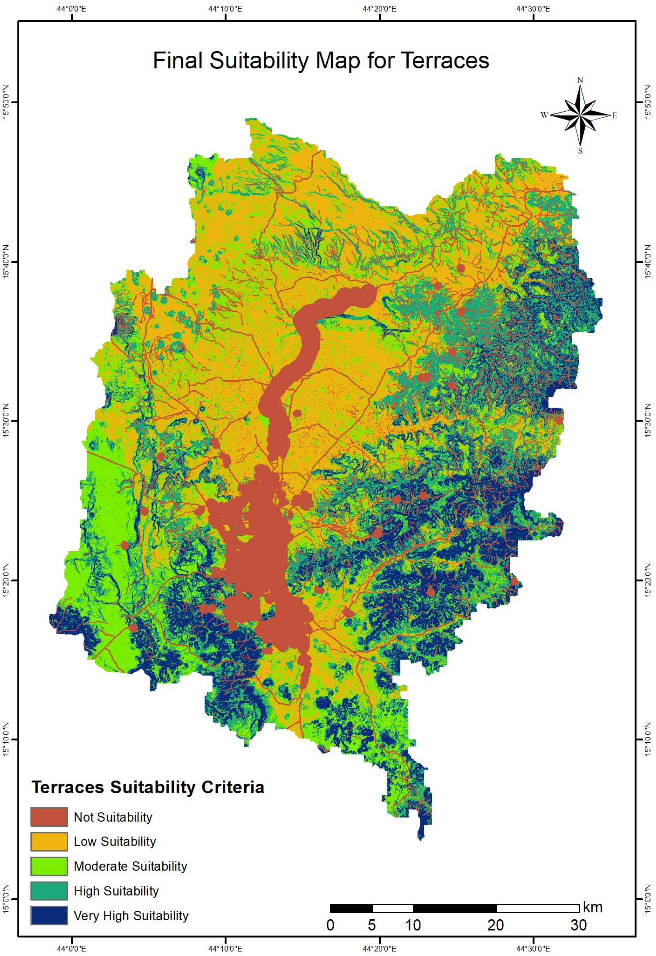


Figure (28): Final Suitability Map (Terraces)

As illustrated, only **33 %** of the total study area is located in the high and very high suitability levels, and therefore suitable for terraces, in which 14 % is very high suitability area. These are sites that have no limitation to sustain the intended purpose. Majority of these sites are found in the west and south of the study area. They are located in locations that have steep mountainous slope. The soil are sandy loam to loam which are suitable for terraces because they have high water retention capacity. This soil is considered as the best soil for the agriculture because its texture has a combination of soil particles. Most of the suitable sites for terraces are located in agricultural land use which are the proper locations for this kind of RWH. On the other hand, big portion of the unsuitable and low suitability sites are located in the terrains with gentle slope because this kind of slope is given less preference for the terraces. Furthermore, all the socio-economic parameters are considered as not suitable for RWH and they represent 17 % of the study area.

Table 17: Percentage and area (ha) for each suitability level (Terraces)

Suitability Levels	PERCENTAGE	AREA (ha)
Not Suitability	17 %	54879
Low Suitability	26 %	84148
Moderate Suitability	23 %	72540
High Suitability	19 %	61837
Very High Suitability	14 %	44637

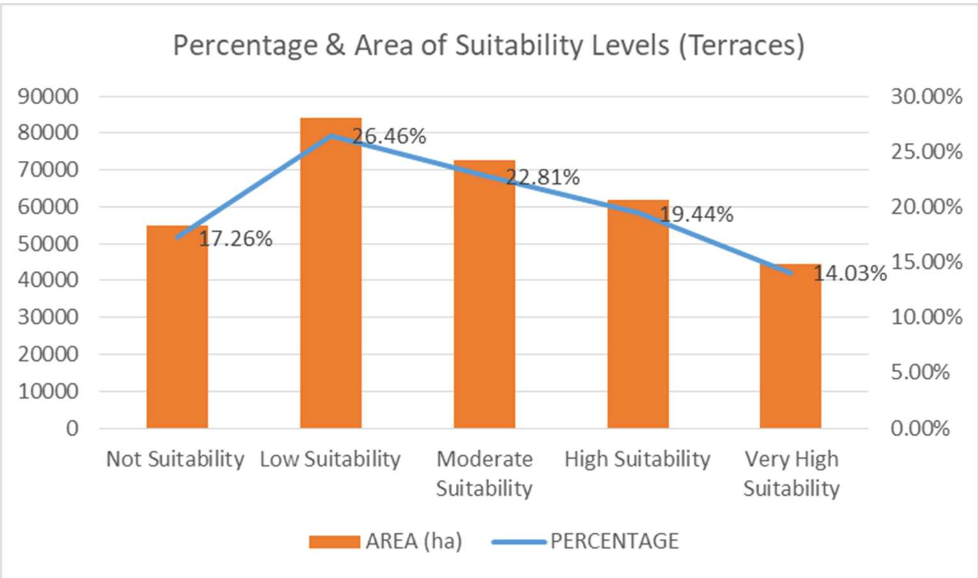


Figure (29): Percentage & Area (ha) for each suitability level (Terraces)

5. 1.2 Check dams suitability map

A suitability map for constructing check dams in Sana'a basin, shown in figure (30), was generated as well as a histogram and a table showing the area and percentage of each suitability level which are shown in figure (31) and table (18).

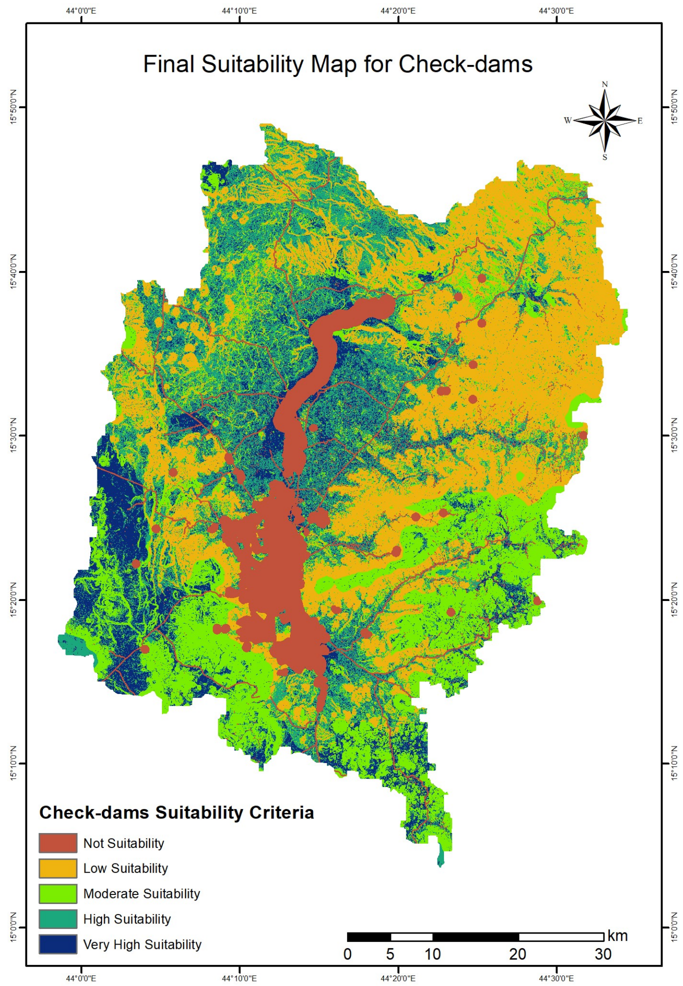


Figure (30): Final Suitability Map (Check-dams)

From the total study area of 3,200 km^2, about **35 %** is located in the high and very high suitability levels and therefore suitable for check dams in which only 13 % is very high suitability area. These are sites that have no limitation to sustain the intended purpose. Majority of these sites are found in the middle and southwest of the study area. These locations are located in areas that have gentle slope. The soil is loam which are suitable for check dams because they have high water retention capacity, which is associated with low seepage and percolation. It is noticeable that the suitable sites for check dams are located in areas with gentle to moderate slope especially in the wadis, where other RWH systems can be established such as spate irrigation, in which the check dams help in slowing down the flood speed and in reducing the soil erosion, thus the farmers can use the rain for the cultivation. On the other hand, most of the unsuitability, low suitability, and moderate suitability sites are located on the northeast part of the study area, this is caused by the less rain this part receives and the rainfall factor is considered as the most important criterion in this study and thus is given the highest relative weight. Furthermore, all the socio-economic parameters are considered as not suitable of RWH and occupy 11 % of the study area.

