UNIVERSITY OF BIRMINGHAM

TOWARDS A HYBRID FRAMEWORK FOR RAINWATER HARVESTING SITE SELECTION IN ARID AND SEMI-ARID REGIONS.

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Abstract

The lack of precipitation and erratic rainfall patterns in arid and semi-arid regions of the world raise concerns about water scarcity. Rainwater harvesting (RWH) is a traditional technique employed to gather and store rainwater for diverse uses such as drinking water and agricultural applications. A number of frameworks, each with its unique set of criteria, have been developed in recent decades to help detect and prioritise locations for rainwater harvesting (RWH), an essential technique not only for the preservation and enhancement of water resources but also as a key component of sustainable integrated watershed management. To rank possible sites, these frameworks were created using what are known as structural criteria (biophysical and socio-economic). While these frameworks are effective in identifying potential sites for RWH, they often do not account for the broader ecological criteria that are essential for the sustainability of the watershed system as a whole. The sustainability of the system, regulatory compliance, climate resilience, biodiversity preservation, water quality improvement, and environmental protection are all dependent on ecological criteria.

In this study, this deficiency is addressed by the development of a hybrid framework which combines structural criteria with important ecological criteria. Planning to identify rainwater harvesting sites in arid and semi-arid regions based on various criteria—namely biophysical, socioeconomic, and ecological—is a complex issue especially when including ecological criteria.

The first part of this thesis involved a systematic review to identify the gaps in knowledge and the criteria used in existing frameworks. The conducted systematic review is based on the two major databases of Scopus and Engineering Village. Sixty-eight relevant studies were found and critically analysed to identify patterns and unique features in the adopted frameworks. The results of this review reveal that 41% of the frameworks consider both biophysical and socioeconomic criteria, whereas the remaining 59% of the frameworks depend solely on biophysical criteria. The importance of each criterion is encapsulated through a suitability score.

The term "scale" is used here to refer to the system or range used to rate or measure how well a site aligns with specific criteria for suitability, whether through a binary indicator (match or no match) or through graded scales of varying levels of detail. The first scale which accounts for 21% of the frameworks uses a binary (0 or 1)

indicator of whether the site matches a criterion or not. While the other frameworks use graded scales of differing granularities, with 52% using a low-resolution scale of 1 to 3, 4, or 5. This is followed by a 7% that uses a medium-resolution scale of 1 to 10, and a further 7% using a high-resolution scale of 1 to 100. The remaining 13% of the frameworks did not specify the scale used. Importantly, this part of the thesis concludes that all existing frameworks for selecting RWH sites are solely based on biophysical and/or socioeconomic criteria; ecological impacts, the consideration of which is vital for building RWH systems sustainably, are currently ignored.

The latter part of the thesis is to identify the important ecological criteria and their corresponding weights as well as to use a case study to apply the framework. The important ecological criteria have been identified based on additional literature review. The inter-relationships of ecological criteria are complex, with "independent" criteria affecting the "mediator" criteria (e.g. dissolved oxygen, phosphorous concentration) which directly impact ecological standards, i.e. the "dependent" criteria such as the number of aquatic organisms. This study focuses on the key independent criteria of temperature and light, which are prioritised based on findings from the analysis of the literature. These findings have shown temperature and light to be the most influential factors affecting water quality criteria. However, the hybrid framework could easily be expanded to include additional ecological criteria, depending on the region to which it is applied. The framework encompasses independent, mediator and dependent ecological criteria identified from the literature, and the importance of each (represented as weightings in the framework) has been quantified through a robust combination of data analysis and expert opinion. The importance of the ecological criteria inclusion is demonstrated through a case study of Erbil Province in Iraq, where both climate change and human actions have seriously reduced water supplies in the past 20 years. A number of proposed rainwater harvesting sites are assessed via a structural and the new hybrid framework. The results demonstrate that the inclusion of these ecological criteria changes the ranking of the sites. Four different sites for rainwater harvesting (RWH) were chosen within Erbil city, each identified by its specific geographic coordinates. The hybrid framework implemented on these sites encompasses two distinct scenarios. The first scenario incorporates three key components: biophysical, socio-economic, and ecological criteria. In contrast, the second scenario integrates two components: biophysical and socio-economic criteria. For the first scenario, the suitability scores for the sites, listed in sequence from site numbers 1 to 4, are as follows: 1 (2.71), 2 (2.52), 3 (2.13), and 4 (3.31). For the second scenario, the suitability scores for the sites, listed in sequence from site numbers 1 to 4, are as follows: 1 (2.53), 2 (2.62), 3 (2.26), and 4 (3.03).

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Statement of Original Authorship

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

Signature: ___________________________

Date: ___________________________

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Chapter 1: Introduction

Water is among the planet's most vital resources, especially in regions where rainfall is limited and scarcity is a constant challenge. Water scarcity refers to the insufficient availability of water or the lack of access to safe and reliable water sources. A region is considered "water-stressed" when it withdraws 25% or more of its renewable freshwater resources (Biancalani & Marinelli, 2021). Across the globe, many areas grapple with severe water shortages, making effective management and conservation crucial. More than two billion people will live in areas with severe water scarcity by 2050 according to the United Nations Environment Program which might affect the development of the countries on the planet (Field & Barros, 2014; Sekar & Randhir, 2007).

Water resources are particularly limited in arid and semi-arid regions, characterised by average annual precipitation of 150–350 mm and 350–700 mm, respectively (Ammar, 2017). Arid and semi-arid regions represent about 50 million km^2 of the earth, which means 35% of the earth has issues related to water scarcity for drinking, crop and other demands see Figure 1-1 (Ziadat et al., 2012). Also, some of these regions have short duration and high intensity of precipitation, and this precipitation occurs only in short wet seasons. In addition, Arid and semi-arid regions face increasing pressure due to rising per capita water use, population growth, irrigation demands, and the uncertainties of climate change (Ammar, 2017).

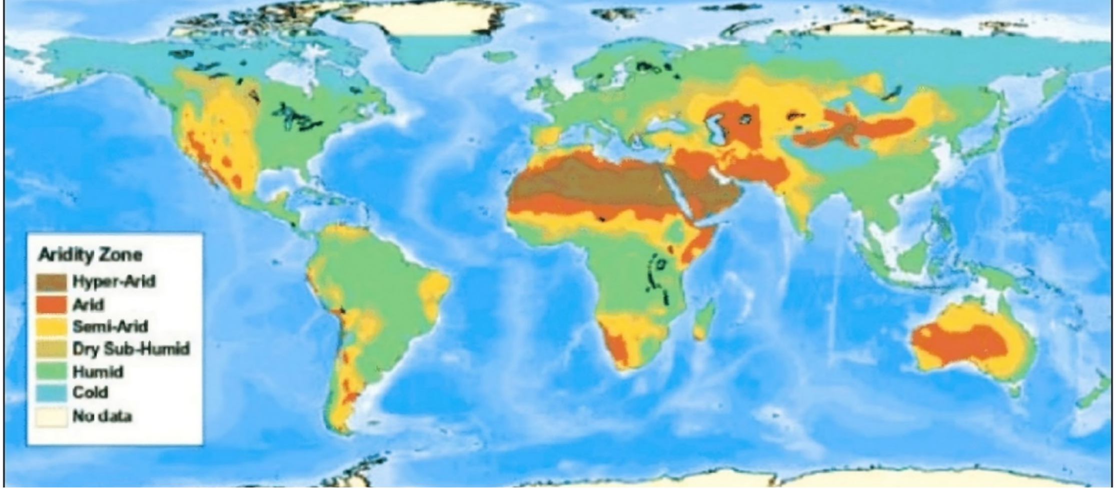

Figure 1-1 displays a map highlighting the arid and semi-arid regions of the world (Ahmad et al., 2021).

To control these issues, it is important to utilise systems to conserve this water for use in the dry season. Therefore, water management is essential in these regions to improve the quality of life and ensure effective use of water resources (Yaseen et al., 2020). Integrated watershed management (IWM), which takes into account the interdependence of water, soil, plant, and human activity within a watershed, is a crucial component of this strategy. Integrated watershed management promotes the sustainable use of water resources, enhances ecosystem health, and lowers the danger of flooding and soil erosion by regulating these factors collectively (Rockstrom et al., 2011).

Rainwater harvesting (RWH) represents a pivotal technique within the realm of water management. This method is considered the most important technique to collect and store rainwater, thus ensuring continuous supply throughout the year (Sayl, 2017). In addition, rainwater harvesting represents long-term sustainability through groundwater recharge, supporting soil conservation, and overall watershed health when incorporated into larger watershed management initiatives.

The water conservation in these regions depends on climate and hydrological data, as a result, an efficient water conservation system must be devised (Agarwal et al., 2001; Sayl et al., 2017; Sayl et al., 2016). The scarce and intermittent rainfall is the main obstacle to development in arid areas. To ensure continuity of water availability for use in domestic, commercial, industry and agriculture, it is important to utilise water harvesting systems (Sayl et al., 2020). According to Zheng et al. (2018b), it is believed to be important to identify potential sites for rainwater harvesting in order to maximise water availability and land productivity in the arid and semi-arid areas of China.

Rainwater harvesting (RWH) structures are critical components of water management strategies. These structures employ various techniques to capture rainwater for different purposes, including percolation dams, ponds, and dikes (Naseef & Thomas, 2016; Oweis, 2012). There are various RWH systems used in different countries, such as cisterns, terracing, wadi-beds, underground tanks, and Khazzan, which are used in Yemen, Libya, and Egypt. In addition, several traditional RWH systems are used in northern Mexico and the southwest United States. Ancient systems have been often used for domestic and agricultural purposes as ponds, cisterns, small dams, and diversion canals (Oweis, 2012).

Rainwater harvesting has some problems which can make the design of the system more complicated. These problems include firstly, one can never be sure of the amount of rainfall that will fall. Secondly, the initial costs of the structure and the costs of maintenance, which can be largely overcome through proper design and using the locally available material to ensure sustainability. Thirdly, the quality of water may be affected by air pollution, birds or animals, insects, organic matter, and dirt. Finally, supply of water is sensitive to drought also the supply might be limited by the size of catchment area, the amount of rainfall and the storage reservoir (Worm, 2006). Watersheds provide a diverse array of ecosystem services, including water yield, climate regulation, soil conservation, primary productivity, and biodiversity. However, watershed problems are critical for the livelihoods of their inhabitants, as they present numerous challenges that can lead to poverty, food insecurity, and social conflict. These challenges are often the result of unsustainable exploitation of natural resources and include climate change, soil erosion, loss of biodiversity, economic conflicts, overemphasis on local alterations of natural hydrological cycles, water quality issues, and reduced groundwater recharge (Cao et al., 2022).

According to FAO (2003), six criteria should be considered when selecting a rainwater harvesting site: hydrology, climate, soil, agronomy, socioeconomic conditions, and topography. The consideration of all these criteria makes the selection of suitable sites more complicated and more time-consuming, especially for large catchments. The type of RWH system depends on the slope of the region. For example, the bonds are used for small flat areas with a slope less than 5%; percolation tanks are used for moderate slopes of 5–10%; terracing is used for steeper slopes of 5–30%; and slopes of 15% are suitable for check dams (Ammar et al., 2016; Krois & Schulte, 2014; Ramakrishnan et al., 2009). Extracting data for site selection has traditionally required significant time and human resources. However, Geographic Information Systems (GIS) and remote sensing (RS) can simplify the process (Sayl, 2017).

Ecological criteria are not currently considered in existing frameworks, despite their important role in preventing environmental harm and ecosystem disruption. A rainwater harvesting (RWH) structure with a comprehensive ecological system should fulfil key ecological functions, including biodiversity conservation, mitigating potential harm to ecosystems, and safeguarding ecological balance and resilience against degradation (Zheng et al., 2018a). One of the most important aspects in selecting RWH sites is soil erosion. High surface runoff is necessary, however, it also causes soil erosion (Zheng et al., 2018a). Zheng et al. (2018a), developed a procedure for the continuous accounting of runoff potential risks of water and soil loss based on the universal soil loss equation to evaluate the potential for water harvesting and based on the Soil Conservation Service curve number. According to Pacheco et al. (2015) sediment deposition is an important factor that affects the volume of reservoirs and the quality of water; as a result erodibility is a crucial factor to consider.

To succeed, a rainwater harvesting (RWH) structure should be chosen in regions where the surface area for runoff is higher, especially in areas experiencing water shortages. Additionally, it should aim to decrease water consumption by vegetation, improve soil quality, increase vegetation coverage and biodiversity, control sediments and silt through the establishment of storage dams, and employ other techniques used to conserve water and soil in regions sensitive to soil erosion (Zheng et al., 2018a).

1.1 KNOWLEDGE GAP

Site selection is an important part of the development of RWH systems. Currently, selection depends on two main groups of criteria, biophysical and socioeconomic. In addition to the biophysical and socio-economic criteria, ecological criteria are important when considering sustainability yet are not included in current frameworks. These criteria include temperature, concentration of dissolved nitrogen (n), total phosphorus (TP), light, pH, dissolved oxygen (DO), salinity, and ammonia. These criteria are utilised to identify optimal sites for RWH structures, aiming to establish a relationship between them to ensure sustainable rates of water withdrawal and effective control of water evaporation (Mahmoud et al., 2016; S. H. Mahmoud & Alazba, 2015; Prinz & Singh, 2000; Sayl, 2017). All prior studies have focused on biophysical and socioeconomic criteria without taking into consideration ecological criteria, which represent the significant pillars of sustainability. Adopting sustainable practices in water usage can help maintain a balance between the demand for water and its availability, especially when this water is used for drinking (Rahman et al., 2014).

The knowledge gap which is addressed by the research detailed in this thesis is how to extend RWH site selection frameworks to include ecological criteria in a RWH site selection framework.

The main obstacle of this work may be divided into two parts: firstly, finding a method to assess the ecological criteria for RWH systems before construction, and secondly, combining these criteria with current biophysical and socioeconomic criteria to identify appropriate locations for RWH.

1.2 RESEARCH QUESTIONS.

The following research questions will be addressed in this study:

1- How do we evaluate the ecological impact of rainwater harvesting in arid and semi-arid regions?
2- How do we include ecological assessment in the selection and positioning of rainwater harvesting structures?
3- Can we combine ecological criteria with the currently used biophysical and socio-economic criteria to enhance the final decision?

1.3 AIM AND OBJECTIVES

The main aim of this study is to create and implement a hybrid framework, which incorporates both structural and ecological criteria, for rainwater harvesting site selection in arid and semi-arid regions. In order to achieve this aim, the following objectives will be met:

1- Identify and understand existing frameworks via a systematic literature review.
2- Identify the direct and indirect ecological criteria of importance for RWH site selection and determine the links between them. This will be through a literature review.
3- Determine appropriate weights for each indirect criterion by quantifying their impact level on direct criteria through literature review and consultation with experts in ecological impacts on water systems.
4- Combine the structural criteria currently used for RWH site selection with the new ecological criteria to produce a comprehensive, hybrid framework.
5- Demonstrate the applicability of the new, hybrid framework via a case study.

1.4 THESIS OUTLINE

This thesis is divided into seven chapters and is structured as follows:

This introduction is followed by a literature review Chapter 2, which presents the background and types of rainwater harvesting. Following this, Chapter 3 present the systematic literature review, the purpose of this chapter is to identify the existing criteria and methods that have been used to identify sites for rainwater harvesting in arid and semi-arid regions based on conducting a systematic review, as well as to identify gaps in knowledge.

Following this, the methodology Chapter 4 outlined the research design, data collection methods which include quantitative and qualitative approaches via a questionnaire, and data analysis techniques employed in the study.

Then, Chapter 5 presents a detailed analysis of the questionnaire findings related to ecological criteria and the analysis weightings of existing biophysical and socioeconomic criteria. It is organised into four sections, each focussing on different aspects of the analysis. The chapter also identifies knowledge gaps in ecological criteria by assessing the weights assigned through a survey conducted among experts.

Chapter 6 demonstrates the application of the framework through a case study and conducts a comparative analysis of the framework in arid and semi-arid regions (RHF-ASAR) with existing framework outputs, specifically focusing on Erbil City, Iraq.

Chapter 7 details the important conclusions derived from the study's findings and gives recommendations for future research in this field.

The dissertation follows a hybrid format, consisting of chapters that include both published papers and traditional chapters. Specifically, it contains two published journal papers, as outlined below:

i. Ahmed, S., Jesson, M., & Sharifi, S. (2023). Selection Frameworks for Potential Rainwater Harvesting Sites in Arid and Semi-Arid Regions: A Systematic Literature Review. *Water*, *15*(15), https://www.mdpi.com/2073-4441/15/15/2782.

ii. Ahmed, S., Jesson, M., & Sharifi, S. (2025). A Novel, Ecology-Inclusive, Hybrid Framework for Rainwater Harvesting Site Selection in Arid and Semi-Arid Regions. Water Resources Management, https://link.springer.com/article/10.1007/s11269-024-04073-7

Chapter 2: Background of rainwater harvesting

This short chapter provides background information on topics relevant to the main body of this thesis. Some parts of the chapter are included in the introduction to the author's published paper which forms Chapter 3: of this thesis and details the systematic literature review and its key findings. Therefore, some repetition of material, as necessary to maintain the coherence of the thesis.

2.1 WATER HARVESTING

Water harvesting is defined as "The collection and management of floodwater or rainwater runoff to increase water availability for domestic and agricultural use as well as ecosystem sustenance" (Mekdaschi Studer & Liniger, 2018).

Due to an increase in water demand, water from streams, rivers, and reservoirs and pumped groundwater are no longer sufficient. subsequently in recent decades new interest in water resources such as rainfall and floodwater harvesting (Ingrao et al., 2023).

Many arid and semi-arid places have used traditional water collection techniques for a long time. For example, rainwater harvesting, floodwater harvesting, fog and dew harvesting, and groundwater harvesting (Kahinda & Taigbenu, 2011). These traditional strategies have been important in the past and were very useful for ancient civilizations in arid and semi-arid areas around the world (Kahinda & Taigbenu, 2011). According to Kahinda and Taigbenu (2011), there are four types of water harvesting: fog and dew harvesting, rainwater harvesting(RWH), floodwater harvesting(FWH), and groundwater harvesting (GWH) as shown in Figure 2-1.

In addition, the study explores rainwater harvesting techniques in macro catchments to address water scarcity in arid and semi-arid regions worldwide. Most of these regions have seasonal rain and dry seasons, such as Iraq, Saudi Arabia, Tunisia, Jordan, etc. The available water quantities must be managed to collect water during the rainy season and utilize it in the dry season for irrigation, drinking, and domestic purposes.

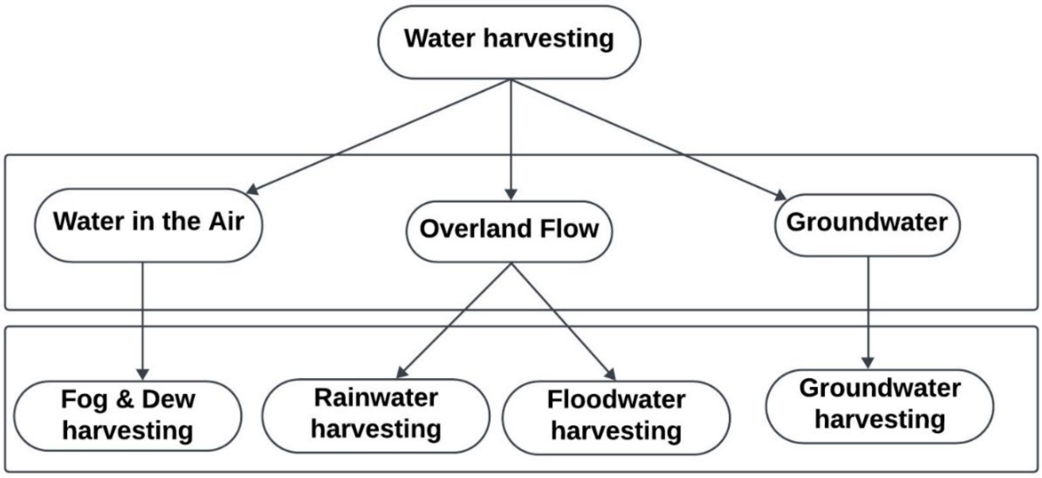

Figure 2-1 Strategies of water harvesting (Kahinda & Taigbenu, 2011).

2.1.1 Rainwater Harvesting (RWH)

Rainwater harvesting (RWH) refers to the process of collecting and storing rainwater for future use. Unlike irrigation, RWH directly connects the catchment area with the benefiting target area, where water is either stored in the soil profile or reservoirs without controlled distribution. This method is versatile and can be used for purposes beyond agriculture, such as domestic or drinking water needs (Oweis et al., 1999).

RWH encompasses a variety of techniques that link runoff-producing areas to runoff-receiving areas. These techniques include collecting water from rooftops, ground surfaces, or larger catchments for agricultural, domestic, or drinking purposes (Mbilinyi et al., 2005). This can include both fluvial and pluvial flows. Based on the method of collection and use, RWH can be categorized into three main forms: water collection, rooftop harvesting, and macro or micro-catchments. Each method is tailored to specific purposes, depending on the geographical and environmental context.

1- Collection of Runoff Water

This approach is employed to mitigate net runoff within a designated area by retaining rainwater and prolonging the duration of infiltration (Mbilinyi et al., 2005). According to Prinz, (1996) believed that this method is diverse and is often a product of local ingenuity and varying cultural practices. For example, water collection includes mixed cropping, trash lines, ridges, borders, terraces, ponds, fog harvesting, deep tillage, and dry seeding. Most of this water is used for irrigation purposes (Rutherford, 2000).

2- Rooftop Harvesting

Rooftop harvesting is a method commonly used to collect clean water for drinking and domestic purposes. This technique involves a small catchment area, typically the roof of a house, where gutters and pipes direct rainwater into a ground-level storage tank. A tap is often attached to the tank for easy access, see Figure 2-2 (Mbilinyi et al., 2005).

However, there are concerns about the quality of rainwater due to atmospheric pollutants, which can contaminate rainfall during collection (Rutherford, 2000). Modern runoff water may also be affected by pesticide residues, elevated mineral levels, bacteria, and other impurities, making it potentially unsuitable for drinking without proper treatment (Palmback, 2004).

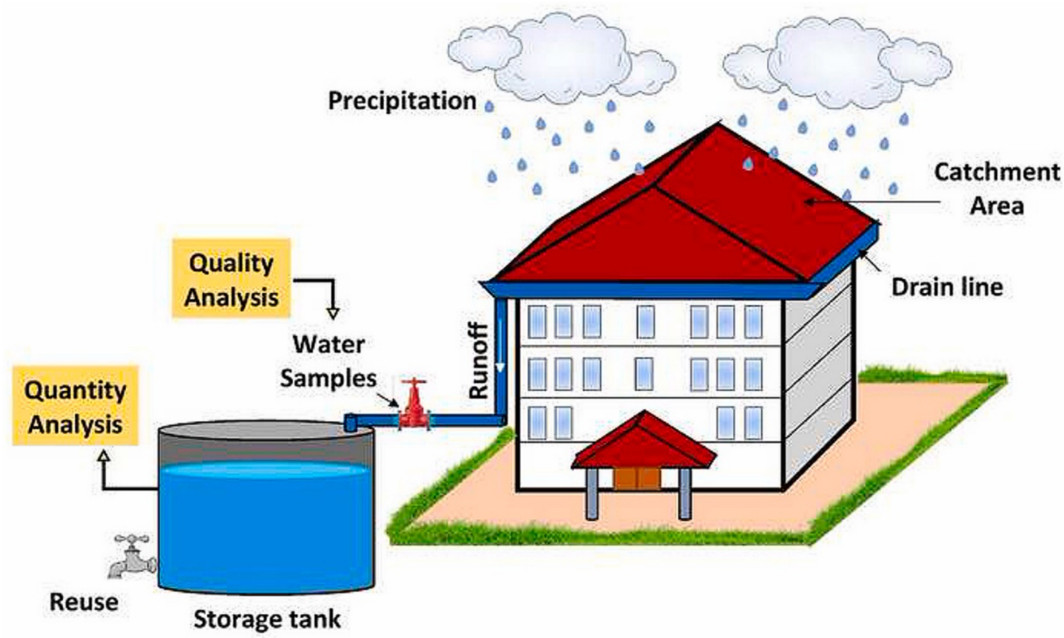

Figure 2-2 A typical rooftop rainwater harvesting system (Anchan & Prasad, 2021)

RWH has two systems (micro and macro systems) that depend on the size of the catchments and the distance for runoff transfer. Macro systems have been more applicable among communities as compared to micro catchment systems (Mzirai, 2010).