Table 18: Percentage and area (ha) for each suitability level (Check-dams)

Suitability Levels	PERCENTAGE	AREA (ha)
Not Suitability	11 %	35761
Low Suitability	30 %	94012
Moderate Suitability	25 %	77987
High Suitability	22 %	70475
Very High Suitability	13 %	39807

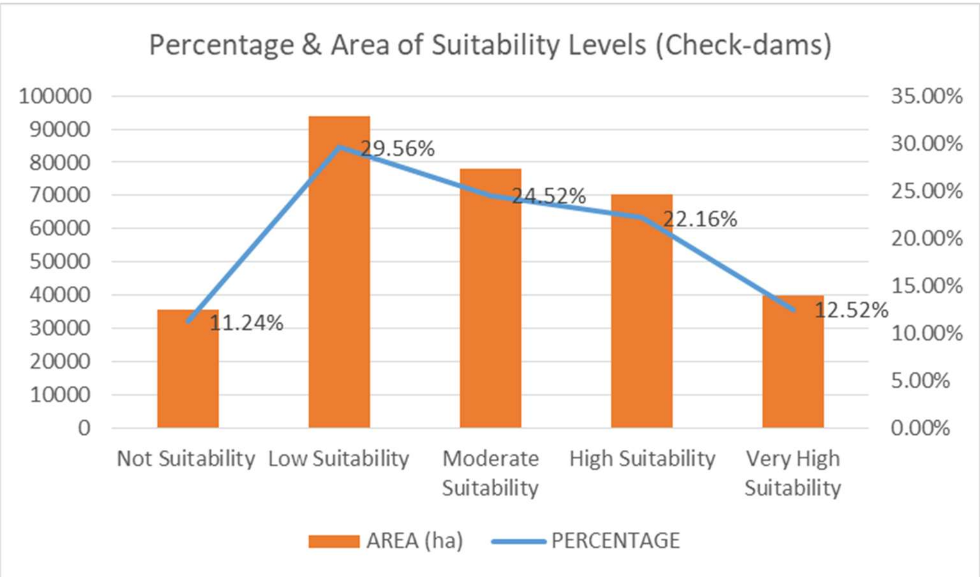


Figure (31): Percentage & Area (ha) for each suitability level (Check-dams)

5.1.3 Ponds suitability map

A suitability map for constructing ponds in Sana'a basin, shown in figure (32), was generated as well as a histogram and a table showing the area and percentage of each suitability level which are shown in figure (33) and table (19).

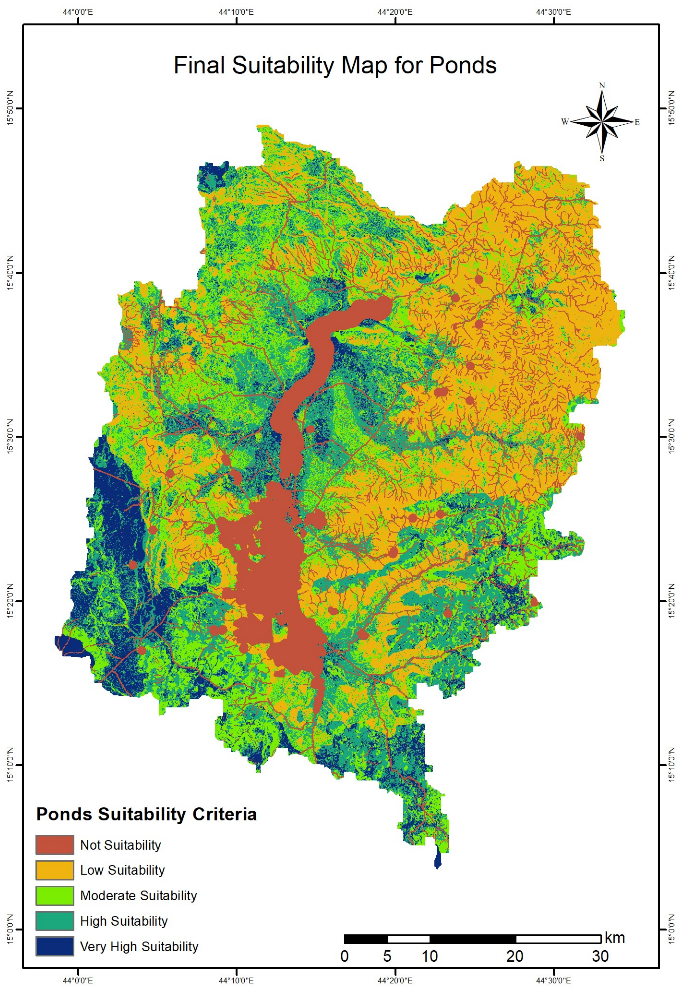


Figure (32): Final Suitability Map (Ponds)

Ponds can be constructed in the sites with high and very high suitability levels. The percentage of the suitable area for ponds is **33 %** from the total study area in which only 9 % is very high suitability. Majority of these sites are found in the middle, southwest and southeast of the study area. The locations classified as very high suitability are located in areas that have gentle to moderate slope, whereas locations in high suitability level are located in areas that have moderate to steep slope. As a result, the proper locations for this kind of RWH were allocated on areas close to the streams network which have high drainage density. The results of this analysis correspond with Mbiliniyi et al. (2005) where the authors found out that RWH, such as water storage systems (ndiva) were constructed, based on the indigenous knowledge of RWH, on places closer to streams with moderate and steep slopes and thus water can easily enter and exit the RWH system by gravity. It is noticeable that the northeast part of the study area is considered to be with low suitability for this kind of RWH, this is caused by the less rain this part receives as well as the slope is very steep which is considered as not suitable. The rainfall and slope factors are given in this study the highest relative weights according to the local experts' opinions. Furthermore, all the socio-economic parameters are considered as not suitable of RWH and occupy 17 % of the study area.

Table 19: Percentage and area (ha) for each suitability level (Ponds)

Suitability Levels	PERCENTAGE	AREA (ha)
Not Suitability	17 %	54879
Low Suitability	27 %	84730
Moderate Suitability	24 %	74990
High Suitability	24 %	74952
Very High Suitability	9 %	28491

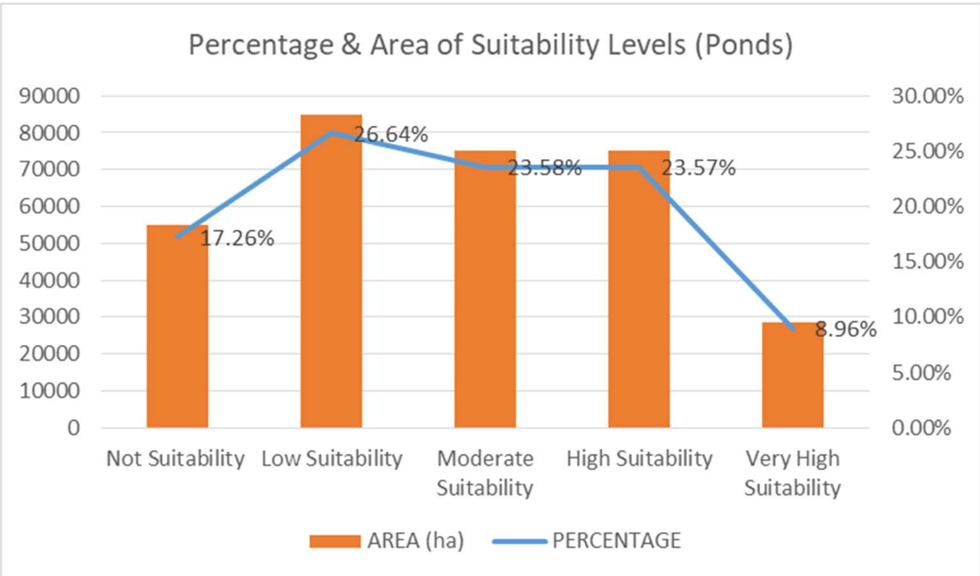


Figure (33): Percentage & Area (ha) for each suitability level (Ponds)

5.1.4 Spate Irrigation suitability map

A suitability map for applying spate irrigation in Sana'a basin, shown in figure (34), was generated as well as a histogram and a table showing the area and percentage of each suitability level which are shown in figure (35) and table (20).