The ranges of the area in macro-catchment systems type start from 0.1 hectares to several thousand hectares. The utilisation area may be located far or near the macro catchments (Ketsela, 2009).

RWH (such as cisterns, or the soil in the target area itself), which are used outside the target area to collect the runoff water from a large catchment see Figure 2-3. To convert the water storage in the usage region, this system requires a storage structure and transfer infrastructure such as a natural stream, channels, and gullies (Zakaria et al., 2012). According to Oweis et al. (2001) "water harvesting from long slopes" or "harvesting from an external catchment" are two terms used to describe macro-catchment systems. In a macro-catchment system, there are two broad categories of constraints: management of harvested runoff at the farm level scale and hydro-climatic factors (Mzirai, 2010).

According to De Pauw (2008), it is more complicated to model the suitability of the macro catchment because of the large area of unknown quantity, and the runoff is generated outside the pixel to be evaluated. It is important to evaluate the catchment area and for use area separately, the criteria are different for catchment and use area (De Pauw, 2008):

1- For the use area, it is preferred to have level or gradually sloping land with deep soils and no additional restrictions on agricultural use.
2- Land suitable for use should have a suitable distance for agricultural

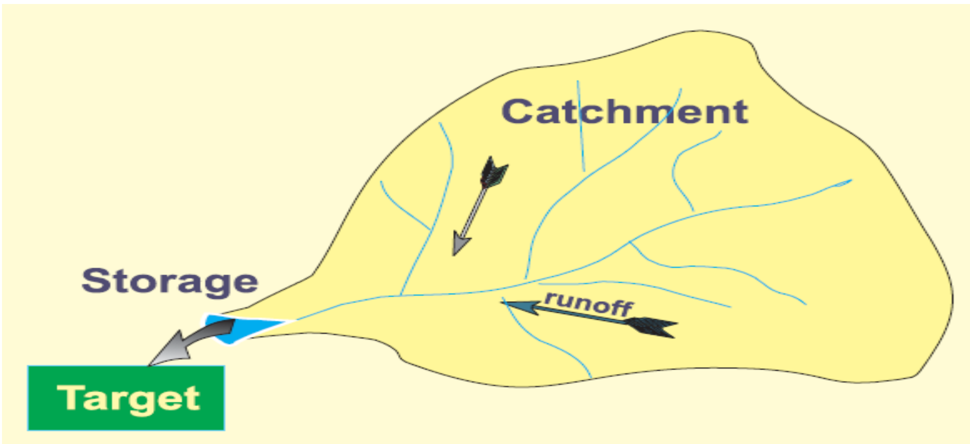

Figure 2-3 A Typical macro-catchment water-harvesting system (Oweis et al., 2001).

2.1.3 Micro-catchment

Micro-catchment rainwater harvesting is a technique used to store water in the root zone of an adjacent infiltration area by collecting surface runoff from a small catchment area (Cofie et al., 2004). The system is mainly used for cultivating crops that require a moderate amount of water, such as groundnuts, millet, and maize, see Figure 2-4 (Cofie et al., 2004).

Runoff is stored in the root zone and used directly by crops. Alternatively, it can be stored in a reservoir for later use. The catchment area may be planted with annual crops. The range of sizes for the catchment area starts from a few square meters to approximately 1000 m^2 (Oweis, 2004).

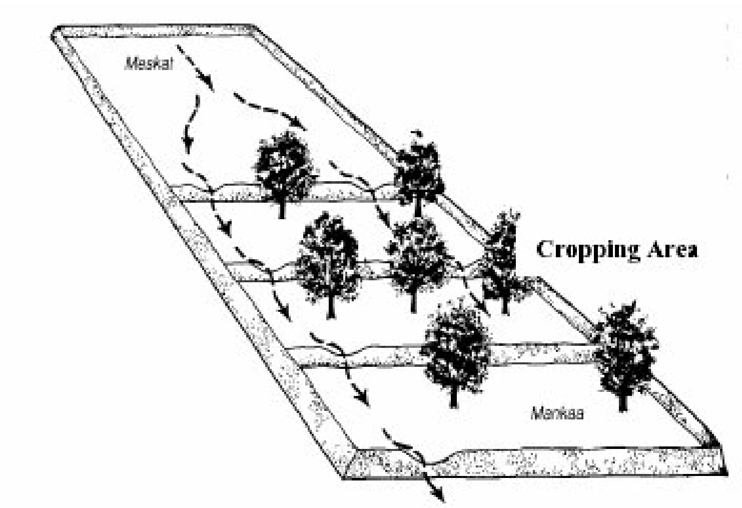

Figure 2-4 Micro catchment System (Abdo & Eldaw, 2004)

Micro-catchment rainwater harvesting (RWH) systems typically involve two main components: a catchment area that collects rainwater from ground surfaces or roofs, and a cultivated area that uses the runoff for watering cropsb (Moges, 2004). Micro-catchment systems offer several advantages over other irrigation methods. They are relatively easy to construct, cost-effective, and can be rapidly built using locally available materials and labor. One of the key benefits is that the runoff water does not need to be transported or pumped, and it typically has low salt content, which helps to keep costs down. Furthermore, these systems often improve leaching and can reduce soil salinity (Bainbridge, 2002). Various types of micro-catchment systems include earth basins, semi-circular bunds, earthen bunds, strip catchment tillage, Meskat-type systems, Negarim micro-catchments (water harvesting in Sudan), contour ridges, and stone lines (Critchely & Siegert, 1991).

The source and target areas in a micro-catchment should be close to each other because they cannot be separated on a scale beyond the field level. In a GIS context, this translates to the source and target areas being in the same pixel of relatively small size (e.g. 100-250 m).In this system, the place of storage is a root zone for immediate or a small reservoir for later use (De Pauw, 2008).

The environmental criteria for appropriateness are based on guidelines for selecting water-harvesting systems in drier settings (Oweis et al., 2001). These guidelines include soil depth, texture, slope, land use/land cover, and geological substratum, with minor adjustments. The suitability of the catchment for this system depends on different factors such as slope, precipitation, soils, and geological material (De Pauw, 2008). See Figure 2-5 illustrates the Classification of water-harvesting systems.

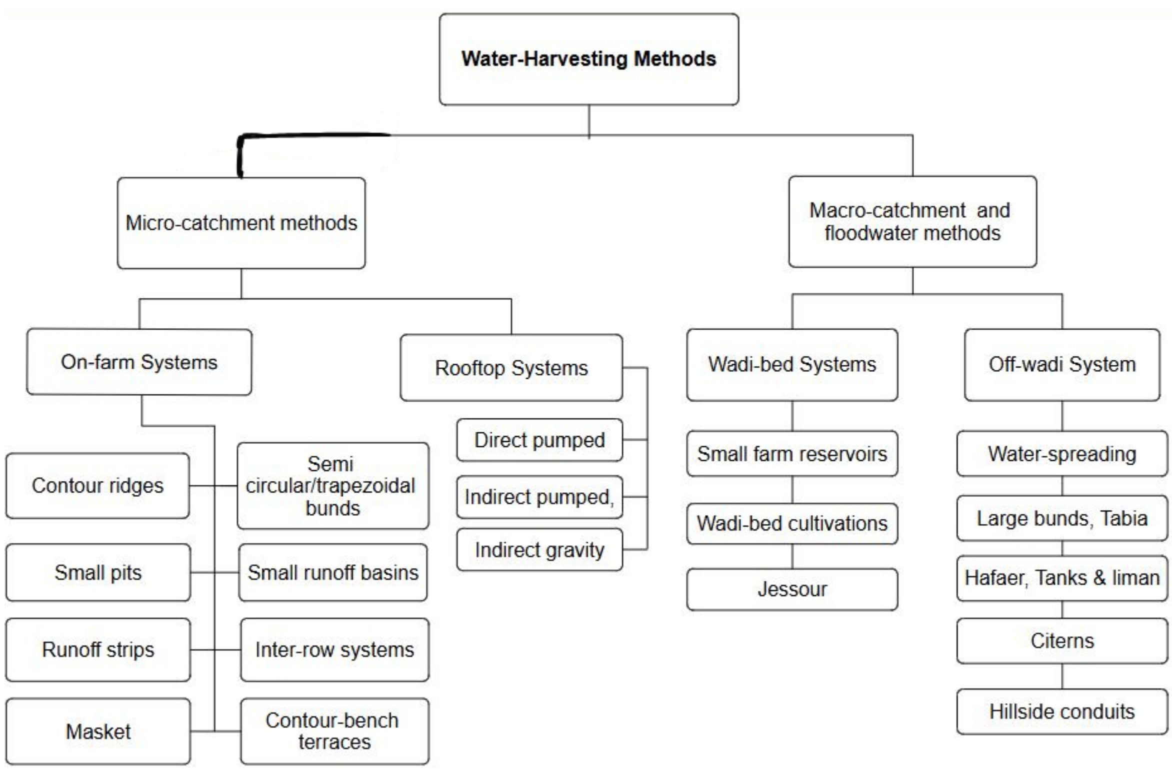

Figure 2-5Classification of water-harvesting systems (Oweis et al., 2001)

2.2 RAINWATER HARVESTING COMPONENTS.

The water harvesting system has three components (Ziadat et al., 2012):

i. Catchment area: it is also called the runoff area, this area has been used to collect water, which has different sizes starting from a few m^2 to several km^2. It also represents several types of rooftops, cultivation, paved roads, bare, etc.

ii. Storage Facility: This facility is used to store surface runoff water for use by people, crops, and animals. There are three types of storage methods: above ground (e.g., large tanks to catch and store rainwater), in the soil profile, and underground (e.g., reservoirs or ponds, cisterns for agricultural use).

iii. Target: symbolises the water harvesting system's final destination, as well as the users of the captured water, such as plants, animals, and people.

Chapter 3: Selection Frameworks for Potential Rainwater Harvesting Sites in Arid and Semi-Arid Regions: A Systematic Literature Review

The aim of this chapter is to identify and understand existing frameworks and criteria, determine the weights for these criteria through analysis, and identify gaps in current knowledge.

This Chapter conducts a systematic literature review to identify rainwater harvesting (RWH) sites in arid and semi-arid regions. After a thorough screening process, 68 papers were found to meet the search criteria and were considered relevant for the study. The study highlights that current frameworks for assessing sustainability primarily rely on biophysical and socioeconomic criteria. The existing frameworks consist of structural criteria (biophysical and socioeconomic), which were identified. Then, the weights of these criteria were analysed to determine the final weight for each criterion. However, these criteria alone are inadequate to fully address the pillars of sustainability. The frameworks fail to account for important ecological aspects, such as the impact of the location of rainwater harvesting (RWH) structures on water quality and living organisms.

This chapter has been published as "Selection Frameworks for Potential Rainwater Harvesting Sites in Arid and Semi-Arid Regions: A Systematic Literature Review.". The first author conducted the systematic literature review which was the basis for the paper, wrote the initial draft and updated this based on review and feedback from the other authors.

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3.1 ABSTRACT

Water shortage is a concern in arid and semi-arid regions across the globe due to their lack of precipitation and unpredictable rainfall patterns. In the past few decades, many frameworks, each with their own criteria, have been used to identify and rank sites for rainwater harvesting (RWH), a process which is critical for the improvement and maintenance of water resources, particularly in arid and semi-arid regions. This study reviews the present state of the art in rainwater harvesting site selection for such regions and identifies areas for additional research. The results of a systematic review performed based on two major databases of engineering research, Scopus and Engineering Village, are presented. Sixty-eight relevant studies were found and critically analysed to identify patterns and unique features in the frameworks used. The results of this study show that 41% of the frameworks consider both biophysical and socioeconomic criteria, whereas the remaining 59% of the frameworks depend on biophysical criteria alone. The importance of each criterion is encapsulated through a suitability score, with 21% of the frameworks using a binary (0 or 1) indicator of whether the site matches a criterion or not and the other frameworks using graded scales of differing granularities, with 52% using a low-resolution scale of 1 to 3, 4, or 5, 7% using a medium-resolution scale of 1 to 10, and a further 7% using a high-resolution scale of 1 to 100. The remaining 13% of the frameworks did not specify the scale used. Importantly, this paper concludes that all existing frameworks for selecting RWH sites are solely based on biophysical and/or socioeconomic criteria; ecological impacts, the consideration of which is vital for building RWH systems sustainably, are currently ignored.

3.2 INTRODUCTION

Adequate water supply is the most important requirement for human life. The water demand has increased due to the increase in the Earth's population, from 2.5 billion to 7.35 billion between 1950 and 2015. However, more than 40% of the earth's surface is covered by arid and semi-arid regions, defined as those that receive an average annual rainfall of only about 150–350 mm and 350–700 mm, respectively

(Ammar, 2017). Historically, arid and semi-arid regions have contained many settlements, such as those in the Middle East, Northern Africa, and Western Asia, and rainfall and other water sources in these areas must be used efficiently.

For as long as people have engaged in agriculture, they have used water harvesting to collect rainwater, floodwater, and groundwater. People rely on water harvesting to meet their water needs where sufficient supplies for drinking water and irrigation are not easily reached (Rutherford, 2000). Water harvesting can be classified into one of four types: fog and dew harvesting, rainwater harvesting, groundwater harvesting, and floodwater harvesting (Beckers et al., 2013). Rainwater harvesting (RWH) is the collection or diversion of rainfall-runoff for productive purposes, and its use is widespread in arid and semi-arid areas (Prinz, 1996).

The very first RWH structures were constructed in southern Jordan over 9000 years ago to provide drinking water for humans and animals (Boers & Ben-Asher, 1982). Over 6500 years ago, Iraqis started to use RWH structures in a simple form to provide water for domestic and agricultural use (Oweis, 2012). Water harvesting systems were also used in China and India some 4,000 years ago (Prinz, 1996). In the southern part of Tunisia, meskat (runoff basin that has a rectangular shape), check dams, jessour and tabias (small water bodies used to recharge aquifers) have been used, with collinaires (agricultural reservoirs) used in Algeria, and ancient hafir (artificial water catchment basin) to help meet domestic and livestock water needs in Sudan. In Niger and Burkina Faso, people have long used rock and earth bunds and stone terraces (elevated platforms on sloping ground) to harvest water. Zay (small pits) combined with bunds (ponds with a semicircular form that are used to collect rainwater) are often used in the west of Africa. These methods were critical to the successful creation of settlements in the desert (Oweis, 2012). In addition, the ancient Greeks demonstrated remarkable ingenuity in the advancement of hydraulic infrastructure and small-scale constructions. Notably, certain examples, such as cisterns, have maintained their full functionality even up until the 20th century (Iliopoulou et al., 2022) and are being used to address the water crises currently occurring in regions of central and eastern Greece. Losses such as evaporation from these cisterns are negligible due to their underground construction (Iliopoulou et al., 2022; Sazakli et al., 2007).

RWH includes all water harvesting from roofs or ground surfaces by different techniques, and utilized for different purposes, whether agricultural, domestic, or drinking. RWH includes two main forms: rooftop harvesting and catchment harvesting (Critchley et al., 1991). Figure 3-1 shows the typical types of rainwater harvesting. This study was conducted for catchment rainwater harvesting systems.

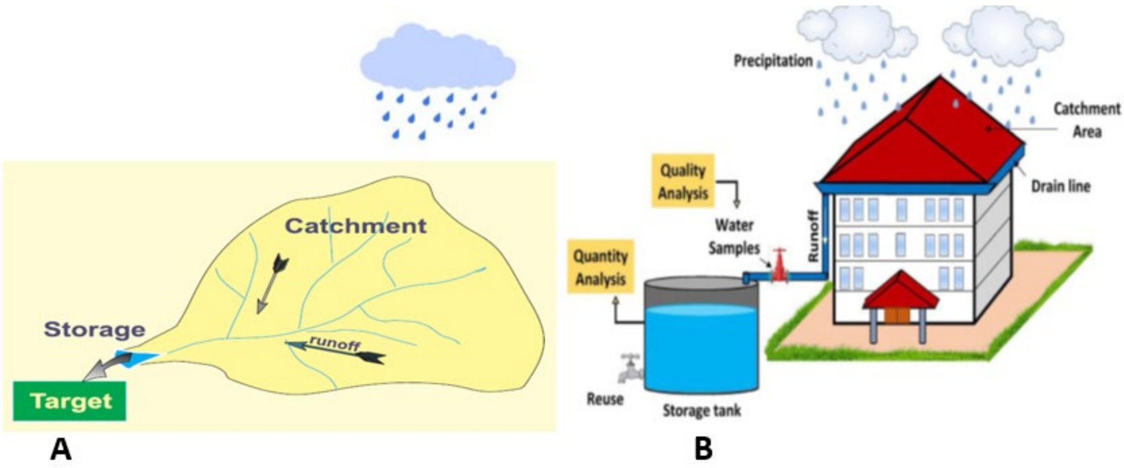

Figure 3-1 A) Typical catchment rainwater-harvesting system (Oweis et al., 2001) B) A typical rooftop rainwater harvesting system (Anchan & Prasad, 2021)

3.3 INDICATOR-BASED FRAMEWORKS AND THEIR CRITERIA

Water resources development projects require the integration of a system that includes multidisciplinary knowledge in social sciences, economics, and agronomy (Pereira et al., 2002). Many projects related to water management around the world, costing billions of dollars, have failed due to only considering the biophysical aspects without looking at the other aspects such as social and ecological impacts (Lund, 2015). The ecological condition of a water body can be evaluated through testing of water samples for important metrics such as total dissolved solids (TDS), dissolved oxygen (DO), nitrogen (N), chlorophyll, bacterial growth, turbidity, total suspended solids, ammonia, PH, total phosphorus (TP), and salinity. It is recognised that other factors, such as the air temperature and amount of sunlight the water body receives, affect these metrics (Qu et al., 2022) and, in our opinion, should be included in assessments of site suitability. Water bodies represent a complex system in terms of the environment because they are transitional between rivers and lakes (Blabolil et al., 2016).

Indicator-based decision-making frameworks play a crucial role in ensuring that diverse factors are considered at every stage of a project. These frameworks help evaluate complex, multi-dimensional aspects that are difficult to assess directly. By using indicators, stakeholders can better understand and clarify these aspects, leading to more informed decision-making (Alsaeed et al., 2022). Through collaboration between experts and stakeholders, an acceptable framework can be developed to simplify complex issues—such as evaluating multiple criteria with different measures—into a single number that is easier for non-experts to understand (Alsaeed et al., 2022) and simplifies the comparison of potential sites for experts, facilitating an objective evaluation. Any indicator framework consists of three main parts: headline categories (also referred to as components), supporting indicators, and lower-level sub-indicators (second-order and third-order) (Juwana et al., 2012). The components serve as broad categories of indicators, each addressing specific themes or concerns based on user needs. Supporting indicators and sub-indicators further break down these components into detailed measures, ensuring a comprehensive evaluation of the framework's objectives (Shafiei et al., 2022) (Figure 3-2).

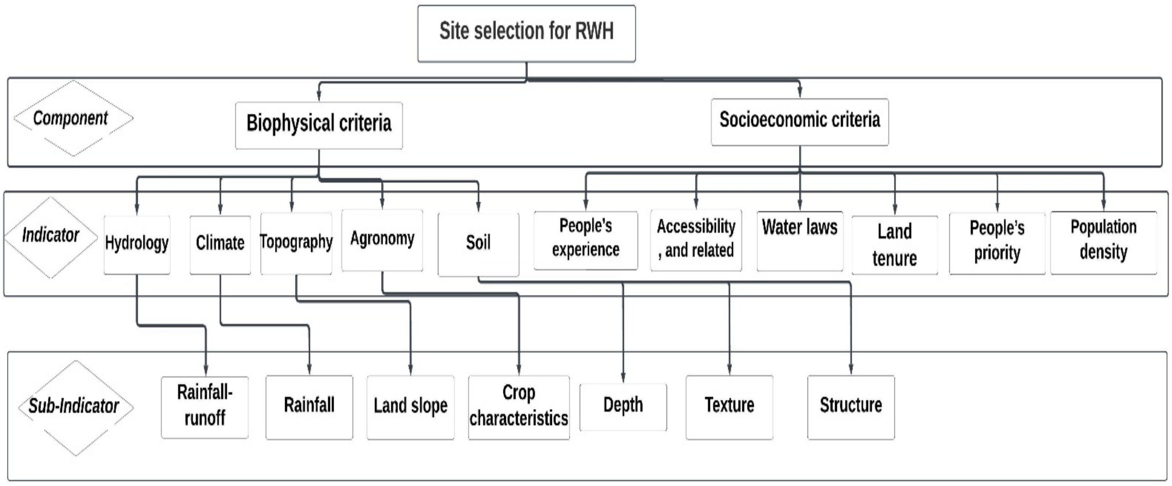

Figure 3-2 Indicators framework hierarchy for RWH site selection.

3.3.1 Indicators

Indicators are the framework's primary element, and they are often chosen based on literature review and expert opinions; their selection should be conditional on the following points (Bradley Guy & Kibert, 1998; Schwemlein et al., 2016):

1. Availability: The data should be easy to access and straightforward to collect or measure.
2. Measurability: The criterion should be simple to measure and analyze using quantitative methods.
3. Repeatability: If the indicator is assessed using the same method, in the same region, and under the same conditions, it should consistently give the same result.
4. Validity: There should be a clear and direct connection between the criterion and the issue it is meant to represent.

may be quantitative or qualitative. Quantitative indicators are directly measurable with a numeric value but potentially different units, such as distance to the nearest road (units of meters, m), runoff ($m^3 s^{-1}$) and slope (dimensionless). Qualitative indicators, for example, subjective opinions, do not have a direct numerical value though they may be quantified using standardization.

3.3.2 Standardization of Indicators

According to Juwana et al. (2012). , in order to reconcile the different measures for indicators, the quantitative values should be converted to a normalized, dimensionless number, which can simplify comparison and aggregation and also aid understanding by non-experts. This process is done using one of two standardization methods (Sayl, 2017), one for quantitative indicators and the other for qualitative indicators:

Empirical standardization normalizes quantitative indicators by the range of values, relative to the minimum value as illustrate in equations (3-1) and (3-2) (Sayl, 2017):

$$X_i = \frac{R_i - R_{min}}{R_{max} - R_{min}} \quad (3\text{-}1)$$

where X_i is the standardised score ($0 \leq X_i \leq 1$), R_i is the raw score for the indicator and R_{min}, R_{max} are the minimum and maximum scores for the indicator, respectively. Equivalently, this standardisation may be scaled to the range $0 \leq X_i \leq 100$:

$$X_i = \frac{R_i - R_{min}}{R_{max} - R_{min}} \times 100 \qquad (3\text{-}2)$$

The second method, used for producing equivalent scores from qualitative indicators, is categorical scaling. Based on pre-established criteria, the values of indicators are categorized and allocated. These classifications might be numerical, such as ranging+ from 1 to 5, or they can be descriptors and points of view, such as "equal importance," "moderate importance," or "strong importance.", so each description in questionnaires has a number that represents the importance of this criterion. For example, if the scale for suitability is from 1 to 3, then 1 will represent "equal importance," 2 will represent "moderate importance," and 3 will represent strong importance (Alsaeed et al., 2022). Also, Classification can take the form of Likert scale statements, whereby participants are prompted to express their degree of concurrence or discordance with a set of predetermined statements, typically spanning from "Strongly Agree" to "Strongly Disagree." The inclusion of a neutral midpoint option, such as "Neither Agree nor Disagree," may be considered in the construction of the scale. The responses are quantified using numerical values, typically within the range of 1 to 5 or 1 to 7, in order to measure the extent of concurrence or discordance (Joshi et al., 2015).