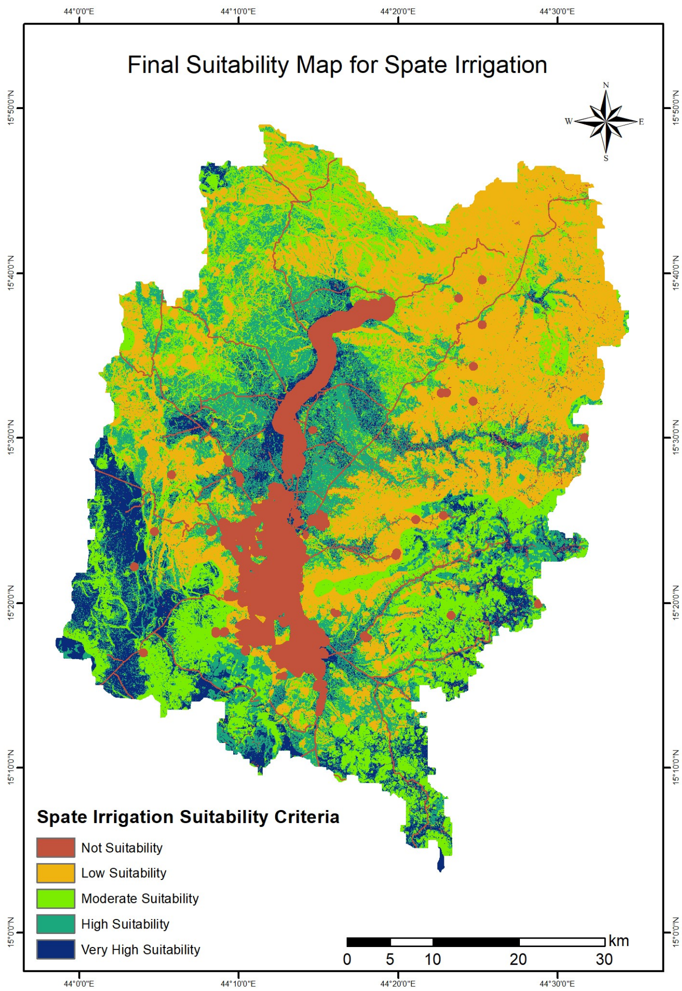


Figure (34): Final Suitability Map (Spate Irrigation)

Area considered suitable for spate irrigation, high and very high suitability levels, covers a total of 100454 hectare which represents **32 %** of the total study area in which only 9 % is very high suitability. Suitable areas are mainly located in agricultural land use and in area with soil having water holding capacities which is considered as the best soil for the agriculture because its texture has a combination of soil particles. Majority of these sites are found in the middle and southwest of the study area. By comparing the suitability map of spate irrigation with the slope map, most of the high and very high suitability areas have been found located in the areas with gentle slope and this is because this kind of slope is suitable of spate irrigation in order to increase the agricultural productivity. It is noticeable that the northeast part of the study area is considered to be with low suitability for this kind of RWH, this is caused by the less rain this part receives and the rainfall factor is considered as the most important criterion in this study and thus is given the highest relative weight. In addition, the northeast part is a barren land and therefore was given a low preference value for the spate irrigation.

Table 20: Percentage and area (ha) for each suitability level (Spate Irrigation)

Suitability Levels	PERCENTAGE	AREA (ha)
Not Suitability	11 %	35761
Low Suitability	31 %	97486
Moderate Suitability	27 %	84340
High Suitability	22 %	71139
Very High Suitability	9 %	29315

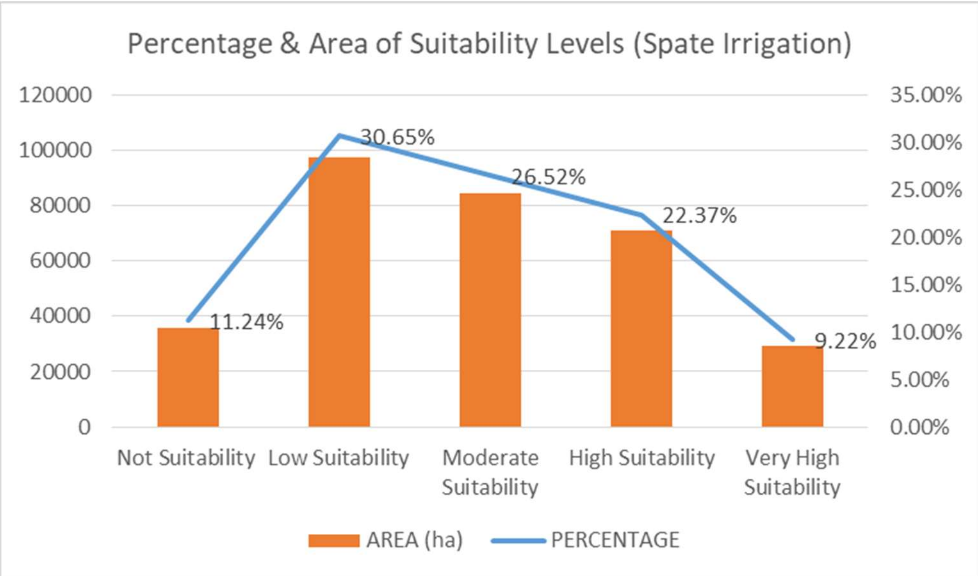


Figure (35): Percentage & Area (ha) for each suitability level (Spate Irrigation)

5.2 Results Validation

For the validation of the outcomes of this study, several steps where carried out. First of all, the local experts are asked to provide information about their perspectives on the proper locations within Sana'a basin for each RWH system based on their knowledge of the study area as shown in Table (21). The proposed locations by the experts gave us an indication in order to validate the results of the final suitability maps of this study. Secondly, a literature review is conducted to find out if there are any suggestions about the suitable sites for those RWH systems and thus comparing those suggestions with the results of this research. Finally, looking for existing RWH systems in the study area which were constructed or practiced based on the indigenous knowledge of the locals and then investigate whether the locations of those systems lie in the suitable sites that are proposed by this study.

Table 21: Local experts' votes for each RWH system per location characteristics.

No	RWH system	Which location in Sana'a basin fits these systems more				
		Upstream	Downstream	Plain areas	Mountain areas	Midstream
1	Sloping/Mountain Terraces	4	1	-	2	-
2	Flood WH/Spate Irrigation	2	3	3	1	-
3	Check dams	2	1	1	3	1
4	Ponds (including Bariks, Siqyat, Niqab, Kuruf, Mawajel, Khazzan…etc)	3	4	1	4	-

5.2.1 Terraces Validation

In order to validate and test the accuracy of the results of the suitability map for terraces, the information gathered from the local experts is used. As shown in table (21) most of the experts indicate that the terraces can be constructed in the upstream areas of the basin. Based on this information, the terraces' suitability map is checked and it is noticeable that most of the suitable and very high suitable areas in the map lie on the upstream of the basin especially in the eastern and southern parts. Furthermore, two of the experts indicated that the terraces can be implemented in the mountain areas and, indeed, most of the suitable sites are in mountainous areas. Moreover, all plain areas are consider as low suitable for terraces in the suitability map and this is confirmed by the experts.

On the other hand, Bamatraf (1994) indicated that the settlers have implemented huge numbers of terraced fields as an effective method of harvesting rainwater on the steep and rugged slopes in the mountain areas of Yemen.

Finally, some of the suitable locations in the suitability map are randomly selected to investigate their accuracy compared to the existing RWH systems in the study area which were constructed or practiced based on the indigenous knowledge of the locals. To do so, the suitability map of terraces is displayed above the imagery layer in ArcGIS as well as google map is used to get used of its good resolution. As a result, many suitable sites in the suitability map are located on areas where existing terraces are implemented. Yet in some suitable places there are no existing terraces but the topography of the locations is with steep slope and therefore can be suitable for terraces.

5.2.2 Check dams Validation

For the testing and validation of the check dams' suitability map, the information gathered from the local experts will be used. In table (21) three out of five experts indicate that the check dams can be constructed in the mountain areas of the basin. Accordingly, the suitability map of the check dams is examined and the result is that there are many suitable sites located in the mountainous areas especially in the flood streams in which they reduce the water flow velocity to counteract erosion and to divert the flood water to the agricultural land for the spate irrigation. In addition, the plain areas are identified as suitable for check dams in the suitability map. However, only one of the local experts indicated that check dams can be implemented in the plain areas. Moreover, as traditional systems, check dams were implemented more in mountain and upstream areas for the purpose of preventing erosion and diverting water to the nearby fields. Nowadays however, they started to be practiced also in plain areas not only to prevent erosion, diversion of water and groundwater recharge but also for the main reason of flood control.

On the other hand, Ward et al. (2010) said that such check dams are advisable to be in the southern part of the basin in both volcanic and an alluvial aquifers where sub-basins 14, 18, 19, 20, 21, and 22. Accordingly, the aforementioned sub-basins are examined to check whether they have sites with high suitability of check dams and the results show that there are many high suitable locations in those sub-basins especially in the plain areas of the wadis. It is noticeable that sub-basin number 14 has a high percentage of its area consider as very suitable for check dams.

Finally, some of the existing check dams in the basin, which were constructed based on the indigenous knowledge of the locals, particularly in the eastern areas (Bani Hoshaish) are compared to the resulted suitability map in order to check its accuracy. The result of the comparison showed that all the existing check dams on that project are located on sites identified to have a very high suitability class. Thus, the comparison results give an indication of the reliability of the resulted suitability map of the check dams in this study.

5.2.3 Ponds Validation

To validate and test the accuracy of the results of the suitability map for ponds, the information gathered from the local experts is used. As shown in table (21) four out of five from the experts indicate that the ponds can be constructed in the upstream and mountain areas of the basin. Based on this information, the ponds' suitability map is evaluated and the result is that there are sites with high suitability for the ponds in the upstream areas (the southern part) as well as in the south-eastern mountainous area. It is noticeable that the plain areas which are in the middle of the basin have also a high potential for ponds. However, only one of the local experts has indicated that.

According to Noman (2004) ponds are classified into 3 classes based on the different topographic conditions of the study area, viz. excavated ponds which can be implemented in flat topography, embankment ponds for hilly and rugged slopes, and excavated-cum-embankment ponds. Accordingly, those kinds of ponds can be constructed in the study area because there are sites with high suitability that have the same topography as mentioned.

Finally, Sana'a Water & Sanitation Local Corporation has constructed two big ponds in the plain areas in order to harvest the rainwater coming from the upstream areas. The location of those ponds are compared with the ponds suitability map of this study to evaluate its accuracy. As a result, the existing ponds are located on sites identified to have a high and very high suitability classes. Furthermore, there are some existing ponds inside the urban areas. Yet those ponds are located in not suitability class in the suitability map due to the excluding of the urban areas from the analysis and considering it as unsuitable within the socio-economic parameters.

5.2.4 Spate Irrigation Validation

In order to validate and test the accuracy of the results of the suitability map for spate irrigation, the information gathered from the local experts is used. As shown in table (21) three out of five experts indicate that the spate irrigation can be constructed in the downstream and plain areas of the basin. Based on this information, the spate irrigation suitability map is evaluated and the result is that most of the suitable and very high suitable areas in the map lie on the downstream and plain areas of the basin especially in the south-western and middle parts. Furthermore, two of the experts indicated that the spate irrigation can be implemented in the upstream and, indeed, there are suitable sites for ponds in the southern part (upstream). Moreover, all mountain areas are consider as low suitable for spate irrigation in the suitability map and this is confirmed by the experts.

In the literature, it is mentioned that agriculture in Yemen has depended on spate irrigation for centuries. According to Noman (2004) spate irrigation is practiced in Yemen along the wadi courses and plain areas. Therefore, the suitability map of the spate irrigation is checked according to this information and the result is that most of the sites which identified as suitable for this kind of RWH are located in the wadis and the plain areas.

Finally, some of the suitable locations in the suitability map are randomly selected to investigate their accuracy compared to the existing RWH systems in the study area which were constructed or practiced based on the indigenous knowledge of the locals. To do so, the suitability map of spate irrigation is displayed above the imagery layer in ArcGIS as well as google map is used to get used of its good resolution. As a result, many suitable sites in the suitability map are located on areas where existing spate irrigation are practiced, such as in Bani Al-Harith and Bani Hoshaish. Yet in some suitable places there are no existing spate irrigation but the topography of the locations is with gentle slope and therefore can be suitable for this RWH system.

5.3 Sensitivity Analysis

Sensitivity analysis was performed to assess how a change in the weights of the criteria can affect the RWH potential site selection. This analysis therefore was applied on the criteria used in this study for one of the RWH systems, namely terraces to help identifying the spatial layers that are critical in determining the spatial extents of terraces suitability. This was achieved by generating the suitability map of terraces using equal weights for the criteria (figure 36) and then comparing the result with the suitability map which was developed using the relative weights gathered from the local experts using the pairwise comparison method (figure 37).

The degree of suitability and areal extent was examined in the two suitability maps. The results of this analysis indicated that generating the suitability map using equal weights gives inaccurate results, for example the plain areas in the middle of the basin is considered as suitable for the terraces and this is not the case in reality. Although the middle part of the basin is suitable for terraces from the land use, soil, drainage density, and rainfall perspectives, this area is with flat and gentle slope which is not suitable for this kind of RWH. On the other hand, the suitability map with equal weights gives similar results in some locations as the one developed using the relative weights especially in the eastern and southern parts of the study area. In addition, the percentage of suitable locations in the suitability map with equal weights is more than the one with relative weights with about 41% and 33 % respectively.

The results of this analysis revealed that developing the suitability maps for potential RWH using relative weights gathered from local experts are more accurate. Furthermore, it is noticeable from the sensitivity analysis that the slope layer is the most sensitive layer among others and inaccuracies in this layer can lead to errors in the identification of the RWH suitable sites. However, the local experts gave the precipitation layer more preference followed by the slope layer.