3.3.3 Weighting Scheme

Weights are employed to aggregate the indicators within a framework into a resultant output index. This gives users of the framework the ability to vary the weights on the various indicators for a particular application. In order to arrive at the final index number, the weighting scheme involves multiplying each component of the indicator-based framework by a value that represents the component's significance, or weight, during each stage of the calculation.

In general, statistical methods and participatory methods are employed to assign weights to various criteria. In the statistical method, weights are assigned based on the analysis of criteria data from the literature, whereas in the participatory method, weights are assigned using questionnaires and workshops meant to gather expert and stakeholder perspectives on weighting (Juwana et al., 2012).

3.4 THE PROCESS OF CONDUCTING A SYSTEMATIC REVIEW

A systematic literature review is employed to answer specific questions by identifying, appraising, and synthesizing relevant literature that fits pre-specified criteria(Piper, 2013). Briefly, such a review includes a comprehensive search that concentrates on providing a summary of the existing literature on a subject and specific goals that have been established. In terms of the strategy for selecting papers, it should be transparent, with explicit inclusion and exclusion criteria for papers established prior to initiating the review. Moreover, the process of assessment of articles should be comprehensive and the selection of the information that is related to the study should be clear and specific, and the summaries of articles should be clear and based on high-quality research.

The aim of the systematic review in this study is to review the current state-of-the-art rainwater harvesting site selection, focusing on applications in arid and semi-arid regions, and identify areas in which further research is necessary. A comprehensive, systematic literature review has been employed for this purpose; the first step of such a review is defining the research questions that the review is designed to answer, in this case:

1. What RWH site selection criteria have been used in existing frameworks?
2. What are the differences and similarities in the way these frameworks combine the criteria they use, i.e. their scaling and weighting methods?
3. What gaps exist in the criteria currently applied, and what future work is necessary to improve frameworks, particularly bearing in mind the need for sustainability?

Two databases of scientific publications were interrogated, Scopus and Engineering Village. These databases have a good search engine for complex queries and cover most of the main engineering journals. To ensure reliable, high-quality sources, the scope was restricted to peer-reviewed books, articles, and conference papers. Only English language papers were included, though with English being the language of most (if not all) of the major engineering journals this is likely to include all important works. Details of the precise query, keywords and filters used for each database are given in the following subsection.

Once papers were identified using the systematic literature review keywords and filters, the search was expanded to include papers which cited those papers, and which were cited by those papers. Again, these papers were filtered by relevance to the review questions.

3.4.1 Search Queries and Keyword Selection

The search queries were designed to search the "title-abstract-keyword" fields in Scopus and (equivalently) the "subject/title/abstract-keyword" fields in Engineering Village. Three groups of keywords were used for the search queries: "scope" keywords, "target" keywords, and "methods" keywords, with keywords in each group. The groups each represent a range of possible acceptable options; therefore, the OR operator was utilized to search for one or more of the group's keywords. The search was narrowed by using AND operators between groups to ensure that at least one keyword from each group appeared in the paper.

The keywords used for the scope group were those that were primarily related to water harvesting; these keywords were used to define the broad frame from which the search should begin. Specifically, these keywords and their variations were *"water harvesting", "rainwater harvesting", "rainwater collection", "RWH", "water storage systems" and "store precipitation".*

The terms for the target group were *"arid"*, *"semi-arid", "water scarcity"*, *"water shortage", "dry areas"*, *"Iran"*, *"Jordan", "Iraq"*, *"Morocco"*, *"Saudi Arabia", "Yemen"*, *"Lebanon", "China", "India", "Tanzania"*, *"Tunisia"*, *"Pakistan"*, *"Ethiopia"*, *"Malawi"*, *"Mongolia"*, *"Egypt"*, *"Kenya"***.** These keywords were selected to ensure all relevant regions were captured by the search query, using aridity-related phrases and relevant country names, i.e., all countries in the Middle East, all countries in northeast Africa, and China, because most of these countries are affected by seasonal rainfall and a lack of water for people, agriculture, and animals.

The final set of keywords was related to the specific purpose of the study, and were *"suitable location", "site selection", "suitable sites", "site suitability"*, *"possible sites", "RWH sites"*, *"potential sites", "criteria"*, *"suitable area".*

Figure 3-3 shows the keyword groups and their relationships. The full query strings used for each database are given in Appendix A TableA-1.

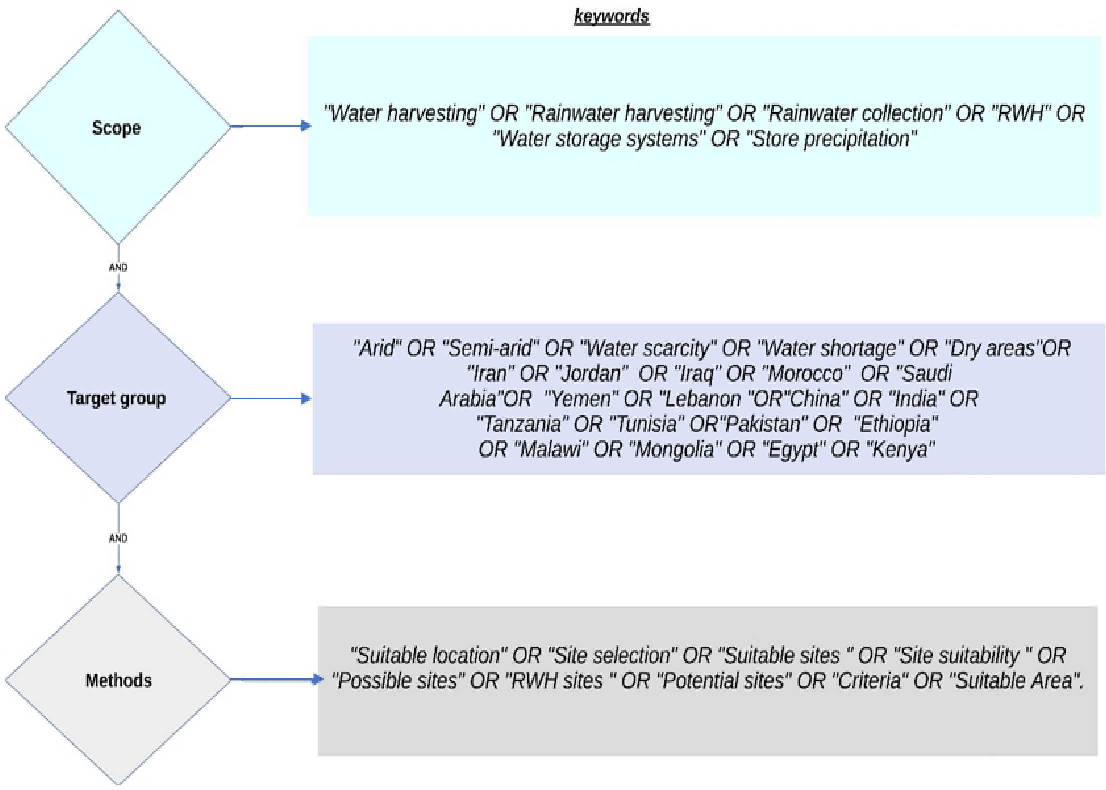

Figure 3-3 keyword group for this search

3.4.2 Database Search

The Scopus and Engineering Village databases were searched on October 29, 2022, using the queries detailed in Section 3.4.1. Specific search was conducted in this study for frameworks relevant to arid and semi-arid regions, available in two literature databases, covering the period from 2000 to 2022. These searches resulted in 244 and 312 articles, respectively. The results were collated using an EndNote library, and duplicates were automatically removed. Two hundred and sixty-two unique articles were returned by this process. To ensure relevance, the results were manually filtered based on the title and abstract, based on the scope of the study and the aim of the review. This stage was conducted based on the inclusion criteria for the articles that related to site selection for rainwater harvesting; 186 articles were excluded based on these criteria.

Seventy-six articles were retained after this process, following which the remaining articles' full text was examined in detail. This final round was added to ensure that each of the 76 papers contained essential elements related to this study, such as arid and semi-arid, and was included in the full-text analysis. And excluded articles were 8 articles. This process is summarised in Figure 3-4. Following the completion of all of the preceding processes, 68 articles were selected for in-depth review. From this review, the design and implementation of existing frameworks were identified and analysed, along with the criteria which they use.

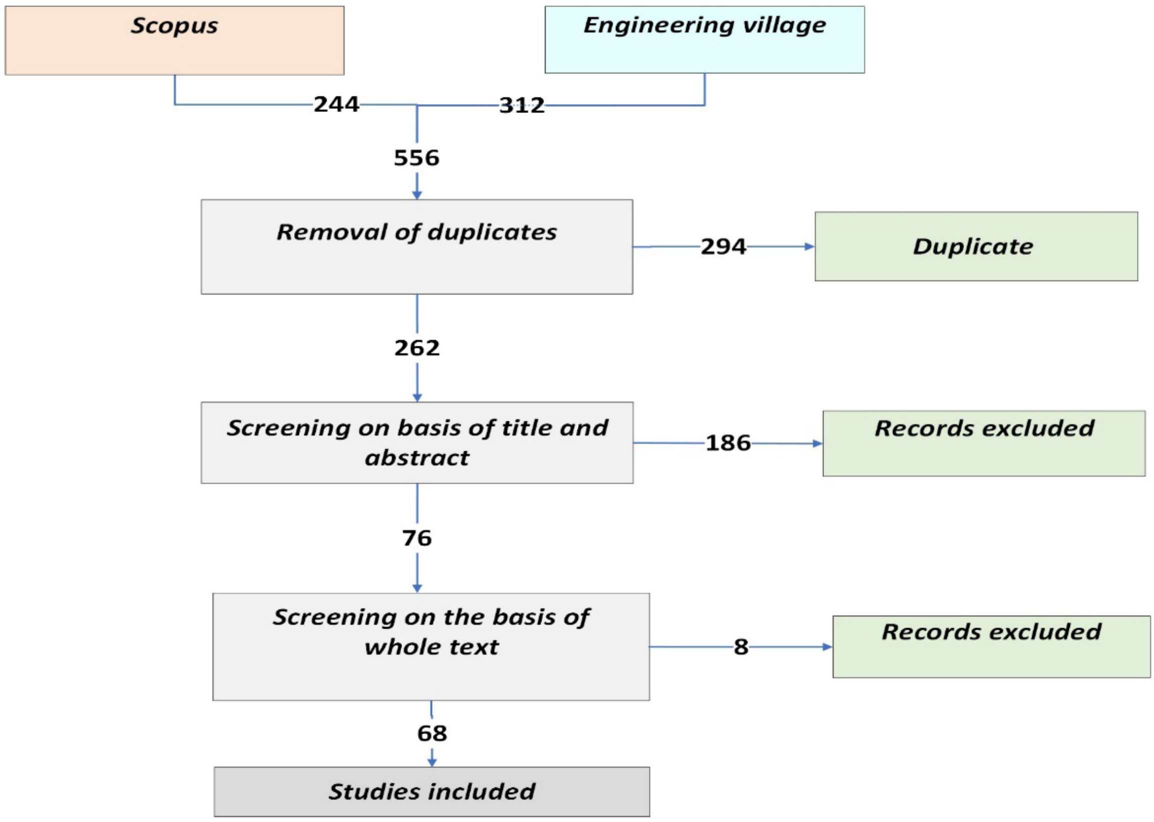

Figure 3-4 Article filtering procedure.

3.4.3 **Overview of Retained Publications**

All but three publications ((Khudhair et al., 2020a; K. N. Sayl et al., 2020; Zheng et al., 2018b)) provided author-specified keywords. "Harvesting", "rainwater", "water", "GIS" and "system" were the most frequently used keyword strings in the chosen articles, as seen in Figure 3-5. This Figure is conducted by NVivo version 14, created by QSR International Software Company Pty Ltd., which is widely used for literature reviews and qualitative data analysis. It helps gather relevant literature from various sources like dissertations, recent journal articles, books, reliable web pages, organisational reports, and conference proceedings (Nanekely, 2020).

Figure 3-5 Word cloud of the author-supplied keywords (NVivo).

The country with the most publications related to RWH site selection was Iraq (12), followed by Iran (8), Egypt (7), Jordon (6) and Saudi Arabia (5) see Figure 3-6.

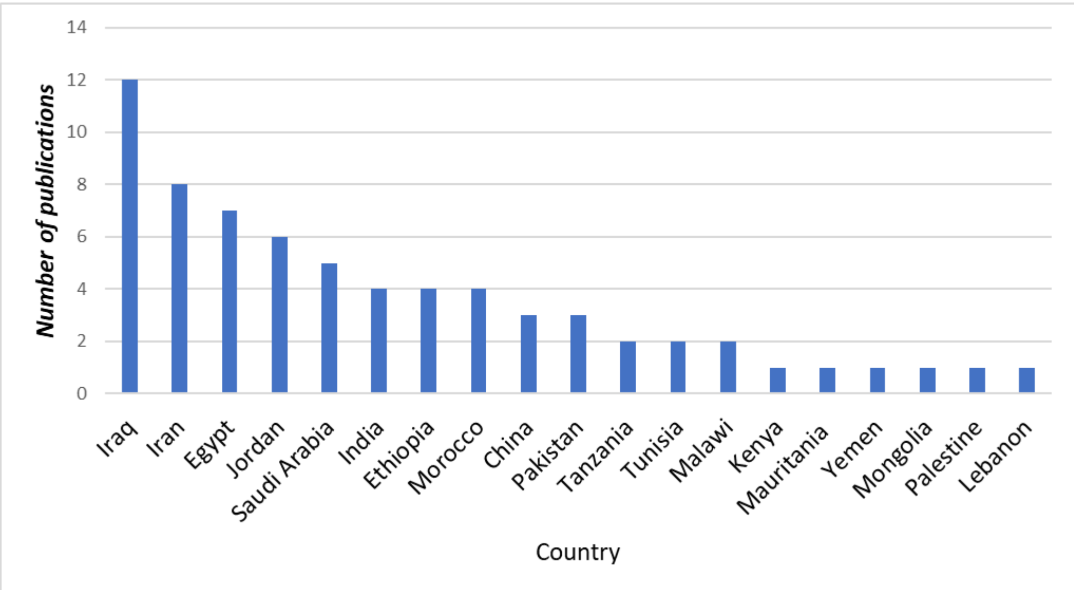

Figure 3-6 Distribution of number of publications by country

Figure 3-7 shows the distribution of articles by year of publication. Although the search included publications going back to 2000, all but 9 of the papers are from within the last 8 years and 36 were published in the last 3-4 years, ensuring that the results of this review are up-to-date. The growth in interest in this area of research over the last 3 years or so is also evident.

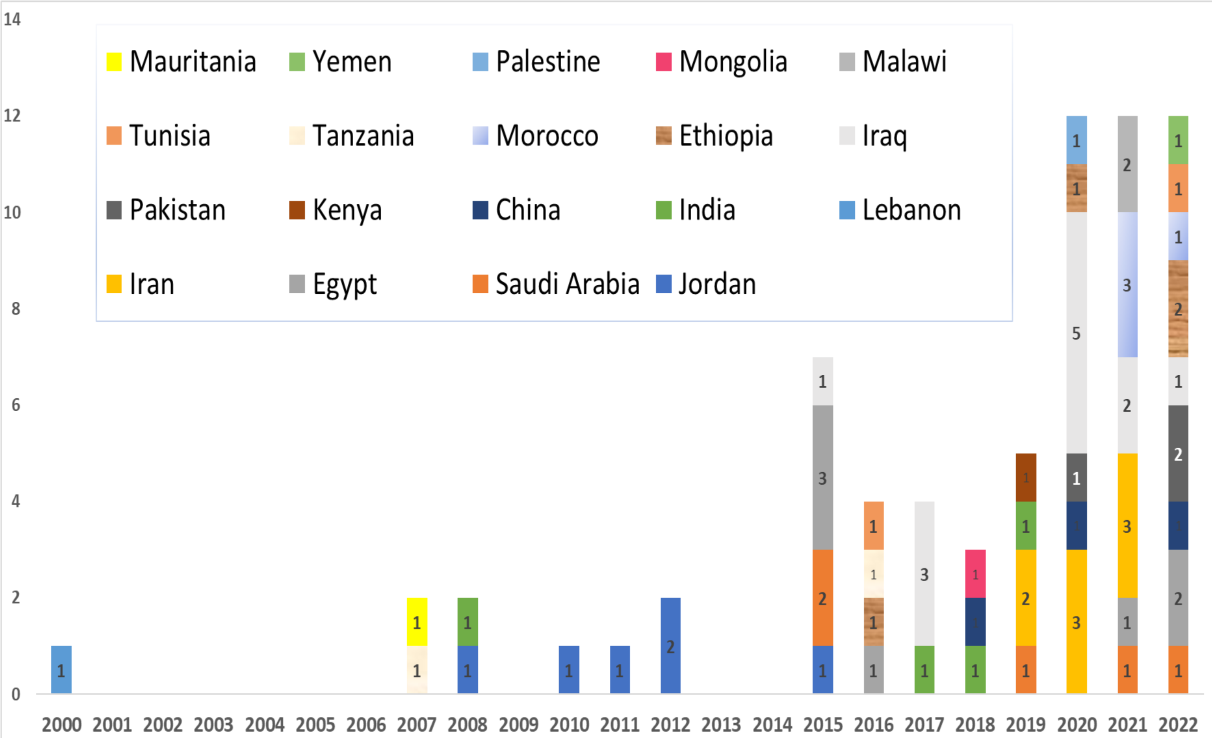

Figure 3-7 Distribution of the relevant publications by country and year.

3.4.4 Current frameworks and their criteria

As shown in Figure 3-4 and explained in Section3.4.2, the final number of papers matching the systematic review criteria from the two databases was reduced to 68 frameworks in the final phases which were considered for a comprehensive assessment. Each of these frameworks was designed for a distinct application at a different scale and within a unique set of local circumstances and situations. Naturally, each of these frameworks serves a unique purpose, employs a unique method of evaluation, and uses a different assessment procedure. The analysis of these frameworks was based on (country, year, keywords), the classification of the criteria (biophysical and socioeconomic criteria), tools, annual rainfall, catchment area, range of the index, and methods of weighting as shown in Appendix **A**. The systematic literature review found that the RWH site selection frameworks use a variety of different criteria, weighting methods, and other tools.

The next section provides a detailed look at the frameworks discussed in these publications, with a focus on the criteria used and how these criteria can be combined to make a quantitative measure of site suitability.

3.4.5 Criteria Currently Used for RWH Site Selection

Two categories of criteria have been identified for use in RWH site selection, namely, biophysical and socio-economic. The biophysical criteria were proposed by the Integrated Mission for Sustainable Development in 1995 and include Drainage system, soil texture, slope, and land use/ land cover. In addition Oweis et al. (1998) introduced a second category of criteria, the socioeconomic criteria, represent by factors like land tenure. Subsequently, the Food and Agriculture Organisation (FAO) (FAO, 2003) revised these categories to include climate (rainfall), agronomy (crop characteristics), hydrology (rainfall-runoff relationship and intermittent watercourses), topography (land slope), soil (structure, depth and texture), and socio-economic conditions (people's experience, workforce, people's priority, population density, water laws, land tenure, accessibility, and related costs).

Of the 68 publications analysed for this review, 59% use biophysical criteria alone while the remainder used both biophysical and socioeconomic criteria. Details of each useful and their frameworks are given in the Appendix A.

Upon analysing the criteria used, it became apparent that various synonymous terms were used to denote equivalent criteria. In such instances, these criteria have been consolidated to achieve the merged criteria, as shown in Table 3-1. These criteria are categorised into two groups, namely biophysical and socioeconomic criteria.

Table 3-1. Groups of existing criteria.

Biophysical Criteria		Socioeconomic Criteria	
Criteria	Synonyms	*Criteria*	Synonyms
1- Rainfall (mm)	▪ Precipitation	1- Distance to roads (m)	
2- Runoff (mm)	▪ Flow ▪ Surface runoff ▪ Flow distance ▪ Discharge ▪ Runoff depth		
3- Hydrological losses (mm)	▪ Evaporation ▪ Infiltration		
4- Slope (%)	▪ Elevation ▪ Digital elevation	2- Distance to agricultural area (m)	
5- Soil	▪ Soil texture ▪ Type of soil ▪ Soil quality ▪ Soil depth ▪ Curve number ▪ Soil permeability	3- People's priority	▪ Stakeholders' priority
6- Land use/land cover	▪ Vegetation		
7- Drainage density ($\frac{km}{km^2}$)	▪ Drainage texture ▪ Stream order	4- Population density	▪ Population and rural density
8- Catchment area (km^2)	▪ Watershed area ▪ Watershed length ▪ Basin area	5- Distance to urban area (m)	▪ Distance to the village ▪ Distance to settlements ▪ Distance to built-up areas
9- Distance to wadis (m)			
10- Distance to faults (m)	▪ Lineament density		
11- Distance to water source (m)	▪ Distance to lake ▪ Distance to ▪ streams ▪ Distance to river ▪ Distance to wells		

3.4.6 Biophysical criteria

1- Rainfall (mm)

The volume and distribution of rainfall can vary significantly depending on geographic location, climate, and season, with higher rainfall clearly increasing the likelihood of harvesting useful amounts (Al-Adamat, 2008). Rainfall measurements are based on meteorological stations, which generally measure a variety of factors such as precipitation, wind velocity, temperature, and humidity. In arid and semi-arid regions of developing countries, many areas do not have enough meteorological stations to give detailed local data and so interpolation from the nearest meteorological stations is used. This method does not require high costs, human resources, or time and can therefore be applied relatively easily in developing countries such as Iraq, Yemen, Palestine, and Kenya, where limited resources and high costs have been shown to make spatial interpolation an appropriate choice to tackle this issue (Team, 2023).

Out of the 68 frameworks examined, four explicitly mention the use of the inverse distance weight (IDW) interpolation method, employing data stored in a geographic information system (GIS).

The catchment suitability clearly depends on the average annual rainfall and is scored based on local requirements. For instance, in Tunisia (*wadi Oum Zessar)* the catchments suitability is based on 5 ranges of average annual rainfall (R) (mm/year) (R100, R (100–175), R (175–250), R (250–325), and R>325), with suitability rated as very low, low, medium, high, and very high, respectively (Al-Adamat et al., 2010; Ammar, 2017). This classification is based on the literature and discussion with experts and stakeholders.