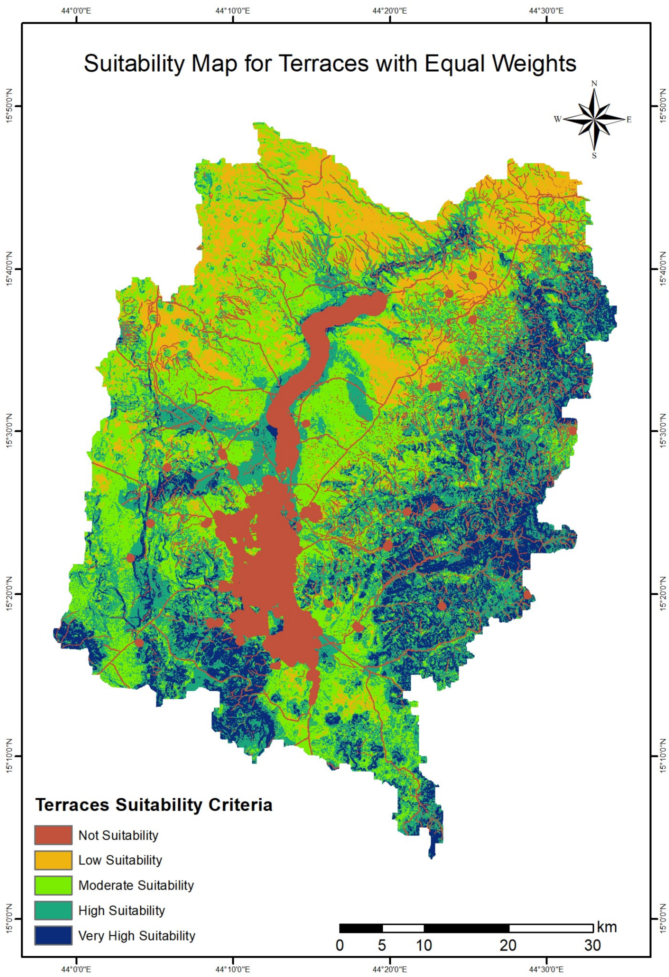


Figure (36): Suitability Map of Terraces using equal weights

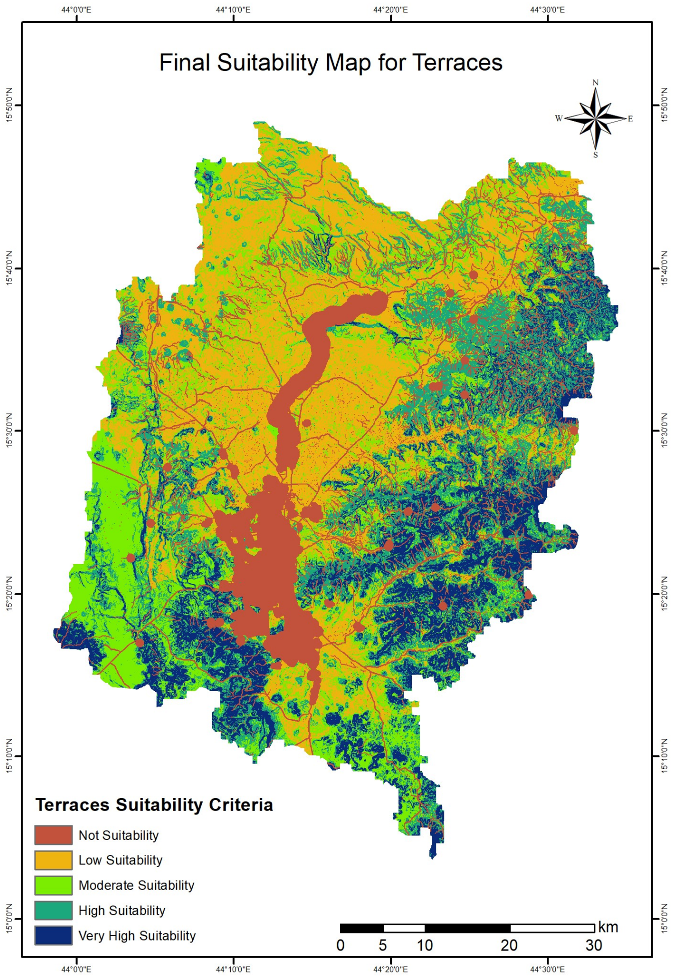


Figure (37): Suitability Map of Terraces using relative weights

6. Conclusion & Limitations

6.1 Conclusion & Recommendations

The identification of suitable sites for RWH is an important step to maximize the water availability, land productivity, and groundwater conservation in arid and semi-arid areas. This study aims to identify the suitable sites for different indigenous RWH systems in Sana'a water basin. To find a solution to this problem, a research has been conducted to answer the following central question: *What are the suitable locations for different indigenous rainwater harvesting systems in Sanaá Water Basin when considering environmental factors?*

To answer this central question, an intensive literature review was carried out to identify the appropriate application to study and map the suitable RWH sites as well as distinguishing number of indigenous RWH systems which can be implemented in the study area and then using them for the analysis. In addition, the analyses were conducted through the use of modern applications such as Geographic Information Systems (GIS), Remote Sensing (RS) and Multi-criteria Analysis (MCA). The selection criteria in this study is based on five biophysical factors, namely precipitation, slope, soil texture, drainage density, and land cover/land use, as well as socio-economic parameters, such as urban areas, roads, water wells, dams, wadis, faults, and sewage passage. These criteria were identified based on intensive literature review. Some local experts (five experts) were asked to evaluate and determine the relative importance of each criterion to each other. It was found that there is a consistency between the experts' opinions by checking the consistency ratio using the pairwise comparison method and a final weight was computed for each criterion. In addition, the local experts provided information about the proper locations within Sana'a basin for each RWH system and this information was used to validate the results of the final suitability maps. Those experts are selected based on their knowledge of the study area in particular and the water issue in Yemen in general.

Based on the questionnaire, four RWH systems were selected in this study, namely, Terraces, Check-dams, Ponds, and Spate Irrigation. Therefore, each RWH system was analysed individually and had its own suitability map. The Weighted Linear Combination (WLC) technique was applied to identify the potential sites for RWH systems in Sana'a basin. The results of this technique was classified into five classes in terms of RWH suitability, namely very low suitability, low suitability, moderate suitability, high suitability, and very high suitability. On the other hand, the Boolean technique was used to exclude the unsuitable sites for the RWH systems based on the socio-economic parameters. The results of this technique was classified into two classes, particularly suitable and unsuitable. After that, the results of the WLC and the Boolean technique were integrated to generate a final suitability map for each RWH system. These final suitability maps were classified into: not suitability, low suitability, moderate suitability, high suitability, and very high suitability.

The results of the suitability maps indicate that a sufficient area of high and very high suitability are existed in the study area for the four RWH systems, particularly terraces, check dams, ponds, and spate irrigation, which are 33.47%, 34.68%, 32.52%, and 31.59% respectively. Accordingly, Sana'a water basin is in general well suited for the implementation of RWH systems.

Arising from the validation of the results, the applications used in this study show that they work effectively to identify potential sites for RWH systems. The validation is performed using the proposed locations by the local experts, literature review, and comparing the results with existing RWH systems in the study area.

The results of the sensitivity analysis revealed that developing the suitability maps for potential RWH using relative weights gathered from local experts are more accurate. Furthermore, it is noticeable that the slope layer was the most sensitive layer in this analysis and inaccuracies in this layer can lead to errors in the identification of the RWH suitable sites.

Furthermore, the powerful capabilities of GIS and RS are demonstrated in handling digital data to identify the suitable sites for RWH systems in Sana'a water basin. Modern scientific applications therefore are needed in Yemen to help the decision makers at various governmental levels in facing the water shortage because of their time and money efficiency. On the other hand, the findings of this study suggest the fact that, the used framework to identify potential suitable sites for different RWH systems is reliable and can be recommended for predicting potential sites for RWH in arid and semi-arid environments which are similar to Sana'a water basin. Moreover, this study will contribute to the enhancement of the water resources availability in Sana'a basin if the selected locations will be utilised for RWH as well as contributing to the sustainable socio-economic development of the study area. Finally, a field work is recommended on the selected sites to investigate whether these sites are in conflict with other land uses in the study area which are not shown through the available data.

6.2 Limitations and constraints

Every academic research is subjected to limitations and constraints either imposed by external factors such as time and resource constraints or imposed by factors relating to the research itself such as data quality and the methods which are used. This research is certainly not an exception to that rule.

One constraint is the nature of the applied methods and tools. The MCA technique which is applied in combination with other techniques in order to make the suitability maps for the RWH systems is often criticized because of the involvement of the subjective judgement in determining the relative weights of the criteria as well as the preference values. Although the relative weights for this study were determined based on the local experts' preferences, they remain subjective or eventually even a political decision (Store & Kangas, 2001).