2- Runoff

The effectiveness of rainwater harvesting is extremely reliant on the volume of water that can be collected under a specific climate. Runoff is characterised as water flowing over the ground surface towards the nearest channel such as a stream, river, etc., which occurs when the soil is saturated or when the catchment has a steep slope. Soil saturation happens through losses of infiltration which is determined by soil texture. The runoff volume is commonly calculated using the Soil Conservation Service Curve Number (SCS-CN) method (Sayl, 2017). The curve number (CN) was established by the Department of Agriculture of the United States of America and is based on soil texture, land use /land cover (LULC) and hydrological surface conditions of the catchment. The range of the curve number is from 0 to 100 where the higher the curve number the higher the percentage runoff and lower the infiltration, and vica versa. Runoff is calculated in accordance with Equations (3-3) and (3-4) (Ibrahim et al., 2022; Sayl, 2017).

$$Q = \frac{(P - O.2S)^2}{(P + 0.8S)} \quad (3\text{-}3)$$

$$S = \frac{25400}{CN} - 254 \quad (3\text{-}4)$$

where Q is the runoff depth in millimetres, S is the maximum possible retention after runoff starts in millimetres, P is the amount of rain in millimetres, and CN is the number of the runoff curve (Sayl, 2017).

3- Hydrological losses

Hydrological losses, which represent the percentage of rainfall that does not contribute to runoff due to evaporation and infiltration, directly impact the quantity of water that will be harvested in RWH structures. Evaporation depends on temperature, humidity, and wind, where low humidity and high temperatures lead to a high rate of evaporation, Thus, it varies with season, with annual evaporation calculated based on the average of the monthly evaporation rates (Thompson & Perry, 1997). Evaporation is measured based on meteorological stations (Sayl, 2017). The infiltration ratio depends on the soil texture, primarily based on the percentage of clay content, with high clay content reducing infiltration see Table 3-2.

Table 3-2 Average values of the final infiltration rate for different types of soil (Oweis et al., 2012).

Soil Type	Infiltration Rate (mm/ h)
Coarse sand	>22
Fine sand	>15
Fine sandy loam	12
Silt loam	10
Silty clay loam	9
Clay loam	7.5
Silty clay	5
Clayey soil	4

4- Slope (%)

The suitability of a site for RWH is influenced by its slope, which affects runoff and the hydrological losses. Generally, slope is defined as the ratio of the vertical change (y-axis) to the horizontal change (x-axis) between two points on the catchment. Out of the frameworks examined, five (Alkaradaghi et al., 2022; Karani et al., 2019; Makhamreh, 2011; Sayl et al., 2019b; Tiwari et al., 2018) out of 68 frameworks employ average catchment slope calculations based on digital elevation models (DEM). However, the remaining frameworks do not provide a detailed explanation of the methods used for slope calculation. This omission hinders follow-up research by reviewers and comprises the transparency of a study. Rainwater harvesting is not recommended for slopes over 5% due to irregular flow and expensive earthwork (Al-Adamat et al., 2010).

5- Site Soil

Soil is essential to the conservation of water within rainwater harvesting (RWH) structures, which benefits humans, animals, and agricultural activities. For example, sand-textured soils can't be used to build RWH structures for water harvesting because of high infiltration losses while a higher percentage of clay in the soil gives it a higher rank of suitability for RWH sites (Al-Adamat, 2008). The existing different frameworks used different expressions for soil criteria, which are soil texture, type of soil, soil quality, soil depth, curve number, and permeability. Soil texture determines the curve number (CN), as shown in Section 2-. The suitability of the catchment area for RWH sites in terms of soil depends on the type of soil, which is classified based on literature and experts' opinions. For example, according to (Adham et al., 2018), conducted in the Western Desert of Iraq, which has six types of soil: clay, silty clay, sandy clay, sandy clayey loam, sandy loam, and others, suitability of each type was rated and adjusted based on discussions with experts as very high, high, medium, low, and very low, respectively. The depth of the soil should permit excavation to the required level for the RWH structure. In addition, the depth of soil is a significant factor as well, which is measured based on a field test based on hammering a steel bar into the earth until it could go no further and measuring the soil levels between successive terraces (Ammar, 2017). According to the Food and Agriculture Organization of the United Nations (FAO), soil depth is classified into five categories based on suitability: Very Deep (>0.75 m, highly suitable), Deep (0.4–0.75 m, moderately suitable), Moderately Shallow (0.3–0.4 m, suitable), Shallow (0.2–0.3 m, less suitable), and Very Shallow (<0.2 m, least suitable) (Kahinda et al., 2008).

6- land use/land cover (LULC)

Land use/land cover (LULC) refers to the function or utilisation of the land and affects the amount of runoff which occurs. For example, there is a link between more vegetation and more interception and infiltration, which reduces the amount of runoff (Ammar, 2017). In rainwater harvesting site selection, LULC classification is carried out to assess LULC impact on runoff; according to Adham's (Ammar, 2017) classification, land use and land cover categories are farmland and grass, moderately cultivated land, bare soil, mountainous and water bodies, and urban areas. The suitabilities for each class were scored and adjusted based on discussions with experts, and were, respectively, very high, high, medium, low, and restricted. Bare soil refers to areas where people have overused the land, destroying the plant cover, which then allows the upper soil to be removed through natural processes (Sayl, 2017). Vegetation coverage rates are used to monitor changes in biomass or to identify land degradation processes. In semi-arid and arid regions, annual and seasonal changes in the quantity of vegetation cover are dramatic (Al-Adamat, 2008). The selection criteria must not include farmland or urban areas since these zones have distinct economic identities that preclude the construction of RWH buildings (Al-Adamat, 2008).

7- Drainage density

Drainage density is often defined as the total length of the channels (network used to transfer water to the outlet) divided by the total unit area (Carlston, 1963). The drainage density is inversely proportional to permeability; hence, a high drainage density indicates that a site will rank higher in suitability for RWH sites than one with a lower drainage density (Matomela et al., 2020; Newton et al., 2020). In addition, Stream order is dependent on the connection between tributaries. Stream order is used to indicate the hierarchical relationship between stream segments and permits the categorization of drainage basins by size. If the number of stream orders increases, permeability and infiltration decrease, and vice versa (Sayl, 2017). The drainage density is calculated in arid and semi-arid regions based on digital elevation model (DEM) (Sayl, 2017). The catchment area for the drainage density is inversely proportional to permeability; hence, a high drainage density indicates that a site will rank higher in suitability for RWH sites than one with a lower drainage density (Matomela et al., 2020; Newton et al., 2020).

8- Catchment area

The catchment area for rainwater harvesting (RWH) is the surface area from which rainwater is collected and directed into a storage tank or reservoir for later use. The runoff processes are notably influenced by the basin area. Consequently, it is a crucial factor in calculating the potential for rainwater harvesting. The augmentation of the basin area results in a proportional increase in the quantity of precipitation accumulated and the maximum discharge of water (Ezzeldin et al., 2022).

9- Distance to wadis

Wadis are the primary carriers of surface water in the region and provide the majority of surface water runoff throughout the winter months (Al-Adamat, 2008). RWH structures cannot be built as part of the Wadi, according to Al-Adamat (2008), for financial, technical, and environmental reasons. The distance to a wadi should be more than 50 m and less than 2000 m (Al-Adamat, 2008; Al-Adamat et al., 2010). This distance ensures that the RWH system can collect water from the wadi when it rains without being damaged by flash floods. It is also close enough to make it easy to collect water and move it to where it is needed (Al-Adamat, 2008).

10- Distance to faults

The distance to faults and lineaments is seen as a problem when choosing a site for RWH, since faults and lineaments are like cracks and joints that increase infiltration (Sayl, 2017; Sayl et al., 2019b). The distance to the water source is a critical factor to consider when implementing RWH systems in arid and semi-arid regions. It will impact the feasibility, effectiveness, and cost of the RWH system, as well as the size and location of the collection surface. The distance to faults measured based on digital elevation model (DEM). The distance to faults should be more than 1000 m for RWH structures (Sayl, 2017).

11- Distance to water source (m)

It is recommended that RWH zones be situated at a safe distance from natural water sources, such as rivers or lakes, to prevent obstruction of water flow and ecological disruption in the surrounding water source area (Matomela et al., 2020). The distance to the water source should be more than 1500 m (Matomela et al., 2020). Wells are very important to the local economy and society. Rainwater harvesting should be selected without including wells. The distance to the well source should be more than 500 m (Al-Adamat, 2008). These thresholds minimise the risk of water source contamination and promote sustainable resource use. These thresholds minimize the risk of contaminating water sources and promote sustainable resource usage. distance from water source is calculated based on remote sensing.

3.4.7 Socioeconomic criteria

1- Distance from roads (m)

The study region's proximity to roads presents a significant socioeconomic advantage for the local community. Through these routes, they may transfer their trucks and tankers from one location to another when hunting for pasture and water for their animals (Matomela et al., 2020). Distance from roads is calculated based on remote sensing, where satellites take high-resolution photos of the Earth. These photos help locate roads, and GIS tools provide accurate measurements of distances, allowing you to quantify the separation between roads and RWH systems. The distance to roads should be more than 250 m (Al-Adamat et al., 2012). This will avoid any potential future confrontation between the growth of the roadways and the built-up ponds (Al-Adamat et al., 2010).

2- Distance from agriculture (m)

The proximity of the RWH system sites to agricultural areas reduces the distance of pumping and diversion systems, making it the most cost-effective choice for stakeholders (Faisal & Abdaki, 2021). This criterion is measured based on remote sensing. The distance to the agricultural area should be more than 250m. This distance is used to reduce the risk of runoff contamination by agricultural activities such as pesticide and fertiliser use. This distance ensures that the collected rainfall is not compromised and is safe for human consumption and other household uses.

3- People's priorities

People's priorities are especially significant in arid and semi-arid areas, which may help explain why so many projects failed because they did not take their priorities into consideration. The project's success can be enhanced by incorporating the community's expertise and knowledge, which align with their priorities and specific needs (Hatibu & Mahoo, 1999). For example, most people in arid or semi-arid parts of Africa have lived with basic subsistence systems, which have helped them set goals for life over the years. No lower priority tasks can be done well until all the higher responsibilities have been taken care of (Hatibu & Mahoo, 1999). Also, Stakeholder participation is crucial for the success and sustainability of rainwater harvesting (RWH) projects. Stakeholders are individuals or groups who have a direct or indirect interest in RWH activities, such as local communities, farmers, government agencies, and private sector organizations (Barron et al., 2008). This criterion is calculated based on a questionnaire survey of people and stakeholders, analysing their responses to these questionnaires, and assigning a rank to each criterion based on this analysis.

4- Population density

Proximity to densely populated regions is a favourable attribute for the suggested locations. Water that has been stored is a significant resource for agricultural purposes and people settlements. Therefore, stakeholders tend to prioritise locating rainwater harvesting (RWH) systems in close proximity to densely populated regions. This approach helps minimise pumping distances, resulting in cost-effective operations (Faisal & Abdaki, 2021).

5- Distance to urban area (m)

One of the targets of the design of RWH structures is the local community; thus, the location of water collection RWH structures near urban centres is vital (Al-Adamat, 2008; Faisal & Abdaki, 2021). Where the expression distance to the urban area is used in some of the frameworks as a synonym, such as distance to the village, distance to settlements, and distance to built-up areas.

Six frameworks (Aghaloo & Chiu, 2020; Al-Adamat, 2008; Al-Adamat et al., 2010; Matomela et al., 2020; Shadmehri Toosi et al., 2020) mention the limitations of criteria in order to apply the RWH system in arid and semi-arid regions as follows:

- Annual rainfall should be more than 100 mm and less than 750 mm.
- The slope should be no more than 10% (not recommended for areas where the slope is greater than 10%).
- Soil should have a clay content of no less than 10%.
- The distance to a wadi should be more than 50 m and less than 2000 m.
- The distance to faults should be more than 1000 m.
- The distance to the water source should be more than 1500 m.
- The distance to a road should be more than 250 m.
- The distance to the agriculture area should be more than 250 m.
- The distance to an urban area should be more than 250 m and less than 2000 m.

3.4.8 Analysis of current frameworks' criteria

After merging the equivalent criteria, a survey of current frameworks led to the formation of the criterion categories shown in Figure 3-8, which shows the frequency of the criteria.

The term "slope" is the most frequently used, followed by "soil", "LULC", "drainage density", "rainfall", "runoff" and, "distance to roads". Word clouds were used to depict the incidence of the criteria terms as well as the frequency with which they occurred as shown in Figure 3-9 where the size of the text denotes the frequency of the term (Heimerl et al., 2014).

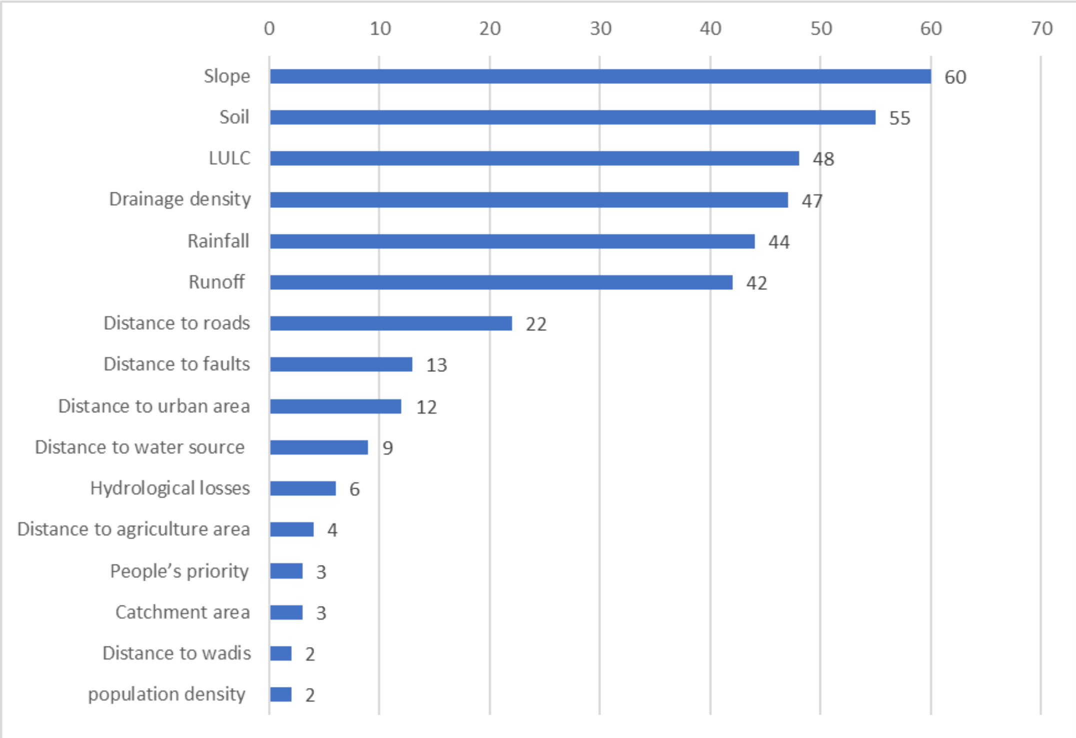

Figure 3-8 Criteria frequency in relevant frameworks.

Figure 3-9 Word cloud of the criteria based on NVivo.

Figure 3-10 shows the criteria that have been used in existing frameworks to identify RWH sites. Whereas 40 frameworks (59% of total frameworks) were based on biophysical, and 28 frameworks (41% of total frameworks) were based solely on biophysical and socioeconomic criteria.

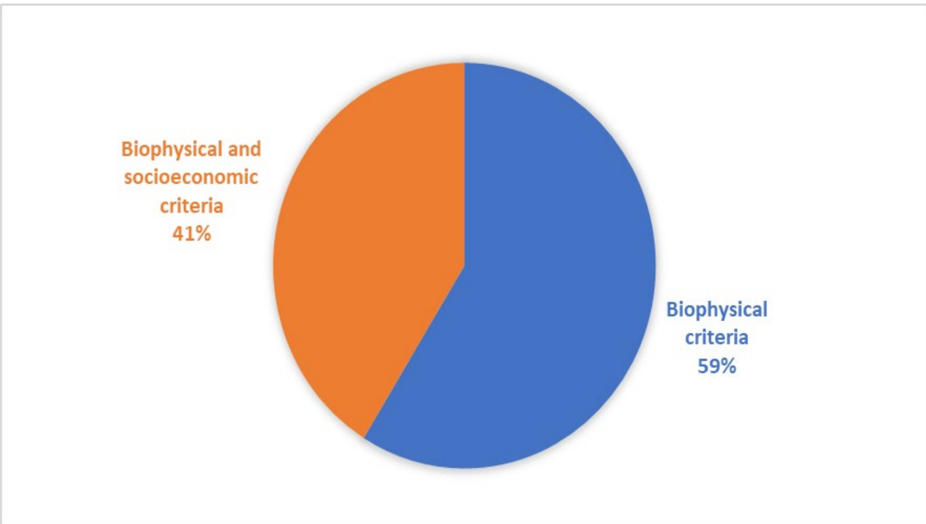

Figure 3-10 Biophysical and socioeconomic criteria.

Figure 3-11 illustrates the distribution of weights assigned to biophysical and socioeconomic criteria in existing frameworks. Biophysical criteria account for 76% of the total weights, while socioeconomic criteria make up the remaining 24%. These percentages were determined by summing the weights assigned to biophysical and socioeconomic criteria across multiple frameworks and calculating their proportions relative to the total combined weights.

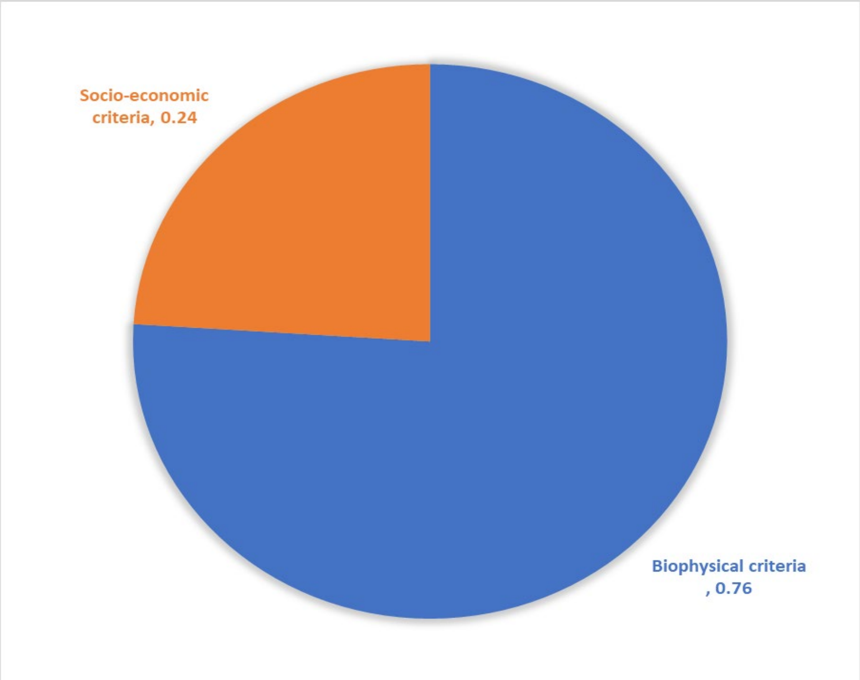

Figure 3-11 Percentages of weights for biophysical and socioeconomic criteria in existing frameworks.

3.4.9 Weighting Process and intervals for suitability

Based on this review, the weighted distribution scheme applied in RWH site selection frameworks can be divided into two distinct schemes:

- Equal weights: imply that each criterion in the framework is accorded the same degree of importance.
- Nonequal weights: indicate that different criteria are assigned varying levels of importance or significance within the framework. weight for each criterion based on the importance of the criterion for the purpose of the framework; for example, if the slope is more important than the soil for the framework, that means the slope is given a higher weight than the soil.

Just one framework adopted equal weights, with Al-Adamat (2008) arguing that a truly valid assessment system should equally balance the main elements of sustainability without introducing bias towards one aspect, especially for complex indicators. Fifty frameworks (74%) adopted unequal weights, such as (Albalawneh et al., 2015; Jamali & Ghorbani Kalkhajeh, 2020; Mahmoud et al., 2016; S. H.

Mahmoud & A. A. Alazba, 2015; Matomela et al., 2020) (Figure 3-12). They argue that doing so gives each criterion its importance based on its effect on the system, and also note that equal weighting does not guarantee equal importance or contribution of the indicators to the composite indicator. However, based on (Ammar Adham et al., 2016; Alkaradaghi et al., 2022; Karimi & Zeinivand, 2021) it was concluded that the unequal weights require additional human resources and time to implement.

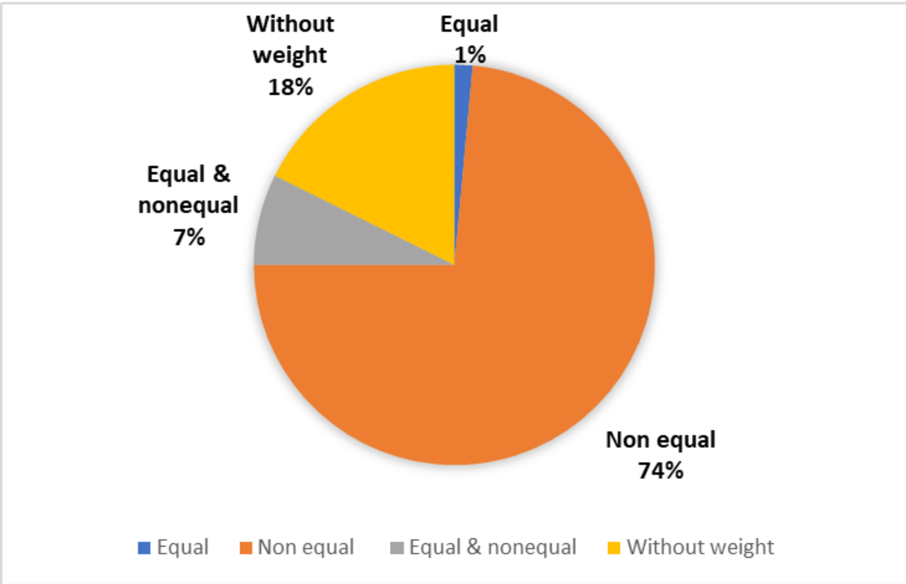

Figure 3-12 Distribution weighting scheme.

Five frameworks (7%), such as (Aly et al., 2022; Elewa et al., 2016; Elewa et al., 2021; Sayl et al., 2017, 2019b) used two scenarios of weights (equal and non-equal weights) in order to adjust the weight of the criteria.

This approach is utilized to compare the two scenarios and ensure that the RWH system is both safe and effective, which is essential for the sustainable utilization of rainwater resources. According to Elewa et al. (2016); Sayl et al. (2017), it is believed that non-equal weights offer more consistency and reliability compared to equal weights. The use of equal weights often leads to high fluctuations in the distribution criteria for the sites.

From this perspective, allocating non-equal weights to each individual criterion ensures a fair distribution of importance, thereby enhancing the accuracy and precision of the obtained outcomes. The range of normalised weights for the criteria is shown in Table 3-3. These weights were calculated by dividing the weight assigned to each specific criterion by the sum of weights for criteria used in the same framework. The table was constructed based on extracting the different weights of different criteria from 56 frameworks; these frameworks were constructed for different purposes, i.e., drinking water, agriculture, or both, which gives every criterion a different weight. Using these weights, the calculation is based on the range of the criteria's maximum, minimum, average, and standard deviation values.

These values give an indication of the degree to which the weights may differ from one another, allowing for the identification of indicators with substantial variations in weight and those with consistent performance. This variation depends on how important this indicator is for the purpose of the framework and regional priorities. For example, the framework (Alkaradaghi et al., 2022) assigned a lower weight for runoff at a value of 5.5% because they have the same soil classes in these regions. Lower values for this indicator indicate a higher capacity of the soil to retain precipitation and, consequently, a reduced amount of runoff. However, the framework (Farooq et al., 2022) allocated a higher weight to runoff because it prioritises effective management of runoff and its potential benefits for water availability. In addition, the framework (El-Awar et al., 2000a) assigned a minimum weight for soil of 3.2% due to these properties' generally low level of variation across the pilot region. While the highest weight for soil was 42.6%, which was allocated by the framework (Mahmoud, Mohammad, et al., 2015), the highest weight for soil in this framework was due to the fact that the purpose of this study was flood management to protect against soil erosion and the variation in soil type in this region.