On the other hand, the accuracy of the suitability maps is affected by the different resolution and limitations of the datasets. In this study, the resolution of the datasets varies from 30 meters (DEM) to about 1 km (precipitation and soil layers), therefore resampling the datasets to a uniform resolution was required. Yet the different resolutions of data may cause uncertainty on the suitability maps.

References

Adeel, Z., Schuster, B., & Bigas, H. (Eds.). (2008). *What Makes Traditional Technologies Tick?: A review of traditional Approaches for Water Management in Drylands*. United Nations University, International Network on Water, Environment and Health.

Adham, A., Riksen, M., Ouessar, M., & Ritsema, C. (2016). Identification of suitable sites for rainwater harvesting structures in arid and semi-arid regions: A review. *International Soil and Water Conservation Research*, *4*(2), 108-120.

Adinarayana, J., Krishna, N. R., & Rao, K. G. (1995). An integrated approach for prioritisation of watersheds. *Journal of environmental management*, *44*(4), 375-384.

Al-Adamat, R. (2008). GIS as a decision support system for siting water harvesting ponds in the Basalt Aquifer/NE Jordan. *Journal of Environmental Assessment Policy and Management*, *10*(02), 189-206.

Al-Adamat, R., AlAyyash, S., Al-Amoush, H., Al-Meshan, O., Rawajfih, Z., Shdeifat, A., & Al-Farajat, M. (2012). The combination of indigenous knowledge and geo-informatics for water harvesting siting in the Jordanian Badia. *Journal of Geographic Information System*, *4*(4), 366-376.

Al-Adamat, R., Diabat, A., & Shatnawi, G. (2010). Combining GIS with multicriteria decision making for siting water harvesting ponds in Northern Jordan. *Journal of Arid Environments*, *74*(11), 1471-1477.

AL-AMERI, A., SCHNEIDER, M., ABO-LOHOM, N. & JANETZ, S. (2014). Characteristics of Stable Isotopes of Oxygen-18 and Deuterium of Groundwater in the Sana'a Basin Aquifer Systems, Yemen. Arabian Journal for Science and Engineering, 39**,** 5625-5636.

Alderwish, A. M. (2010). Induced recharge at new dam sites—Sana’a Basin, Yemen. *Arabian Journal of* Geosciences, *3*(3), 283-293.

Alderwish, A. M., & Dottridge, J. (1998). Recharge components in a semi-arid area: the Sana’a Basin, Yemen. *Geological Society, London, Special Publications*, *130*(1), 169-177.

Al-Sakkaf R. A. M. (2006). Environmental Management in Sana'a Basin: Urbanization and Degradation of Groundwater Quality. Tanta University, Egypt. *First International Environmental Forum*. Retrieved from: http://www.yemenwater.org/wp-content/uploads/2015/06/AlSakkaf_2006.pdf

Al-shabeeb, A. R. (2016). The Use of AHP within GIS in Selecting Potential Sites for Water Harvesting Sites in the Azraq Basin—Jordan. *Journal of Geographic Information System*, *8*(01), 73.

Al-Wadaey, A., & Bamatraf, A. (2010). Indigenous knowledge of water harvesting for sustainable rainfed farming systems in North Yemen, *in: Meeting the Challenge of Sustainable Development in Drylands under Changing Climate – Moving from Global to Local. Presented at the 10th International Conference on Development of Drylands, International Dryland Development Commission, Cairo, Egypt 12-15 Dec 2010,* p. 55.

Bakir, M., & Xingnan, Z. (2008). GIS and remote sensing applications for rainwater harvesting in the Syrian Desert (Al-Badia). In *Proceedings of Twelfth International Water Technology* Conference, IWTC12. Alexandria, Egypt (pp. 73-82).

Balci, A. N., Sheng, T. C., & Dembner, S. A. (1989). Watershed management field manual: Slope treatment measures and practices. FAO Conservation Guide 13/3.

Bamatraf, M. A. (1994). Water harvesting and conservation systems in Yemen. *FAO Proceedings of the Expert Consultation about "Water Harvesting for Improved Agricultural Production",* Water Report 3.

Banai-Kashani, R. (1989). A new method for site suitability analysis: the analytic hierarchy process. Environmental Management, 13 (6), 685 – 693.

Beckers, B., Berking, J., & Schütt, B. (2013). Ancient water harvesting methods in the drylands of the Mediterranean and Western Asia. *eTopoi. Journal for Ancient Studies*.

CES, BRGM, (2010). Conducting Baseline Survey for Future Impact Evaluation_Sana'a Basin: 2005079/WR/Final Report_ Final Report.pdf.

Craig, G. (2012). Yemen's Water Crisis: Review of background and potential solutions. USAID Knowledge Services Center (KSC). Washington, DC. Retrieved from: http://www.yemenwater.org/wp-content/uploads/2014/10/pnadm060.pdf

Critchley, W., & Siegert, K. (1991). Water Harvesting. A manual for the Design and Construction of Water Harvesting Schemes for Plant Production. *FAO – Rome*.

Dai, X. (2016). Dam site selection using an integrated method of AHP and GIS for decision making support in Bortala, Northwest China. *Lund University GEM thesis series*.

Eastman, I. R., W. Jin, P. A. K. Kyem & J. Toledano. (1995). Raster Procedures for Multi-Criteria/Multi-objective Decisions. Photogrammetric Engineering & Remote Sensing, 61 (5), pp. 539-547.

Eastman, J.R., 1997. IDRISI for Windows, User's Guide, Version 2.0, Clark Labs for Cartographic Technology and Geographic Analysis. Clark University.

Edmunds, W.M., Cardona, C., (2006). Unesco G-Wadi Meeting On Water Harvesting, BGS Report, Final Report, Aleppo Syria

El-Awar, F. A., Makke, M. K., Zurayk, R. A., & Mohtar, R. H. (2000). A hydro-spatial hierarchical method for siting water harvesting reservoirs in dry areas. *Applied Engineering in Agriculture*, *16*(4), 395.

Elkhrachy, I. (2017). Vertical accuracy assessment for SRTM and ASTER Digital Elevation Models: A case study of Najran city, Saudi Arabia. *Ain Shams Engineering Journal*.

Falkenmark, M. (1997). Meeting water requirements of an expanding world population. *Philosophical Transactions of the* Royal *Society of London B: Biological Sciences*, *352*(1356), 929-936.

FOPPEN, J. W. A., NAAMAN, M. & SCHIJVEN, J. F. (2005). Managing water under stress in Sana'a, Yemen. Arabian Journal for Science and Engineering, 30**,** 69-83.

Francaviglia, V.M., (2000). Dating the Ancient Dam of Ma'rib (Yemen). J. Archaeol. Sci. 27, 645–653. https://doi.org/10.1006/jasc.1999.0518

Goins, L.D. (2002). An Introductory guide to water harvesting in Ambos Nogales. Soil, Water and Environmental Science, Bureau of Applied Research in Anthropology, University of Arizona. http://arannogales.webhost.uits.arizona.edu/sites/all/files/english/water-harvesting/pdf/introductory-guide-water-harvesting-ambos-nogales.pdf (Last accessed December 2017)

Guttmann-Bond, E., 2010. Sustainability out of the past: how archaeology can save the planet. World Archaeol. 42, 355–366. https://doi.org/10.1080/00438243.2010.497377

Harb, R. (2015). Assessing the potential of rainwater harvesting system at the Middle East Technical University–Northern Cyprus campus. *Middle East Technical University Library Web site*.

Heywood, I., Cornelius, S, & Carver, S, (2011). An Introduction to Geographical Information Systems, second edition, Pearson Education Limited: Essex.

Hydrosult, 2009. Hydrogeological and Water Resources Monitoring and Investigations. Activity 3: Aquifer modeling studies, Final Draft Technical Report, Sana'a, June 2009.