While the standard deviation can be used to examine the dispersion of values and identify outliers, but it provides little insight into the actual values themselves (Lee et al., 2015). For example, when analysing the weights of criteria, a high standard deviation would indicate that the weights of people's priorities (0.3) are widely spread out and that some frameworks may give this criterion significantly higher or lower weights than the mean or average value. In contrast to population density, which was 0.011, which indicates that data points are generally close to the mean or average value. The relative standard deviation (RSD) is a frequently employed statistic that facilitates statistical analysis. It is calculated by multiplying the standard deviation by 100 and dividing the result by the mean value. The primary objective of the relative standard deviation (RSD) is to assess and contrast the degree of variability exhibited by data in relation to its mean value. This method offers a convenient means of evaluating the accuracy and reliability of scientific measurements (Parsons et al., 2009).

Table 3-3 Maximum and minimum weights of the existing criteria.

	Criteria	Max. Weight (%)	Min. Weight (%)	Average (%)	Standard Deviation (%)	Relative Standard Deviation (RSD)	Frequency of Criteria in Existing Frameworks
1-	Rainfall	45.7	6	23.2	10.5	45.26	44
2-	Runoff	53	5.5	32	12.8	40.00	42
3-	Slope	35.4	6	19.8	8.3	41.92	60
4-	Soil	42.6	3.2	18.9	10	52.91	55
5-	Land use/land cover (LULC)	35.5	4	11.7	8.6	73.50	48
6-	Drainage density	41.6	4.1	14	9.9	70.71	47
7-	Hydrological losses	13.3	4.8	8	3.4	42.50	6
8-	Catchment area	22.2	9.81	14.8	6.5	43.92	3
9-	Distance to wadis	19	17	18	1.4	7.78	2
10-	Distance to faults	13.6	4.6	4.6	2.8	60.87	13
11-	Distance to water source	19.8	5	11.4	5.9	51.75	9
12-	Distance to roads	25	1.63	7.6	7.4	97.37	22
13-	Distance to agricultural area	21.3	4.07	10.4	8.1	77.88	4
14-	People's priorities	64.4	9.6	30	30	100.00	3
15-	Population density	4.3	2.77	3.5	1.1	31.43	2
16-	Distance to urban area	13	2.3	7.2	4	55.56	12

Figure 3-13 shows the percentage of normalised weights for the merged criteria that are used in current frameworks. Runoff and People's priority obtained the greatest weights, 14% and 13%, respectively. These percentages were calculated based on the average weight for each criterion in existing frameworks divided by the sum of average weights for all criteria in existing frameworks. One hundred percent is the total weight of the criteria, which represents the total importance of each criterion on the framework.

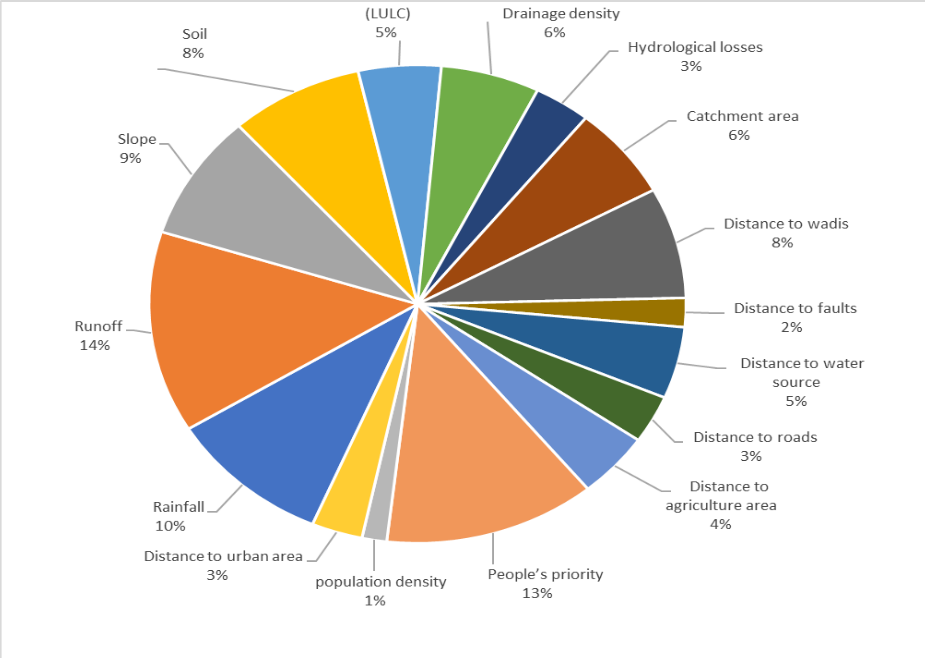

Figure 3-13 The percentages of normalised weights for the main criteria.

Figure 3-14 shows the interval of the final index, which quantifies the significance of each criterion that was used in existing frameworks. A notable finding is that a significant proportion, specifically 21%, of the frameworks employ a binary (0 or 1) indicator, whereby a site is classified as either meeting or not meeting requirements. In contrast, the other frameworks utilise graded scales with varying degrees of granularity; the most common intervals used in existing frameworks were low-resolution scales of 1 to 3, 4, or 5, with 52%. Then, a medium-resolution scale of 1 to 10 was used by 7%. And 7% was used for a high-resolution scale of 1 to 100. The rest of the frameworks did not specify the scale used, which was 13%. According to the analysed frameworks, the intervals (1–5 and 0–1) seem to be the most popular option among both experts and stakeholders.

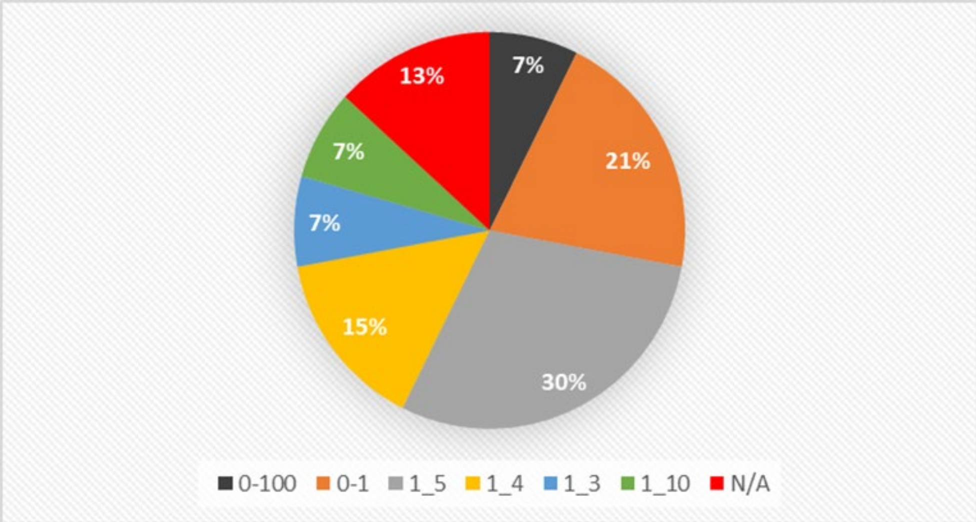

Figure 3-14 Interval of Final Index Value

The advantage of having such a number is that it makes the outcome of the entire framework simple to comprehend, not least for a wide variety of various stakeholders, and this can be accomplished without the need for a more in-depth evaluation (Chaves & Alipaz, 2007).

From this standpoint, the higher range of interval indicates flexibility in choices. If the final index is a percentage, for instance, it may be more intuitive to report numbers between 0 and 100 than to use a different range. In contrast to ranges (1-3), (1-4), and (1-5) that are more commonly used for qualitative criteria.

3.4.10 Discussion

This research sought to identify RWH framework elements for arid and semi-arid regions based on a systematic literature review. The assessment was helpful in identifying essential qualities that a framework has to have for it to be regarded as suitable for implementation in arid and semi-arid regions. The framework's development should include participation by stakeholders, experts, etc. to identify the criteria and assign weights, and determine the appropriate number of criteria.

The findings of this review reveal that of the 68 different frameworks, 40 of them are based on biophysical criteria, and the other 28 are based on biophysical and socioeconomic criteria in site selection for RWH, as shown in Figure 3-11. The most common criteria that were used in existing frameworks were slope, soil, and land use/land cover. In addition, the number of criteria varied from framework to framework. The number of criteria was determined based on the size of the issue, the availability of data, and the opinions of experts and stakeholders (see Tables A1 and

A2 in Appendix A). Furthermore, the most commonly used intervals for evaluating suitability in the existing frameworks were (1–5) and (0–1); see Figure 3-14. The interval (1–5) provides decision makers with more options than the interval (0–1), which is more limited.

This review work contributes, although in a limited manner, to closing the knowledge gap. This research was restricted to two databases (Scopus and Engineering Village). Based on this study, it appears that the scholars, in their research in this field, have not yet investigated how ecological factors affect site selection for RWH.

3.4.11 Conclusion

This paper presents a systematic literature review to identify RWH sites in arid and semi-arid regions, focusing on criteria for site selection. Following the screening procedure, 68 papers met the search criteria and were deemed relevant. The purpose of this study was to discern the guiding principles of different frameworks used for identifying suitable RWH sites and to identify existing gaps in knowledge. According to this review, many frameworks have been developed for this purpose. This review helps in identifying the core components of the framework and investigating methods of data collection. In addition, the comparison between different frameworks and the identification of the similarity and differences between them help identify the gap in knowledge. This study shows that the criteria used in existing frameworks were biophysical and socioeconomic criteria, which are insufficient to achieve the pillars of the sustainability system. Forty frameworks (59 percent of the total) were founded on biophysical criteria, whereas 28 frameworks (41 percent of the total) were founded on both biophysical and socioeconomic factors. In addition, "slope" was the most common criterion, followed by "soil," "LULC," "drainage density," "rainfall," "runoff," and "distance to roads," with biophysical criteria representing for 76% of the weights and socioeconomic criteria for 24% see Figure 3-11.

These frameworks for rainwater harvesting (RWH) are developed without fully considering how the location of the structures and the duration of their use might affect ecological factors such as water quality and the surrounding living organisms. While rainwater is initially free from microbial contamination, it can become polluted due to human and animal activities. Improper storage conditions can further promote the growth of pathogens, increasing the risk of infectious disease outbreaks. Additionally, the quality of water in RWH structures is heavily influenced by the location of the structures and the characteristics of the catchment area. (Radaideh et al., 2009; Schets et al., 2010).

In light of this, it is imperative to develop more comprehensive RWH system frameworks that promote sustainability, preservation of natural resources, and minimize water contamination. A rainwater harvesting (RWH) structure is expected to align with the pillars of sustainability, including ecological considerations. Therefore, it is crucial to take into account the ecological aspects when designing such RWH framework. As a result, ongoing efforts are being made to develop a framework that effectively addresses this matter.

3.4.12 Future work

The subsequent research will need to concentrate on developing a framework for RWH site selection in arid and semi-arid regions relying on all the factors discussed in Section 3.3 to ensure its practical applicability and relevance. A conceptual framework will be formulated for site selection RWH in such regions which will entail the following steps:

1- Identification of the most important structural criteria (biophysical and socioeconomic).

2- Formulation of a methodology to identify the most significant ecological criteria and combine them with structural criteria.

3- Engagement of stockholders and experts to weight the criteria and validate the framework.

4- The resultant hybrid framework will be applied to a case study to demonstrate its use as a decision-support tool for potential users. The selection of the case study will be based on criteria such as its location in an arid or semi-arid region, and the availability of relevant information about the region.

Chapter 4: Methodology

4.1 OVERVIEW

This chapter describes the methods and tools used in the study. It explains the many approaches that were used to achieve the objectives of the study. Data was gathered using a mix of quantitative and qualitative techniques.

Following the introduction, the research methodology in this study is outlined in the following sections: designing the framework, selecting the right methodological approach, research strategies, correlation between direct and indirect criteria, the mediation analysis, design questionnaire and calculation of site suitability.

These sections provide a comprehensive discussion of the limitations and potential biases that may have influenced the findings.

4.2 DESIGNING THE FRAMEWORK

A composite framework for rainwater harvesting has been formulated with the purpose of assisting stakeholders in arid and semi-arid regions in the identification of suitable sites for RWH. This framework is predicated on a comprehensive evaluation of structural and ecological criteria. A framework consisting of three groups of criteria, biophysical, socioeconomic, and ecological, has been developed. The criteria for two of the groups - biophysical and socioeconomic - have been identified based on a systematic review, and the data for these criteria have been analysed in depth in Chapter 3 to identify the weights. While the ecological criteria have been identified based on a literature review, Then, the weights of ecological criteria were determined based on surveys by experts. See Figure 4-1.

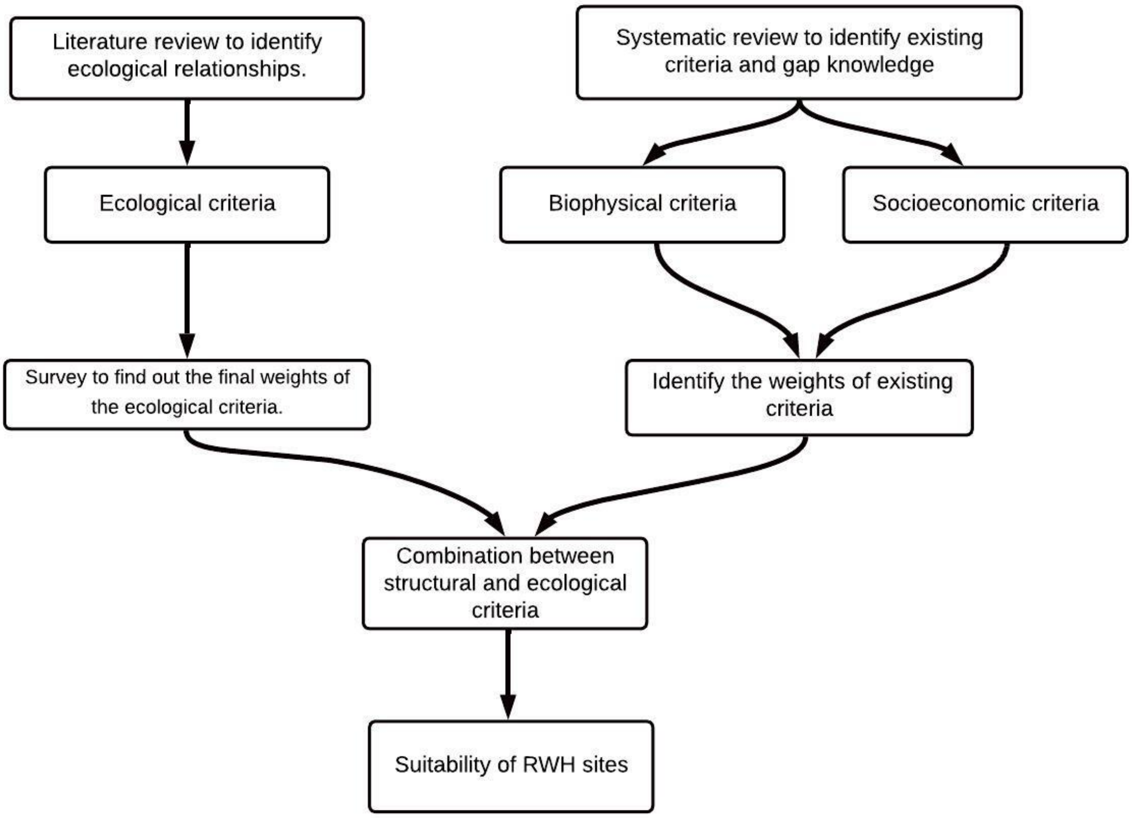

Figure 4-1 Steps for constructed framework

4.2.1 General overview of methodology steps used in the research project.

The following steps outline the methodology employed to achieve five objectives: (see Figure 4-2):

1. The systematic review aims to review the current state-of-the-art in rainwater harvesting site selection, focusing on applications in arid and semi-arid regions, and to identify areas in which further research is necessary. A systematic literature review is employed to answer specific questions by identifying, appraising, and synthesising relevant literature that fits pre-specified criteria (Piper, 2013). The articles related to rainwater harvesting (RWH) in arid and semi-arid regions were identified based on included and excluded criteria. A comprehensive, systematic literature review has been employed for this purpose. The weights assigned to the biophysical and socioeconomic criteria have been

determined by in-depth analysing the current frameworks in a systematic study as detailed in Chapter 3:.

2. Identify the most significant direct and indirect criteria for ecological criteria based on a literature review and identify the link between direct and indirect criteria based on the literature. This objective is conducted in Section 4.5 and Section 4.6 .
3. Evaluate the impact of indirect criteria on direct criteria through literature analysis and contacting experts in water system ecology to determine appropriate weighting. The determination of weights for ecological factors was accomplished by the administration of questionnaires to experts. This objective was conducted through the online survey to experts which conducted in the Section 5.3.
4. Create a hybrid framework for RWH site selection by combining structural and ecological criteria. Appropriate parts of existing framework methods combined with a new method for evaluating ecological criteria based on the identified indirect criteria, direct criteria and weightings to produce a comprehensive, hybrid framework. This framework combined the currently used structural criteria (biophysical and socioeconomic criteria) with new ecological criteria. This objective is implemented in Chapter 5:.
5. Demonstrate the functionality of the new hybrid framework through a case study. The hybrid framework that emerged utilised a case study to showcase its efficacy as a decision-support tool for prospective users. The case study is chosen based on the geographical location in either an arid or semi-arid area, as well as the accessibility of pertinent information about the region. Extracting data for site selection has traditionally required significant time and human resources. However, Geographic Information Systems (GIS) and remote sensing (RS) can simplify the process (Sayl, 2017). This study used a Quantum Geographic Information System (QGIS) with powerful capabilities to digitise raster data. This objective is implemented in Chapter 6:

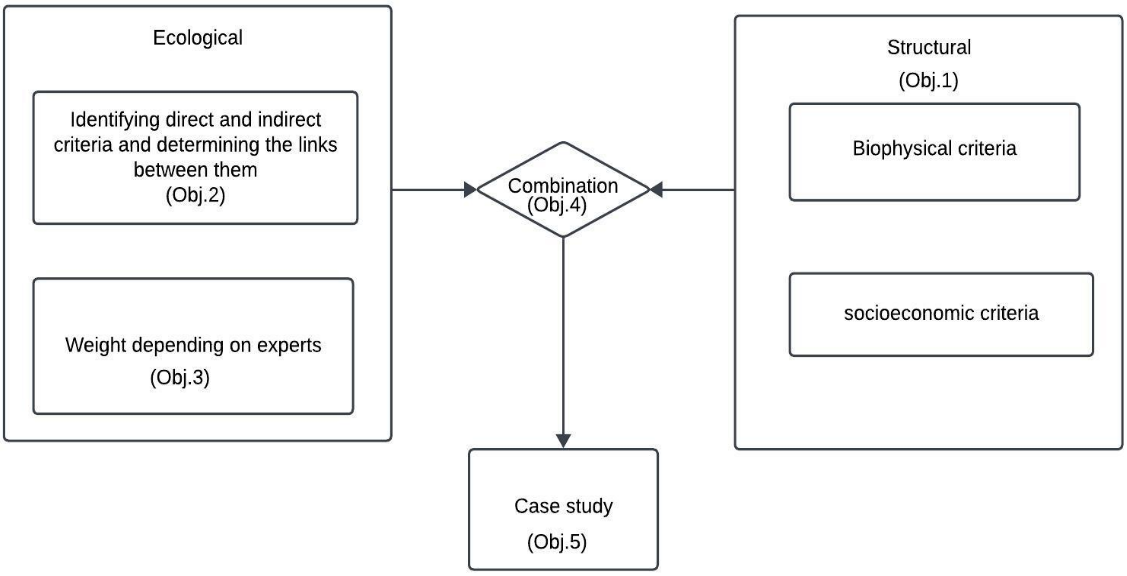

Figure 4-2 The schematic of methodology for site selection for RWH based on ecological and structural criteria.

4.3 APPROACH TO THE RESEARCH

This study uses various research techniques, including surveys, analysis, and case studies. The study strategy is classified into two primary categories:

- A comprehensive systematic review was conducted to find out the existing frameworks and criteria and identify gaps in knowledge. Also, the data was analysed in depth for selected frameworks to identify the weights of criteria used in existing frameworks.
- This study examines how ecological criteria can be included as a potential strategy for ensuring environmental protection, maintaining biodiversity, water quality improvement, climate resilience, regulatory compliance and sustainability of the system. Furthermore, most existing studies on site selection for rainwater harvesting have been conducted without considering ecological criteria. As a result, it is necessary to develop a theoretical

framework for rainwater harvesting that incorporates ecological considerations.

4.4 RESEARCH STRATEGIES

This study employed three distinct strategies to collect data: a systematic literature review, a survey in the form of a questionnaire, and a case study.

4.5 CORRELATION BETWEEN DIRECT AND INDIRECT CRITERIA

The criteria for evaluating water quality and ecology encompass chemical, physical, and biological elements that are measured directly by collecting samples from water bodies and analysing them in a laboratory. However, when identifying sites for rainwater harvesting in areas where no existing water bodies are available for testing, an alternative method is required to assess the ecological impact. It has been determined that certain criteria indirectly affect ecological factors.

Temperature, light, wind speed, wind direction, lagged wind speed, humidity, and evaporation are ecological factors that are important to the ecosystem's health inside a rainwater harvesting (RWH) system (El-Jabi et al., 2014a). Temperature and light are given top priority in this study because, according to a thorough review of the literature, they have the greatest impact on water quality standards. For instance, temperature and light directly influence water quality parameters such as total phosphorus (TP), salinity, nitrogen (N), pH, dissolved oxygen (DO), and ammonia. These water quality parameters, in turn, have a direct impact on ecological factors such as vegetation and organisms. The process of evaluating sites for rainwater harvesting based on ecological criteria is complex. This study aims to obtain data that will help address this issue.

To identify the impact of independent variables, namely temperature and light, on dependent variables such as vegetation and organisms, it is advisable to employ mediation analysis, as discussed in Section 4.6.