Hydrosult, 2010. Assessment of the Water Resources of the Sana'a Basin Strategic Options for the Sustainable Development of the Basin's Water Resources. Sana'a Basin Water Management Project, Sana‟a, Yemen.

Isioye, O. A. (2012). A Multi Criteria Decision Support System (MDSS) for identifying rainwater harvesting site (S) in Zaria, Kaduna state, Nigeria. *International Journal of Advanced Scientific Engineering and Technological Research*, *1*(1).

Kahinda, J. M., Boroto, R. J., Dube, R., & Taigbenu, A. E. (2007). Preliminary Conceptual Model of the GIS based Rainwater Harvesting Decision Support System.

Krois, J., & Schulte, A. (2014). GIS-based multi-criteria evaluation to identify potential sites for soil and water conservation techniques in the Ronquillo watershed, northern Peru. *Applied Geography*, *51*, 131-142.

Mahmoud, S. H. (2014). Delineation of potential sites for groundwater recharge using a GIS-based decision support system. *Environmental Earth Sciences*, *72*(9), 3429-3442.

Mahmoud, S. H., & Alazba, A. A. (2014). The potential of in situ rainwater harvesting in arid regions: developing a methodology to identify suitable areas using GIS-based decision support system. *Arabian Journal of Geosciences*, *8*(7), 5167-5179.

Malczewski, J. (2004). GIS-based land-use suitability analysis: a critical overview. *Progress in Planning 62*, 3-65.

Mati, B., De Bock, T., Malesu, M., Khaka, E., Oduor, A., Meshack, M., & Oduor, V. (2006). Mapping the potential of rainwater harvesting technologies in Africa. *A GIS overview on development domains for the continent and ten selected countries. Technical Manual*, *6*, 126.

Mati, B., De Bock, T., Malesu, M., Khaka, E., Oduor, A., Meshack, M., & Oduor, V. (2006). Mapping the potential of rainwater harvesting technologies in Africa. *A GIS overview on development domains for the continent and ten selected countries. Technical Manual*, *6*, 126.

Mbilinyi, B. P., Tumbo, S. D., Mahoo, H. F., Senkondo, E. M., & Hatibu, N. (2005). Indigenous knowledge as decision support tool in rainwater harvesting. *Physics and Chemistry of the Earth, Parts A/B/C*, *30*(11-16), 792-798.

Mbilinyi, B. P., Tumbo, S. D., Mahoo, H., & Mkiramwinyi, F. O. (2007). GIS-based decision support system for identifying potential sites for rainwater harvesting. *Physics and Chemistry of the Earth, Parts A/B/C*, *32*(15-18), 1074-1081.

Miyan, M. A. (2015). Droughts in Asian least developed countries: Vulnerability and sustainability. *Weather and Climate Extremes*, *7*, 8-23.

Moges, G. (2009). Identification of potential rainwater harvesting areas in the central Rift Valley of Ethiopia using a GIS based approach. *Master of Science minor thesis. Weganingen University*.

Moore, S., & Fisher, J. B. (2012). Challenges and opportunities in GRACE-based groundwater storage assessment and management: an example from Yemen. *Water resources management*, *26*(6), 1425-1453.

Mosate T. (2016) Application of GIS to determine suitable sites for surface rainwater harvesting in a semi-arid catchment. A case study of Notwane Catchment. Unpublished Msc. Thesis. *University of Dar es Salam*.

MSU. (N/A). Soils. Department of Geography, Michigan States University. https://geo.msu.edu/extra/geogmich/soils.html (Last accessed January 2018)

Munyao, J. (2010) Use of satellite products to assess water harvesting potential in remote areas of Africa. A case study of Unguja Island, Zanzibar. Unpublished Msc. Thesis. *ITC, Enschede, The Netherlands*

Nasr, M. (1999). Assessing desertification and water harvesting in the Middle East and North Africa: Policy implications, ZEF Discussion Papers on Development Policy, No. 10

Noman, A. A. (2004). Indigenous knowledge for using and managing water harvesting techniques in Yemen. Civil Engineering Department, Water and Environment Center (WEC), Sana'a University, Yemen.

Nunes, A. N., De Almeida, A. C., & Coelho, C. O. (2011). Impacts of land use and cover type on runoff and soil erosion in a marginal area of Portugal. *Applied Geography*, *31*(2), 687-699.

Oberle, A. (2004): GIS Based Identification of Suitable Areas for Various Kinds of Water Harvesting in Syria. Diss., University of Karlsruhe, Karlsruhe.

Oweis, T., Hachum, A., & Bruggeman, A. (2004). Indigenous water-harvesting systems in West Asia and North Africa. Indigenous water-harvesting systems in West Asia and North Africa.

Oweis, T., Prinz, D., & Hachum, A. (2001). *Water harvesting: indigenous knowledge for the future of the drier environments*. ICARDA. Aleppo, Syria.

Oweis, T.Y., Prinz, D., Hachum, A.Y., (2012). Rainwater Harvesting for Agriculture in the Dry Areas. CRC Press, ISBN 978-0-415-62114-4.

Pacey, A., & Cullis, A. (1986). *Rainwater harvesting: the collection of rainfall and runoff in rural areas*. Intermediate technology publications. 216 pp.

Pauw, E., Oweis, T., & Youssef, J. (2008). Integrating Expert Knowledge in GIS to locate biophysical potential for water harvesting: Methodology and a case study for Syria. *ICARDA, Aleppo, Syria*, 59.

Prinz, D. (1996). Water harvesting—past and future. In *Sustainability of irrigated agriculture* (pp. 137-168): Springer.

Prinz, D., Oweis, T., & Oberle, A. (2004). Water Harvesting for Dry Land Agriculture Developing a Methodology Based on Remote Sensing and GIS.

Saaty, T. L., (2008). Decision Making With the Analytic Hierarchy Process. *International Journal of Services Sciences, 1(1)*, p.83.

Saaty, T. L., (2013). The Analytic Network Process. *Decision Making With the Analytic Network Process*, 195, pp. 1-40.

Saaty, T.L. (1980). The Analytic Hierarchy Process: Planning, Priority Setting, Resources Allocation. *McGraw-Hill*, New York.

Samra, J., Sharda, V., & Sikka, A. K. (2002). Water harvesting and recycling: Indian Experience. Dehradun, India: Central Soil and Water Research and Training Inst.

SBWMP (2010). Assessment of the water resources of the Sanaá basin. Strategic options for the sustainable development of the basin's water resource. Summary report. *Ministry of Water and Environment. Yemen*.

Sieghart, L. C. (2009). Unilateral Clean Development Mechanism–An approach for a least developed country?: The case of Yemen. *Environmental Science & Policy*, *12*(2), 198-203.

Singh, J., Singh, D., & Litoria, P. (2009). Selection of suitable sites for water harvesting structures in Soankhad watershed, Punjab using remote sensing and geographical information system (RS&GIS) approach—A case study. *Journal of the Indian Society of Remote Sensing, 37*(1), 21-35.

Sivanappan, R. K. (1997). Technologies for water harvesting and soil moisture conservation in small watersheds for small-scale irrigation. *Water Reports (FAO)*.

Stanley Consultant INC. (2006). BAHMAN Check dams. Final Report. Sana'a Basin Water Management Project. Retrieved from: http://www.spate-irrigation.org/wordpress/wp-content/uploads/2011/06/BAHMAN_Design_Report-.pdf

Steenbergen, F. V., Lawrence, P., Haile, A. M., Salman, M., Faurès, J. M., Anderson, I. M & Ratsey, J. (2010). Guidelines on spate irrigation. *FAO irrigation and drainage paper*, (65).

Store, R., & Kangas, J. (2001). Integrating spatial multi-criteria evaluation and expert knowledge for GIS-based habitat suitability modelling. *Landscape and urban planning*, 55(2), 79-93.

TAHER, T. M. (2016). Groundwater abstraction management in Sana'a Basin, Yemen: a local community approach. Hydrogeology Journal, 24**,** 1593-1605.