4.6 THE MEDIATION ANALYSIS

Mediation analysis involves incorporating a third variable that functions as an intermediary between independent and dependent criteria. This mediating effect, also known as an indirect effect or mediation, relies on the intermediary variable to establish the association between the independent and dependent variables (Carrión et al., 2017). Weightings of ecological criteria were determined through expert consultation. The complex relationships between the ecological criteria were modelled using mediation analysis. Specifically, ecological criteria have complex interrelationships which must be accounted for in a robust framework. The criteria which are a direct measure of ecological health of a system (e.g. the diversity of aquatic life and water quality) are often not measured but are inferred through our understanding of the relationship between, for example, phosphorous concentration and aquatic life. The *direct* criterion (phosphorous) is what is measured and included in the framework. There may be more complex relationships, with one indirect criterion affecting another which, in turn, affects the direct criterion. These relationships may be quantified using mediation analysis. In the language of mediation analysis, the indirect criteria are *independent*, the ecosystem criteria are *dependent*, and any intermediate criteria are *mediators* (Carrión et al., 2017), as illustrated in Figure 4-3**.** Following the notation in this figure**,** the total effect of *X* on *Y* is quantified by its *weighting*, *C*, in the absence of mediators (Figure 4-3a), but an additional effect occurs when *X* also affects mediator *M*, which affects *Y* in turn (Figure 4-3b) (Carrión et al., 2017). The total direct effect of *X* on *Y* can be quantified as the total weighting, C, using:

$$C = C' + (a \times b) \tag{4-1}$$

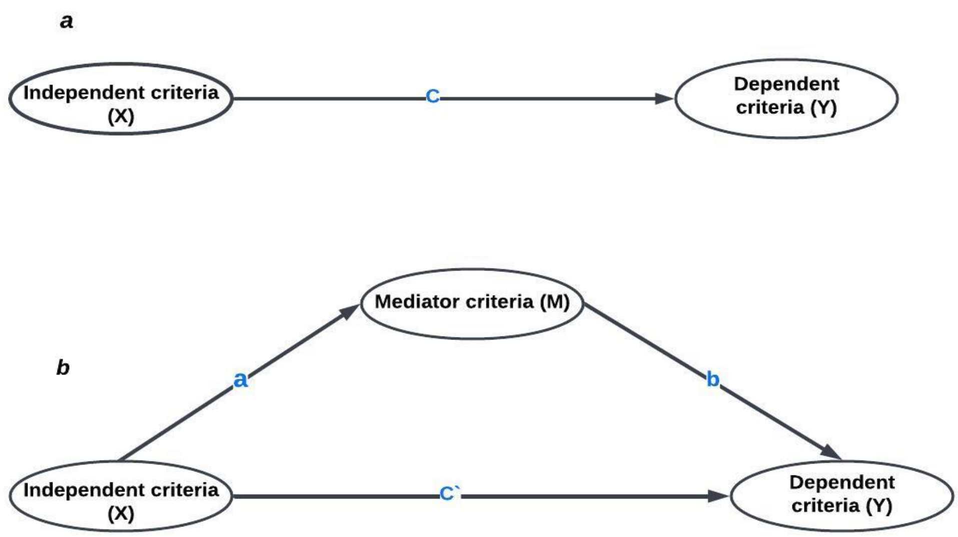

Figure 4-3 Cause-and-effect relationship and b) general mediation model (Carrión et al., 2017)

where C' is the weighting for the effect of *X* on *Y*, a is the weighting of *X*'s effect on *M* and *b* is the weighting for the effect of *M* on *Y*.

Figure 4-4 shows the relationships between independent (temperature and light) and dependent (ecosystem criteria) through mediator criteria, where lowercase "*a*"s represent the weightings for the effects of temperature on the mediator criteria, "*b*"s represent the weighting for the effects of light on the mediator criteria, "*c*"s represent the direct relationship between the independent and dependent criteria, "*d*"s are the weightings between mediators and dependent criteria, and "*e*"s are the weightings for the effects between mediator criteria. The total weighting for temperature, C_T, and light, C_L, are therefore given by eq.(4-2) and eq.(4-3) respectively, following the principles of mediation analysis discussed in Section 4.6:

$$\boldsymbol{C_T = a_1d_1 + a_2d_2 + a_2d_5 + a_3d_3 + a_4d_4 + a_4d_6 + a_4e_2d_7 + a_4d_4 + a_4d_6 + a_4e_1d_8 + C_1 + C_3} \quad (4\text{-}2)$$

$$\boldsymbol{C_L = b_1d_6 + b_1e_2\,d_7 + b_1e_1\,d_8 + b_2d_7 + b_3d_8 + C_2 + C_3 + C_4 + C_5} \quad (4\text{-}3)$$

It is these weightings which have been determined via the consultation with experts in the field.

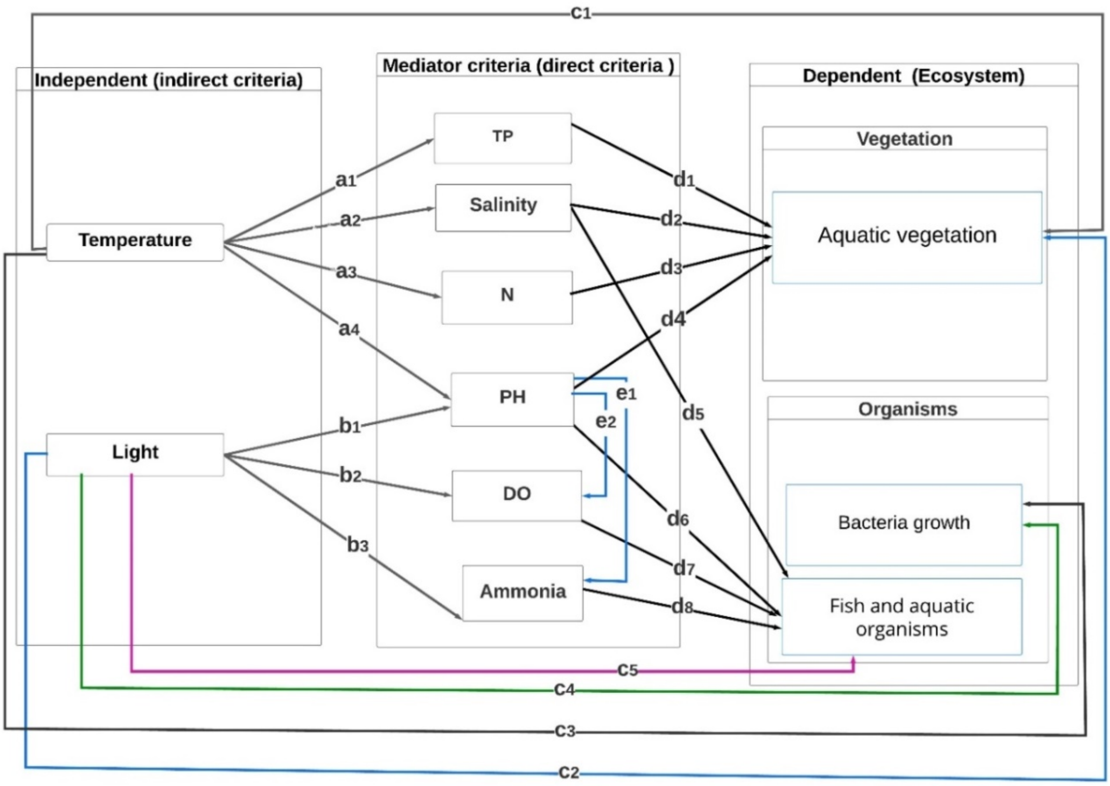

Figure 4-4 Shows the relationships between direct and indirect criteria constructs based on literature review on literature review.

4.7 DESIGN OF THE QUESTIONNAIRE

There are two primary types of surveys used to collect data from participants: interviews and questionnaires. Interviews involve verbal questioning and nonverbal cues to gather complex cognitive, emotional, and social data. However, they may introduce bias due to the subjective nature of interpretation and the influence of the interview . For this reason, interviews were not used in this study. On the other hand, questionnaires are self-report tools in which respondents provide written answers to predefined questions, offering a more standardized approach to data collection (Akbayrak, 2000). An online survey was conducted as the preferred method to assess and evaluate the specified criteria. The method has high applicability for gathering large samples, low cost, high dependability, and time savings (Nanekely, 2020). It might be inexpensive and simple to obtain truthful responses from thousands of individuals by using a self-administered questionnaire (Mitchell & Jolley, 2012). The communication with participants was conducted based on electronic media (i.e., research gate, direct email and LinkedIn) which targeted different groups of participants such as academics at universities and academic investigators at research institutions with different specialists such as ecologists, hydrologists and environmentalists.

Before designing a questionnaire, it is advisable to review the literature to identify relevant criteria and existing frameworks that align with the research hypothesis (Edwards, 2010). The methods for measuring the variables and the requirements of interest should be clear to the researcher (Edwards, 2010).

The questionnaire was carefully designed to ensure accurate measurement of the intended characteristics, considering factors such as content, language complexity, format, sequence, and the data collection method. The structure was designed to conform to the suggested mode of delivery, as stated by Kazi and Khalid (2012), ensured the questions were clear, logically organized, and suitable for the target audience. The questionnaire was sent out to 249 participants in round 1 and was amended based on feedback (detailed in Section 5.3.1). Following the incorporation of feedback, the questionnaire was revised and subsequently sent to 454 participants in Round 2, as also discussed in Section 5.3.1.

It is essential to validate a measure in order to guarantee its correctness. A legitimate questionnaire should produce more similar and high-quality data, regardless of the responder, as this increases data credibility and minimises work. A valid questionnaire must have the following essential qualities: it must be viable and simple, have clear language, be reliable, align with the intended measurement goal, take the underlying idea into mind, and be able to assess change (Kazi & Khalid, 2012).

It is essential to test the data for skewness by comparing the mean and the median in order to determine the weights of the ecological criteria. Skewness can greatly impact the analysis results. Identifying and correcting skewness leads to a more accurate weighting of the ecological criteria.

The average, often known as the mean, is an effective method for determining the midpoint of a set of data that are uniformly distributed. However, if the data are heavily clustered on one side, the average can be distorted by extremely high or low values. In such instances, it is preferable to utilise the median, which represents the central value when the numbers are organised in ascending or descending order. Normal distributions, characterised by a uniform distribution of values, are suitable for utilising the mean (Sartori, 2006).

The mean values were calculated based on eq.4-4, while median values were calculated by rearrangement of the experts' opinions for each statement in ascending order, then selecting the middle of these numbers, which was two numbers, and then summing these two numbers divided by two. The statements of “don’t know” responses have been excluded from the analysis.

$$X' = \frac{\sum_{i=1}^{30} x_i}{\sum_{i=1}^{30} N} \qquad 4\text{-}4$$

Where:

X′: The mean of responses,

x_i: Response of $expert_i$ for the statement x

N: Total number of experts.

The University of Birmingham ethics team reviewed and approved the initial draft of the questionnaire (approval code: ERN_1341-Jun2023). The pilot study was followed by revisions to the questionnaire.

A questionnaire has been devised, encompassing a total of 33 questions. These questions have been predominantly organised into four distinct sections, namely:

1. Introduction and consent form: This section explains the purpose of the questionnaire. If the participants wish to proceed at this point, they must indicate their approval on the consent form in order to proceed to the next section. After approving the consent form, participants will answer seven background questions, such as their country of residence, experience in the water sector, and level of understanding of rainwater harvesting.
2. Brief explanation of the survey's findings: A brief explanation of the framework and its mechanism is provided, followed by a question using a five-level Likert scale asking if participants agree to give equal weight to the three groups of criteria (biophysical, socioeconomic, and ecological).
3. Ecological criteria: This section demonstrates the evaluation of ecological criteria in water bodies using mediation analysis. It examines the effect of independent criteria (light and temperature) on the dependent criteria (vegetation and organisms) through mediator criteria (e.g., measurements of pH, dissolved oxygen (DO), nitrogen (N), ammonia, total phosphorus (TP), and salinity).

This section includes three groups of questions, each rated on a six-level Likert scale (including 0 for those who do not know):

- Temperature Effect: this group consists of six questions related to the effect of temperature on the following:

  a) Total phosphorus levels
  b) Salinity levels and concentrations
  c) Nitrogen retention
  d) pH levels
  e) Aquatic vegetation
  f) Bacterial growth

- Light Effect: This group consists of five questions related to the effect of light on the following:
  a) pH levels
  b) Dissolved oxygen (DO)
  c) Ammonia concentrations
  d) Aquatic organisms
  e) Bacterial growth
- Mediator Effect: This group consists of ten questions related to the mediator effect on vegetation and organisms.

Each group aims to provide insights into how changes in temperature and light, as well as mediator criteria, influence the health and dynamics of aquatic ecosystems.

4. Feedback Questions Section: This section includes three questions. The first two questions are based on a five-level Likert scale regarding the use or support of policy or decision-makers to use rainwater harvesting in the future. The scale ranges from 1 to 5, with 1 being "Very unlikely" and 5 being "Very likely." The midpoint, 3, is labelled as "Neither likely nor unlikely."
   The third open-ended question invites any feedback to improve the questionnaire's output.

The main aim of conducting this survey is to derive the final version of the RWH framework from the opinions of participants. The purpose of this questionnaire is to solicit the expert opinion or practical insights of individuals with expertise in ecological and environmental aspects, particularly in the context of arid and semi-arid regions. The questionnaire aims to assess the suitability of selected components and indicators, which have been derived from existing literature as well as tailored to cater to the unique characteristics of arid and semi-arid regions.

4.8 CALCULATION OF SITE SUITABILITY

The hybrid framework includes three groups of criteria: the biophysical and socioeconomic criteria used in existing frameworks and the newly incorporated ecological criteria. The score, *S*, for each of these *n* groups are combined to give the overall site score (S_O), taking into account weightings (*W*) which represent the relative importance of each group, following (4-5):

$$S_O = \sum_{i=1}^{n} S_i \times W_i \tag{4-5}$$

An equivalent formula is used to determine *S*, the group score, from the scores (*s*) and weightings (*w*) of the *N* criteria within that group:

$$S = \sum_{i=1}^{N} s_i \times w_i \tag{4-6}$$

The weighting of criteria for biophysical and socioeconomic factors were calculated through a literature review. However, for the ecological criteria each criterion was ranked via the expert opinion questionnaire, and this was converted to a weighting, the results of which are summarised in the Chapter 5.

Temperature plays a crucial role in the vulnerability of aquatic plants to pests and illnesses. Warmer temperatures can increase the risk of disease outbreaks and infestations in aquatic plant populations by favouring the growth and spread of diseases and pests (Qu et al., 2022). Hence, regions with higher temperatures are given a lower rank.

On the other hand, the amount of light present has a significant impact on water quality. Adequate light improves water quality by breaking down pollutants and is necessary for life. Therefore, regions with higher-intensity light are given a higher rank. According to a case study, the criteria were divided into four intervals (0-4), with 0 representing the not important and 4 representing the most important (see Table 4-1). The average weights of the existing criteria utilised in eq.(4-5) and (4-6) are shown in Table 3-3. The ecological criteria, namely temperature and light, were determined through mediation analysis, which is elaborated in Section 4.6 .

Table 4-1 The rank of biophysical, socioeconomic and ecological criteria.

Rank / Criteria	0	1	2	3	4	**References**
Rainfall (P) (mm)	-	P<100	100≤P<300	≥ 300 P<500	P >500	(Al-Adamat et al., 2010)
Runoff (R) (mm)	-	R<100	100≤R<300	≥ 300 R<500	R >500	(Al-Adamat et al., 2010)
Slope (S) (%)	-	S>10	5 ≤S< 10	3≤ S < 5	S <3	(Al-Adamat et al., 2010)
Soil	-	Loam	Sandy Clay Loam, silty Loam	Silty clay	Clay Loam	(Ahmed et al., 2023b)
Land use/land cover (LULC)	Urban/Built-Up Area Water Bodies	Forest	Cultivated Land	Grassland	Bare soil	(Ahmed et al., 2023b)
Drainage density ($\frac{km}{km^2}$)	0-0.21	0.212-0.33	0.34-0.46	0.47-0.61	>0.62	(Khalid Mahmood et al., 2020)
Hydrological losses (%)	-	75-100	50-75	25-50	0-25	Normalisation
Catchment area (Km^2)		9.33–84.71	84.72-226.51	226.52–527.70	>527.2	(Ezzeldin et al., 2022)
Distance to wadis (D) (m)	< 50	D ≥1000	2000>D ≥1000	1000>D ≥500	51>D<500	(Al-Adamat et al., 2010)
Distance to faults (m)		500-2000	2000-10000	10000-20000	>20000	(Noori et al., 2019)
Distance to water source (m)	< 1500	1500-2000	2000-2500	2500-3000	≥ 3000	(Matomela et al., 2020)
Distance to roads (m)	<250	>2000	1500-2000	1000-1500	250-1000	(Faisal & Abdaki, 2021)
Distance to agricultural area (m)	<250	>700	500 –700	300–500	250-300	(Alem et al., 2022)
People's priorities	<250	>700	500 –700	300–500	250-300	Suggestion
		Agriculture	Agriculture	Agriculture	Agriculture	
Population density	-	0-10	10-20	20-40	>40	(Faisal & Abdaki, 2021)
Distance to urban area (m)	<250	500-1000	1000- 1500	≥ 1500 < 3000	≥ 3000	(Matomela et al., 2020)
Temperature (°C)	-	20_25	15_20	10_15	5_10	Equal interval
Light (kWh/yr)	-	1700_1720	1720_1740	1740_1760	1760_1780	Equal interval

Chapter 5: Results and discussions

5.1 INTRODUCTION

The analysis of the questionnaire responses related to ecological criteria and the additional analysis of weights for existing criteria (biophysical and socioeconomic criteria) are explained in detail in this chapter, which is divided into four sections.

Section 5.2 presents additional analysis not included in Chapter 3: , focusing on the weights assigned to existing criteria (biophysical and socioeconomic). This section compares the median and mean values to determine the most appropriate way to represent the data. Section 5.3 analyses the survey data to determine the final weights for the ecological criteria.

5.2 WEIGHTS FOR EXISTING CRITERIA (BIOPHYSICAL AND SOCIOECONOMIC CRITERIA)

In Chapter 3:, Section 3.4.9, an analysis was conducted to assign weights to criteria based on biophysical and socioeconomic factors. The mean and median of the criteria were calculated, and Table 3-3 presents the results, highlighting the skewness of the data. This summary is expanded upon here, giving more detail of the analysis.

It is more advisable to examine the data based on mean and median to see which one is representative the central tendency in order to reduce the influence of skewness in the data. The mean values were calculated based on eq. (5-1), while median values were calculated by rearrangement of the experts' opinions for each statement in ascending order, then selecting the middle of these numbers, which was two numbers, and then summing these two numbers divided by two.

$$X' = \frac{\sum_{i=1}^{30} x_i}{\sum_{i=1}^{30} \mathrm{N}} \qquad 5\text{-}1$$

Where:

X´: The mean of responses,

x_i: Response of $expert_i$ for the statement x

N: Total number of experts

Figure 5-1 visually compares the mean and median, revealing significant gaps for certain criteria. Notably, Statement 14 (people priority) exhibited the largest disparity, followed by Statement 6 (drainage density), Statement 5 (Land Use and Land Cover - LULC), Statement 2 (runoff), Statement 12 (distance to roads), Statement 13 (distance to agriculture area), Statement 8 (catchment area), Statement 4 (soil), Statement 11 (distance to water source), Statement 16 (distance to urban area), Statement 1 (rainfall), and Statement 3 (slope). The differences between mean and median for these criteria were 37%, 10%, 10%, 8%, 8%, 6%, 6%, 6%, 3%, 3%, 2%, and 1%, respectively.

Conversely, Statements 7, 9, 10, and 15 displayed no skewness, with zero differences between mean and median. This analysis shows that, for all criteria, the mean is a more reliable measure as it accurately represents the data.

In conclusion, the difference in mean and median in the data was below 10% for all statements except for Statement 14 (people priority), where the difference was 37%, indicating a high level of skewness. However, it's essential to note that this statement is based on a small data size of only 3 samples. This emphasises the significance of selecting an appropriate measure of central tendency to represent these data accurately.

The mean, identified as a reliable choice, emerges as the preferred option to ensure a more robust representation of the criteria weights. This consideration holds crucial importance in maintaining the integrity of the analysis and preventing undue influence from outliers in the dataset.

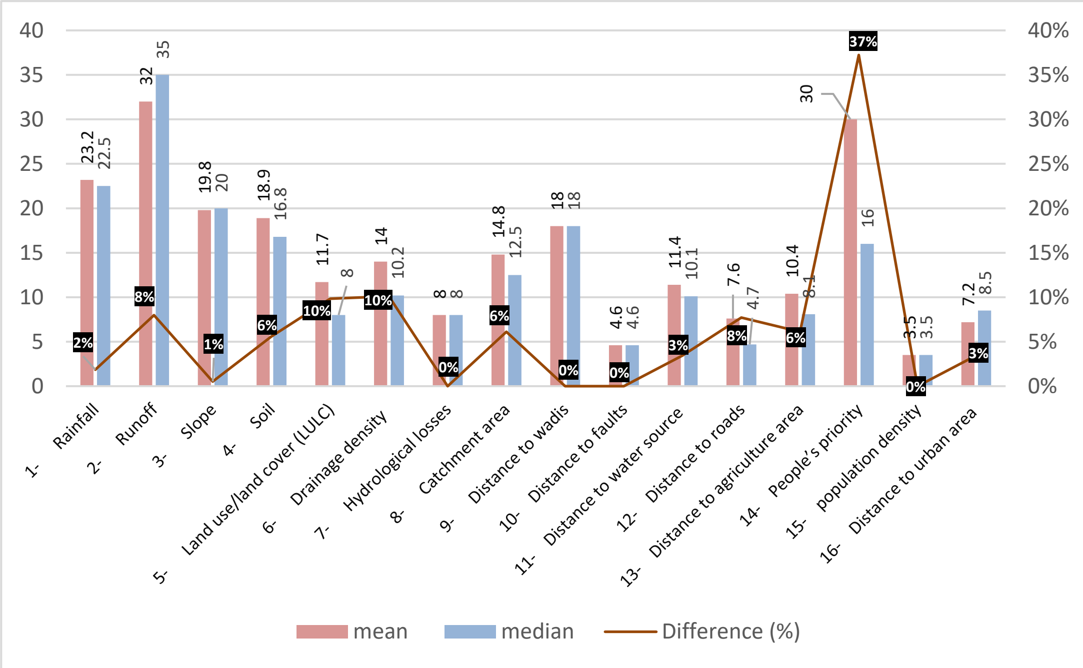

Figure 5-1 Mean and median weights for biophysical and socioeconomic criteria for existing frameworks.

5.3 WEIGHTS FOR ECOLOGICAL CRITERIA

5.3.1 Development of Questionnaire

Initially, the survey was administered by integrating the Google Form with Quilgo among eight doctoral students for time evaluations. The mean completion time was determined to be 13 minutes. Consequently, it is stipulated that experts may require approximately 15 minutes to successfully complete the survey.

Then, the first round was conducted on 249 participants (146 direct email, 94 research gate and 9 LinkedIn) as shown in Figure 5-2. The study involved a total of 33 participants, comprising 13 hydrologists, 12 civil engineers specialising in water resources, 7 environmentalists, and 1 ecologist. It is crucial to take the feedback of experts into consideration to enhance the survey's quality and effectiveness.

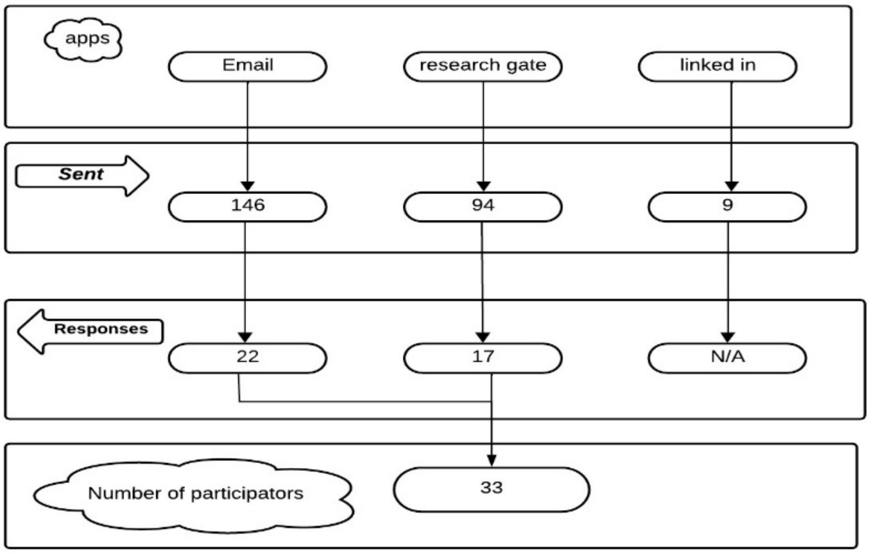

Figure 5-2 First round survey process

The feedback for this survey from experts was interesting and valuable. The first comment was “I may not have answers for all the questions, so it would be helpful to provide options to accommodate those who may not be familiar with some aspects”. The second comment was “Most of the questioners are on ecological factors and thus the questioner could have been addressed by an environmental engineer than an expert on water resources (RWH) expert like me”. In response to the valuable feedback received from experts during the initial survey phase, several adjustments were made to enhance the precision and significance of the results. These modifications were implemented with careful consideration of the experts' advice, and the changes are outlined below:

1. Including the option "I don't know" in the Likert scale was a notable modification. This change was made in response to the first expert's criticism, which recognised that respondents' experience with particular topics may vary widely. By allowing for participants who might not have clear answers to every question, this option aims to collect more accurate and nuanced responses.
2. Enhanced Target Audience: In response to the observation made by the second expert, the second round of the survey was designed to explicitly target experts who possess knowledge of the ecological side of water. To ensure that the questions are answered by experts who are knowledgeable about the pertinent ecological issues, a change was made to the questionnaire to better match the expertise of the respondents. The goal of the survey is to

collect more specialised and intelligent replies by limiting the target audience, which will improve the overall quality of the data gathered.

The questionnaires were designed based on the experts' comments, so the results from the first round were ignored to avoid uncertain responses for those who did not know about some questions and to collect more accurate responses from those who have specialised in the ecology of water.

The second-round survey was distributed to a total of 454 participants, comprising 359 individuals contacted via direct email and an additional 95 through ResearchGate. These participants were specialists in the ecology of water hailing from various countries. However, the number of responses received was limited, with only 30 participants providing feedback.

The formula for the prevalence study using the online Raosoft calculator (Raosoft, 2004) was used to determine the sample size for the expert's population. The parameters included a 90% confidence level and a 10% margin of error. The response distribution depended on the skewness of the responses for each question, with the highest skewness (response distribution) being 17% and the second highest 13%. The calculated required sample sizes were 36 and 29. Clearly, the 30 responses received is an adequate sample size based on this analysis for all but one question, for which it is slightly smaller than would be ideal.

5.3.2 Analysis of the questionnaire responses

The analysis below related to the data was conducted to determine the final weights for ecological criteria (temperature and light). This analysis aimed to establish the central tendency and mitigate skewness in the data, ensuring more accurate weights for the ecological criteria.

Figure 5-3 reports the importance rating for 21 statements in the context of ecological criteria for rainwater harvesting. These statements cover the criteria that effect plant and organisms in the Aquatic ecosystem. The majority of total responses 74% rated all the various propositions as either most important 30%, important 28% and moderately important 16%. The indication of these high percentages means these criteria have a significant effect in terms of ecosystems. However, 13% of total responses were slightly important 7% or not important (6%). These percentages were calculated based on eq.(5-2). Additionally, the total response to statements "I don't know" was 12% the majority of these were in statements 3, 21, 13, 5, 19, 20, 18, and 15. The number of participants who gave the response "I don't know" was 9, 9, 8, 7, 7, 6, and 6, respectively.

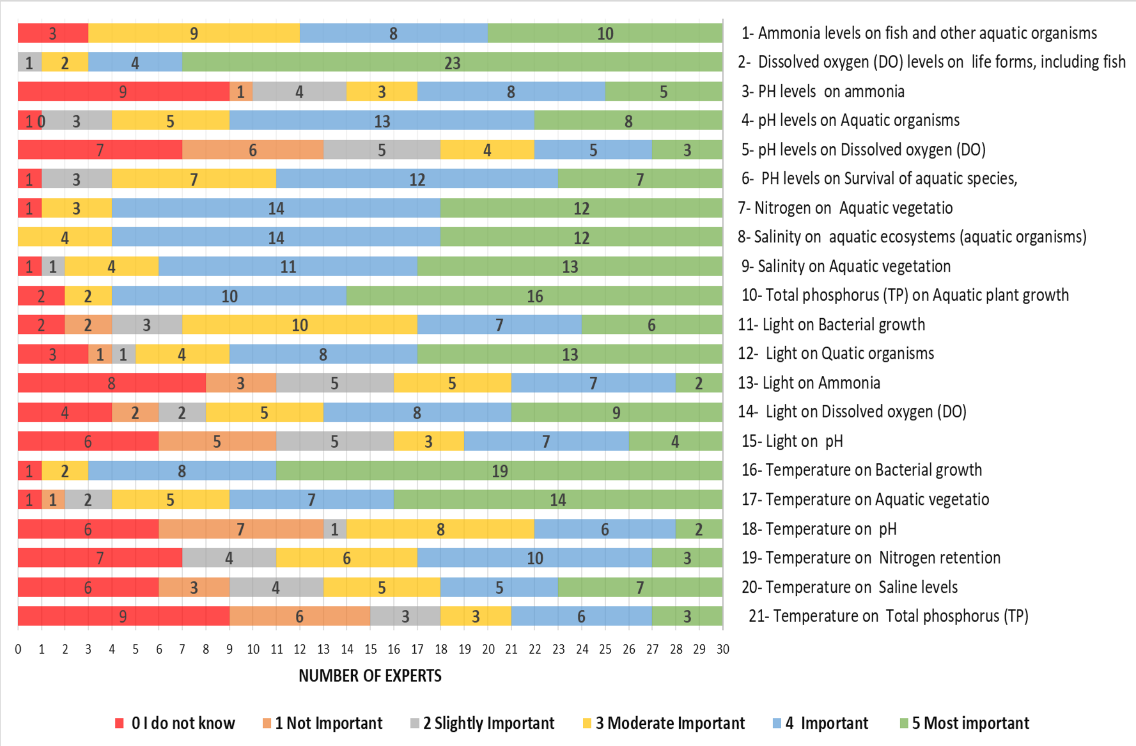

Figure 5-3 The importance of statements related to ecological criteria.

$$\text{PSR} = \frac{\sum_{j=1}^{21} S_j}{\sum_{j=1}^{21} R_j} \times 100 \qquad (5\text{-}2)$$

Where:

PSR: The percentage of similar responses (e.g. most important).

S_i: Responses that are similar across 21 statements (e.g. most important).

R_j: Total experts' responses for all statements.

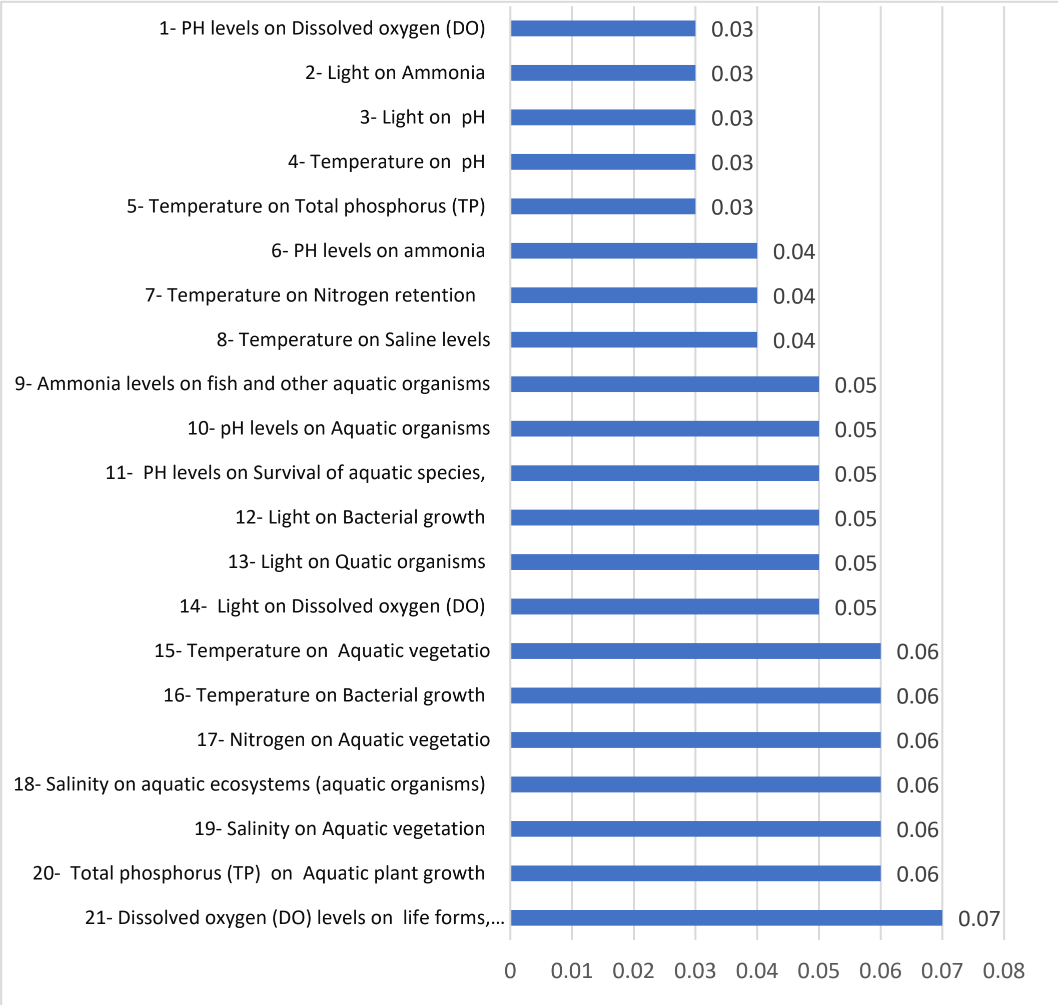

Figure 5-4 Weights of criteria affecting the ecosystem according to experts' opinions.

Figure 5-4 shows the normalisation rank as percentages of the ecological criteria on the aquatic system for all groups. The normalisation weights for each criterion were calculated based on eq. (5-2). The higher rank was for the effect of dissolved oxygen (DO; statement number 21), which was 0.07, while the lower was for statements 1 to 5, which were 0.03 for each statement. In addition, the rank for each statement from 6–8, 9–14, and 15-20 were 0.04, 0.05, and 0.06, respectively.

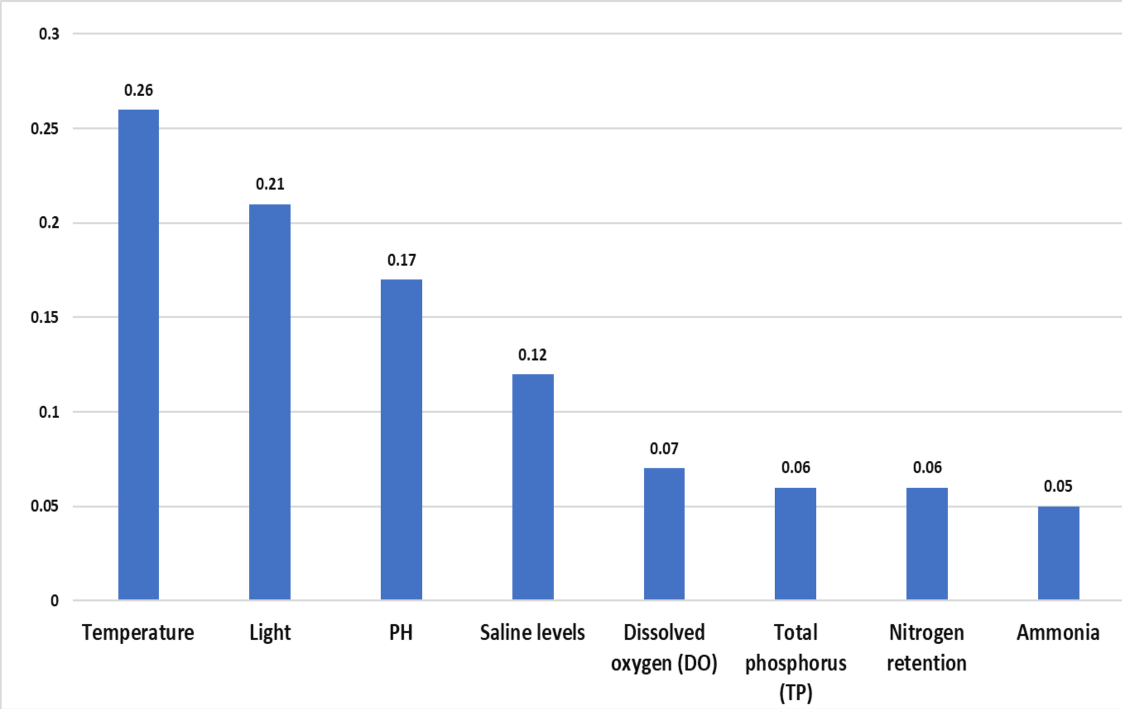

Figure 5-5 Total of normalisation rank for each criterion

Figure 5-5 shows the total effect for each criterion. These percentages were calculated based on the sum of the effects for each criterion in Figure 5-4. For example, the temperature criterion has a 0.26 percentage effect from six statements (statements 4, 5, 7, 8, 15, and 16), with a weighting from each statement of 0.03, 0.03, 0.04, 0.04, 0.06, and 0.06, respectively. The most significant criteria, as indicated by their respective magnitudes, were temperature and light, with values of 0.26 and 0.21, respectively. The pH level was closely followed with a value of 0.17, while the salinity level was recorded at 0.12. Conversely, the criteria that were shown to have the smallest influence were dissolved oxygen (DO) with a value of 0.07, total phosphorus (TP) with a value of 0.06, nitrogen with a value of 0.06, and ammonia with a value of 0.05.

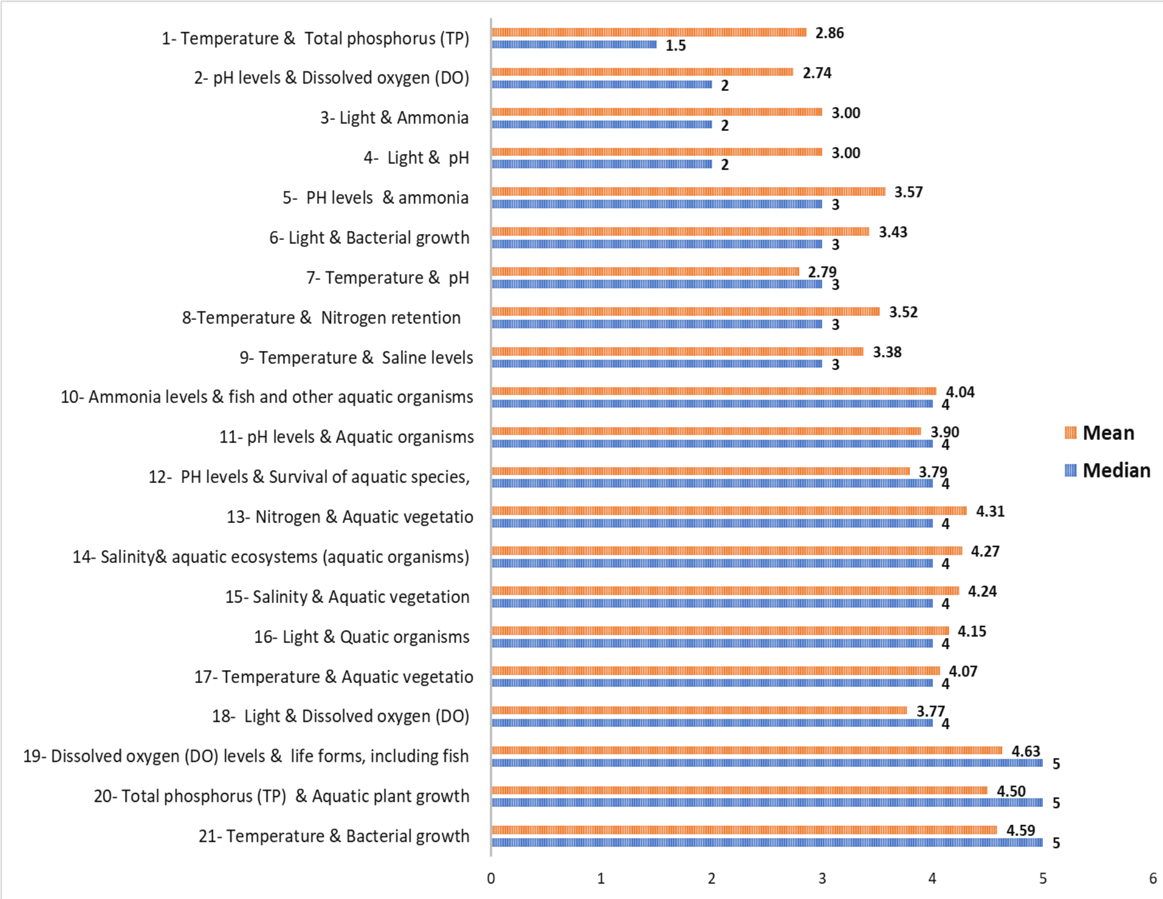

Figure 5-6 Mean and median statements of each criterion based on experts' opinion.

Figure 5-6 illustrates the distribution of mean and median for responses obtained from a survey of 30 experts in the ecology. The disparities between the mean and median responses exhibit variations across the statements. Notably, the first four statements (1, 3, 4, and 2) demonstrate a larger gap between their mean and median values. The specific values for this difference are 1.36 (15%), 1 (11%), 1 (11%), and 0.74 (8%), respectively. Following closely are seven statements (5, 8, 20, 6, 21, 9, and 19) with smaller yet notable differences, approximately 35% of which were as follows: 0.57 (6%), 0.52 (6%), 0.5 (5%), 0.43 (5%), 0.41 (5%), 0.38 (4%), and 0.37 (4%), respectively. Conversely, statements 13, 14, 15, 18, 7, 12, 16, 11, 17, and 10 exhibit a narrower gap between their mean and median values, amounting to approximately 20%. This range includes values from 0.31 (3%) to 0.04 (0.4%). These statements reflect a closer alignment between the central tendency measures, indicating a more symmetrical distribution of responses. The analysis reveals varying degrees of skewness in the distribution of responses across the statements, with some statements showing a pronounced disparity between mean and median, while others demonstrate a more balanced distribution.

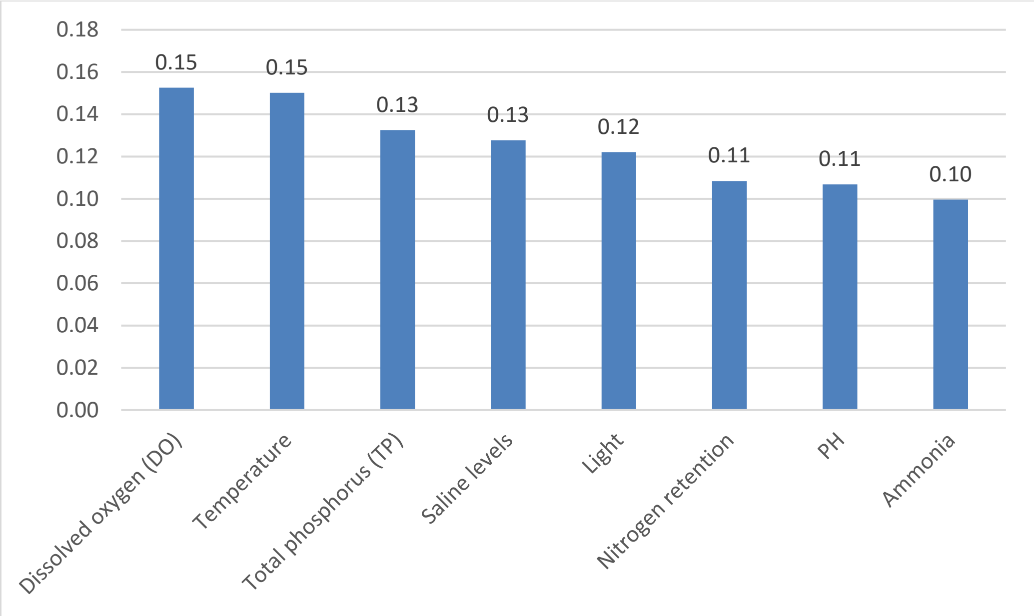

Figure 5-7 The normalisation of weights of ranking criteria Q30

Figure 5-7 shows the normalisation weights effect of the ecological criteria on the aquatic system. The percentage of normalisation weights was calculated based on the sum of the expert's ranking for each criterion, divided by the sum of expert's opinions for all ranking criteria.

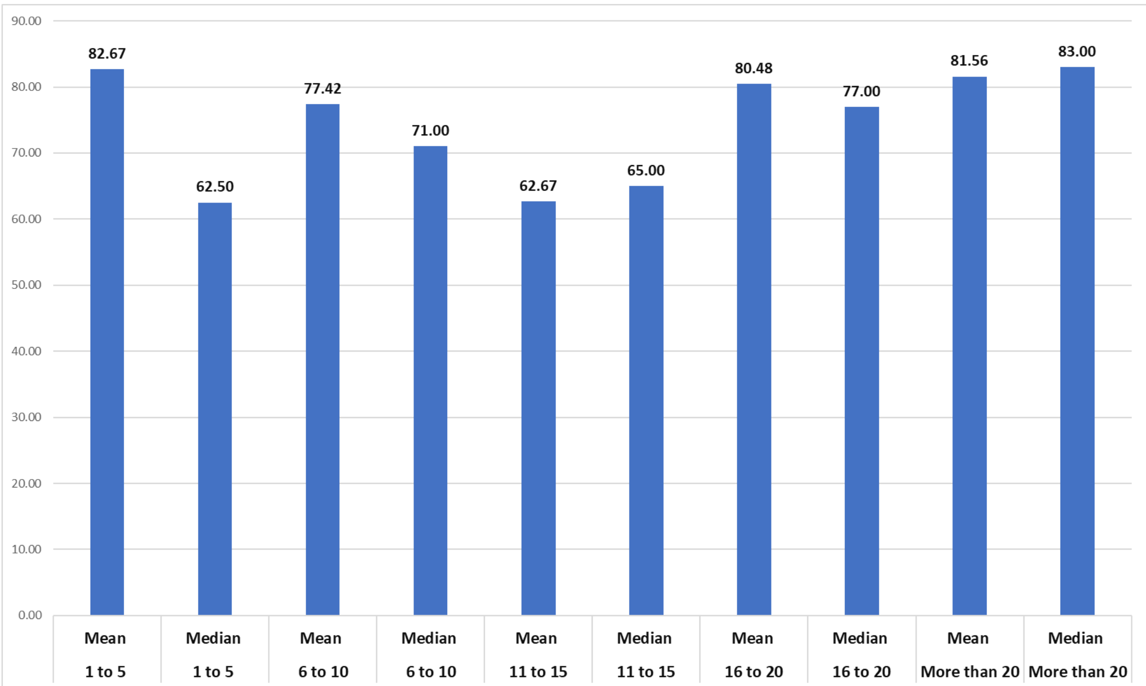

Figure 5-8 Mean and median responses of experts across different groups categorized by years of experience.

Figure 5-8 demonstrates the aggregate mean and median responses of experts categorized by years of experience. The differences between the mean and median were varying for each group. The differences between mean and median for 1–5 and 6–10 years' experience were 20.17 and 6.42 respectively, while the differences between mean and median for 11–15, 16–20, and more than 20 years' experience were 2.33, -3.48, and -1.44 respectively. A small gap between mean and median for the last three groups (11–15, 16–20, and more than 20 years' experience) indicates a more normal distribution, while a large gap for the first two groups (1–5) and (6–10) years' experience signals potential skewness caused by outliers. Outliers may account for the greater disparity between the 1-5 years and 6-10 years' experience categories, with a few individuals possessing significantly lower or higher levels of experience. On the contrary, the narrower experience ranges indicated by the smaller gap between 11-15 years, 16-20 years, and more than 20 years of experience indicate a greater concentration of specialists. The observed variation can be attributed to the distinct expertise prerequisites or attributes associated with the roles comprising each category.