Thames, J. L., (1989). Water harvesting. Role of forestry in combating desertification. Food and Agriculture Organization of the United Nations, Rome, Italy.

Tumbo, S. D., Mbilinyi, B. P., Mahoo, H. F., & Mkilamwinyi, F. O. (2014). Identification of suitable indices for identification of potential sites for rainwater harvesting. *Tanzania Journal of Agricultural Sciences*, *12*(2).

UNU-INWEH, (2009). Seeing traditional technologies in a new light: using traditional approaches for water management in drylands; World Water Assessment Programme side publications series, ISBN 978-92-3-104118 [WWW Document]. URL http://unesdoc.unesco.org/images/0018/001817/181799E.pdf (accessed 11.26.14).

Ward et al., (2010). *The water crisis in Yemen: Managing extreme water scarcity in the Middle East* (Vol. 21). IB Tauris.

WEC, Water and Environment Center (2016). Water Buffer Management *(Recharge, Retention and* Reuse *(3R) of Al Sayla Water in Sana'a Basin)*. Final Report. WEC & NUFFIC & NICHE.

Weiss, C., Gerlach, I., (2009). Qadhat—a comparative study of ancient and new lime mortar from the Marib province/Yemen. Archaeol. Anthropol. Sci. 1, 87–94. https://doi.org/10.1007/s12520-009-0007-2

Yusof, K. W., Serwan, M., & Baban, J. (2000). Identifying optimum sites for locating reservoirs employing remotely sensed data and geographical information systems. In *Proc. 21st Asian Conference on Remote Sensing* (pp. 4-8).

Appendix (1)

A questionnaire on determining the suitable systems and locations of Yemeni indigenous rainwater harvesting techniques in Case study of Sana'a Basin

(i) What Yemeni traditional/indigenous water harvesting systems that are more suitable to increase water use efficiency, reduces drought and flash floods risks in Sana'a Basin?

#	Systems	Their importance (No 1 is the more suitable and important no 5 is less important)	which location in Sana'a basin fits this systems more					Comments
			Upstream	Downstream	Plain Areas	Mountain areas	Other location	
1	Sloping/Mountain terraces							
2	Flood WH/Spate irrigation							
3	Check Dams							
4	Ponds (including Bariks, Siqyat, Niqab, Kuruf, Mawajel, Khazzan...etc)							
5	Roof top RWH*							
6	....							
7	....							
8	....							
9	....							
10	....							

* Roof top Rainwater Harvesting will not be considered in this study

(ii) Do you have any further suggestions or comments for the selection process of traditional water harvesting systems for Sana'a Basin?

....

(iii) What is the level of your knowledge and experiences in this field? Give a number from 1 to 10 (10 is very experienced)?

....

(iv) Factor weighting score

(**) Relative weights of the criteria used for Water Harvesting in **General**

Factor	Factor Weighting score																	Factor
	More importance than								Equal	Less importance than								
Rainfall	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Soil
Soil	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Slope
Slope	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Drainage
Drainage	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Land use/Cover
Land use/Cover	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Geology
Geology	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....

Factor	More importance than								Equal	Less importance than								
Rainfall	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Slope
Soil	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Drainage
Slope	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Land use/Cover
Drainage	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Geology
Land use/Cover	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Geology	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....

Factor	More importance than								Equal	Less importance than								
Rainfall	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Drainage
Soil	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Land use/Cover
Slope	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Geology
Drainage	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Land use/Cover	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Geology	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....

Factor	More importance than								Equal	Less importance than								
Rainfall	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Land use/Cover
Soil	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Geology
Slope	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Drainage	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Land use/Cover	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Geology	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....

Factor	More importance than								Equal	Less importance than								
Rainfall	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Geology
Soil	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Slope	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Drainage	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Land use/Cover	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Geology	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....

(1) Relative weights of the criteria used for **Terraces**

Factor	Factor Weighting score																	Factor
	More importance than								Equal	Less importance than								
Rainfall	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Soil
Soil	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Slope
Slope	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Drainage
Drainage	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Land use/Cover
Land use/Cover	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Geology
Geology	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....

Factor	More importance than								Equal	Less importance than								
Rainfall	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Slope
Soil	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Drainage
Slope	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Land use/Cover
Drainage	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Geology
Land use/Cover	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Geology	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....

Factor	More importance than								Equal	Less importance than								
Rainfall	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Drainage
Soil	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Land use/Cover
Slope	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Geology
Drainage	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Land use/Cover	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Geology	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....

Factor	More importance than								Equal	Less importance than								
Rainfall	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Land use/Cover
Soil	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Geology
Slope	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Drainage	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Land use/Cover	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Geology	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....

Factor	More importance than								Equal	Less importance than								
Rainfall	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Geology
Soil	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Slope	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Drainage	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Land use/Cover	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Geology	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....

(2) Relative weights of the criteria used for **Spate Irrigation**

Factor	Factor Weighting score																	Factor
	More importance than								Equal	Less importance than								
Rainfall	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Soil
Soil	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Slope
Slope	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Drainage
Drainage	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Land use/Cover
Land use/Cover	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Geology
Geology	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....

Factor	More importance than								Equal	Less importance than								
Rainfall	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Slope
Soil	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Drainage
Slope	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Land use/Cover
Drainage	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Geology
Land use/Cover	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Geology	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....

Factor	More importance than								Equal	Less importance than								
Rainfall	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Drainage
Soil	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Land use/Cover
Slope	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Geology
Drainage	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Land use/Cover	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Geology	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....

Factor	More importance than								Equal	Less importance than								
Rainfall	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Land use/Cover
Soil	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Geology
Slope	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Drainage	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Land use/Cover	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Geology	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....

Factor	More importance than								Equal	Less importance than								
Rainfall	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Geology
Soil	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Slope	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Drainage	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Land use/Cover	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Geology	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....

(3) Relative weights of the criteria used for **Check Dams**

Factor	Factor Weighting score																	Factor
	More importance than								Equal	Less importance than								
Rainfall	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Soil
Soil	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Slope
Slope	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Drainage
Drainage	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Land use/Cover
Land use/Cover	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Geology
Geology	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....

Factor	More importance than								Equal	Less importance than								
Rainfall	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Slope
Soil	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Drainage
Slope	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Land use/Cover
Drainage	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Geology
Land use/Cover	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Geology	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....

Factor	More importance than								Equal	Less importance than								
Rainfall	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Drainage
Soil	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Land use/Cover
Slope	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Geology
Drainage	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Land use/Cover	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Geology	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....

Factor	More importance than								Equal	Less importance than								
Rainfall	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Land use/Cover
Soil	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Geology
Slope	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Drainage	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Land use/Cover	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Geology	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....

Factor	More importance than								Equal	Less importance than								
Rainfall	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Geology
Soil	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Slope	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Drainage	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Land use/Cover	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Geology	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....

(4) Relative weights of the criteria used for **Ponds**

Factor	Factor Weighting score																	Factor
	More importance than								Equal	Less importance than								
Rainfall	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Soil
Soil	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Slope
Slope	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Drainage
Drainage	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Land use/Cover
Land use/Cover	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Geology
Geology	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....

Factor	More importance than								Equal	Less importance than								
Rainfall	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Slope
Soil	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Drainage
Slope	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Land use/Cover
Drainage	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Geology
Land use/Cover	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Geology	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....

Factor	More importance than								Equal	Less importance than								
Rainfall	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Drainage
Soil	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Land use/Cover
Slope	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Geology
Drainage	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Land use/Cover	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Geology	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....

Factor	More importance than								Equal	Less importance than								
Rainfall	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Land use/Cover
Soil	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Geology
Slope	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Drainage	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Land use/Cover	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Geology	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....

Factor	More importance than								Equal	Less importance than								
Rainfall	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Geology
Soil	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Slope	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Drainage	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Land use/Cover	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....
Geology	...	...	...	...	...	...	...	...	......	...	...	...	...	...	...	...	...	....