Figure 5-9 displays the normalisation weights for three expertise groups: one for all expertise levels (1-5, 6-10, 11-15, 16-20, and over 20 years), another for 1-5 and 6-10 years of expertise, and a third for 11-15, 16-20, and over 20 years of expertise. This classification conducted based on the analysis in Figure 5-8 which shows the gap between these different groups. Figure 5-9 there are no variations among the groups for 10 statements: 2, 4, 5, 9, 11, 16, 18, 19, 20, and 21. However, for the remaining statements, differences exist. Specifically, differences are observed in 7 statements solely for the second group (1-5 and 6-10 years), namely: 1, 6, 7, 8, 13, 14, and 17. On the other hand, the differences in the other 4 statements are exclusive to the third group (11-15, 16-20, and over 20 years). The first group (all groups) was matched with at least one group for each statement. The calculations were conducted based on separating the responses of experts for each group and then finding the normalisation weight for each group based on eq. (5-2).

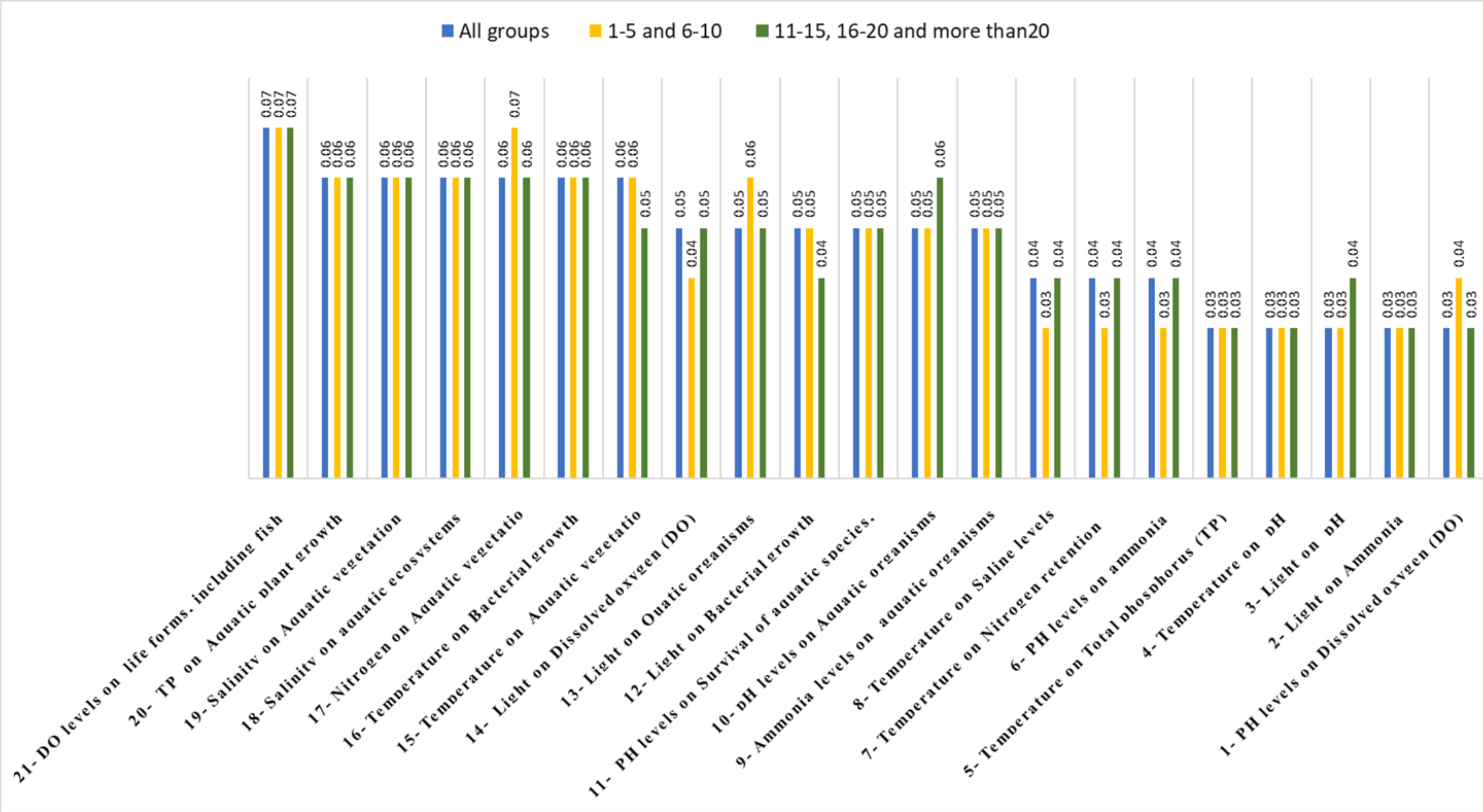

Figure 5-9 Normalisation weights for different groups categorised by years of experience

5.3.2.1 Bell shape analysis to test the distribution for sample data

The normal curves are a set of probability distributions that exhibit a consistent form resembling a bell. The term "distribution" refers to a summary of the frequencies of the various values or ranges of values of a random variable. A random variable is a function that maps elements from a probability space to elements in a measurable space called the state space (Sartori, 2006).

There are three parameters used to identify the centre of distribution: mean, median, and mode. The mean is used to measure the central tendency, and the centre of distribution is estimated based on the centre of tendency. The median is the score located precisely at the midpoint of a given set of values, with half the scores surpassing the median and the other half falling below it, and mode is the score that occurs most frequently (Sartori, 2006). The mean, median, and mode of a normal distribution are all equal and correspond to the value at which the curve reaches its maximum height.

The average, often known as the mean, is an effective method for determining the midpoint of a set of data that are uniformly distributed. However, if the data are heavily clustered on one side, the average can be distorted by extremely high or low values. In such instances, it is preferable to utilise the median, which represents the central value when the numbers are organised in ascending or descending order. Normal distributions, characterised by a uniform distribution of values, are suitable for utilising the mean (Sartori, 2006).

The primary purpose of a bell curve, which is also referred to as a normal distribution, is to illustrate the symmetrical nature of data distribution around a central mean. This curve is frequently employed in statistics to analyse patterns in data sets and determine the probability of different values occurring. Evaluate the data distribution of 21 statements by applying the bell-shaped equation to each statement. Refer to Figure 5-10 through Figure 5-30 for visual depictions of histogram and the normal distribution which have conducted by excel and Minitab respectively. The absence of symmetry in the distribution of the bell-shaped in most of figures for the group (1-10 years’ experience) indicates that the data are not following a normal distribution. The mean is very sensitive for the skewness data, which does not work with data with outliers, so it is not the best choice to use the group (1-10 years of experience) to represent these data, so the excluded this group may be the best option to represent the central tendency of these data, which is less affected by the outlier. The distributions in Figure 5-10, Figure 5-13,Figure 5-15, Figure 5-17, Figure 5-29 and Figure 5-30 exhibit left skewness for the group with 1–10 years of experience, while approaching a normal distribution for groups with more than 10 years of experience. Conversely, Figure 5-11,Figure 5-19, Figure 5-23 and Figure 5-26 display right skewness for the 1–10 years' experience group. Figure 5-12, Figure 5-14, Figure 5-16, Figure 5-18, Figure 5-21, Figure 5-22, Figure 5-25, Figure 5-24, Figure 5-27 and Figure 5-29 show distributions that closely resemble normal distributions for both the 1–10 years' and >10 years' experience groups. Finally, Figure 5-28 and Figure 5-30 demonstrate close to normal distribution for both groups. Based on this analysis, which includes Figure 5-8 illustrating a significant gap between the mean and median for the 1-10 years’ experience group—indicating lower confidence and higher skewness—this group, representing 30% of the data, was excluded from the study.

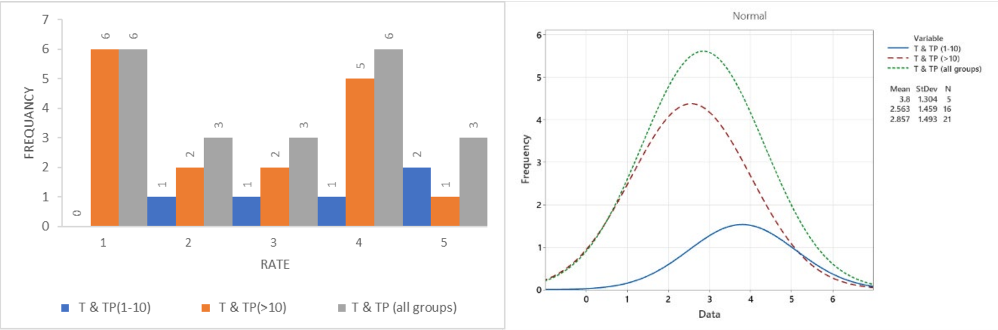

Figure 5-10 Temperature on total phosphorous

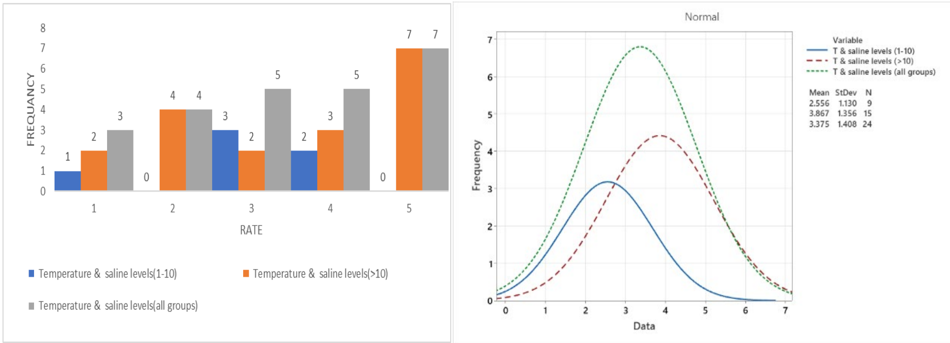

Figure 5-11 Temperature on saline level

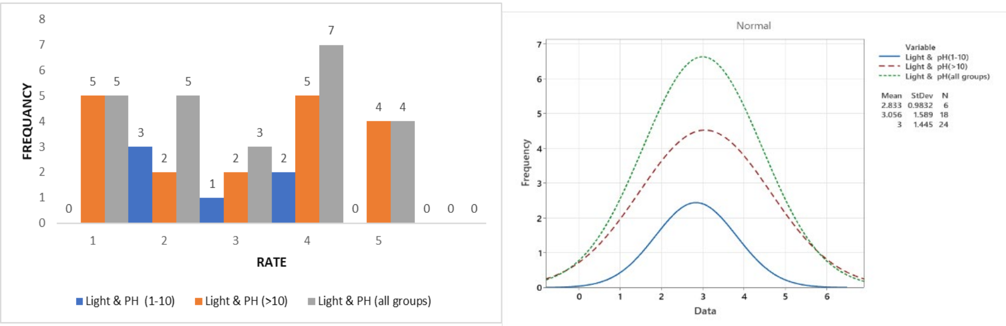

Figure 5-12 Light on pH

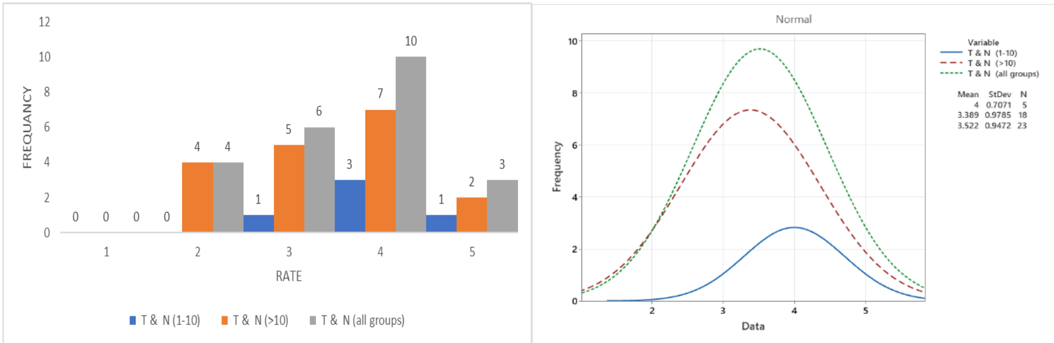

Figure 5-13 Temperature on nitrogen

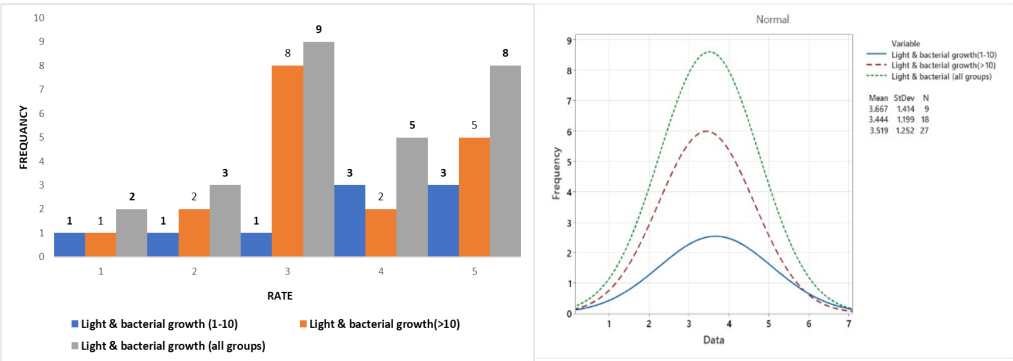

Figure 5-14 Light on bacteria growth

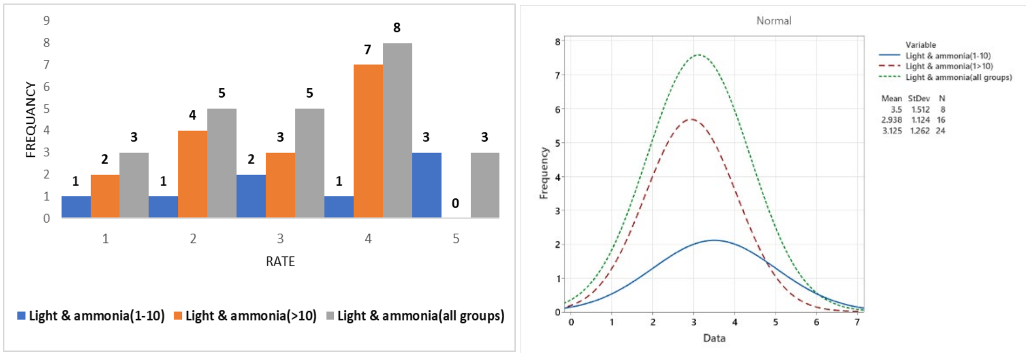

Figure 5-15 Light on ammonia

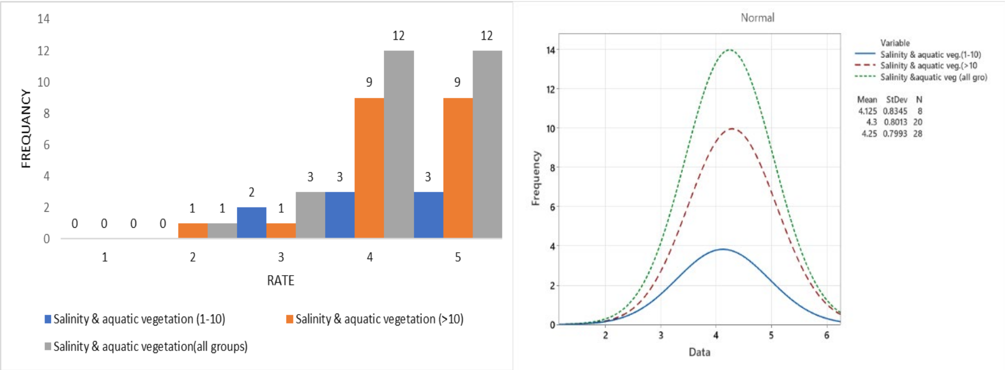

Figure 5-16 Salinity on aquatic vegetation

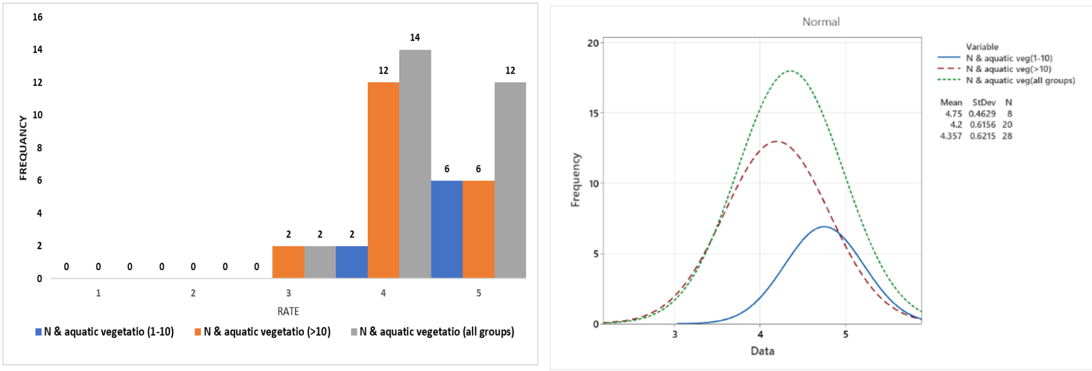

Figure 5-17 Nitrogen on aquatic vegetation

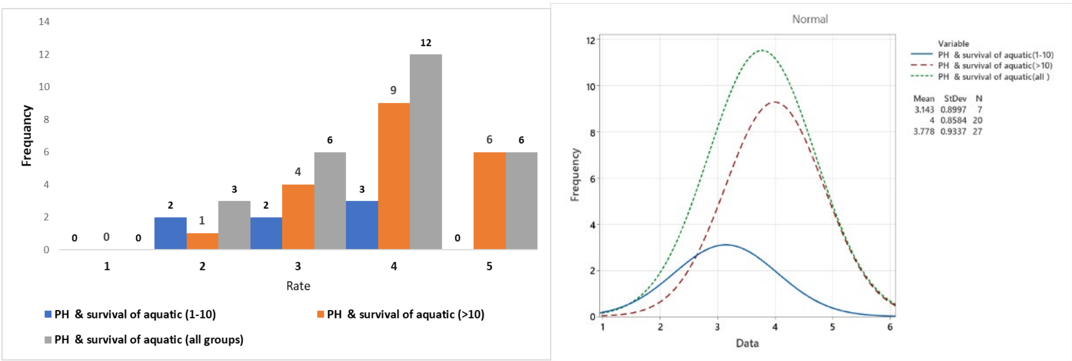

Figure 5-19 pH on survival of aquatic

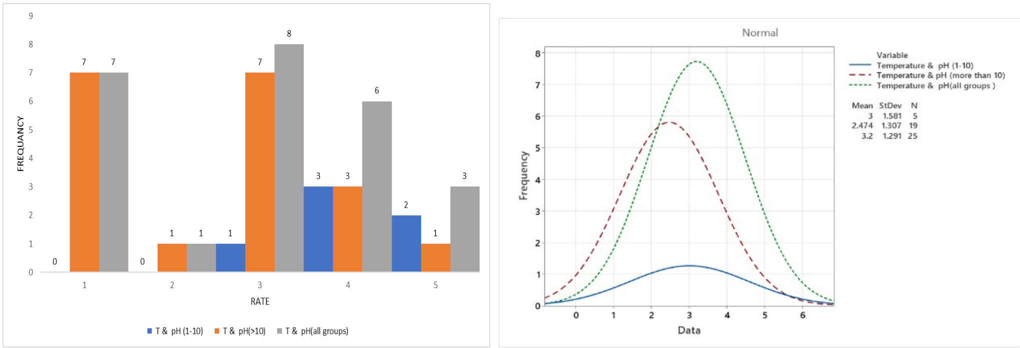

Figure 5-18 Temperature on pH

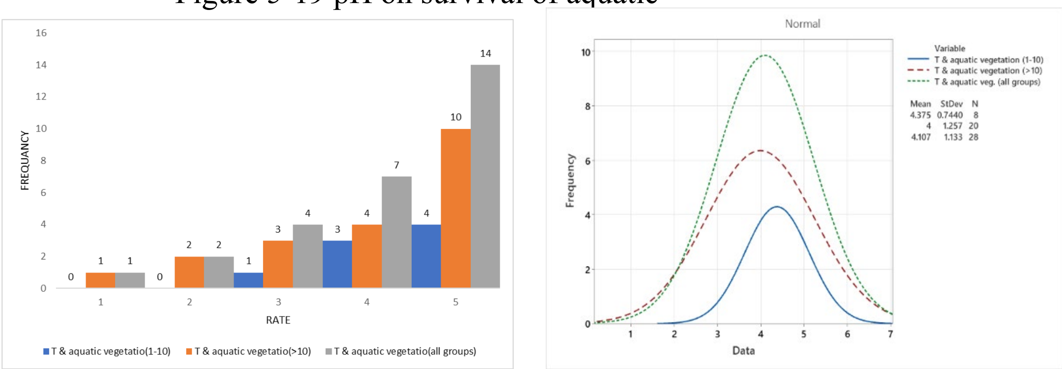

Figure 5-20 Temperature on aquatic vegetation

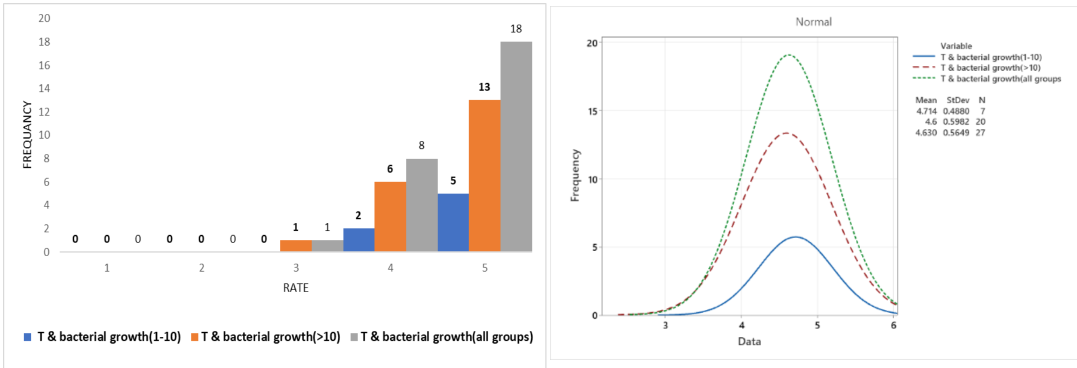

Figure 5-21 Temperature on bacteria growth

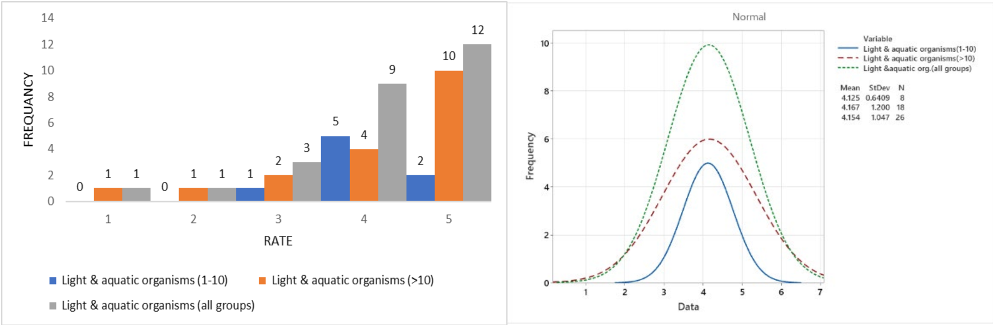

Figure 5-22 Light and aquatic organisms

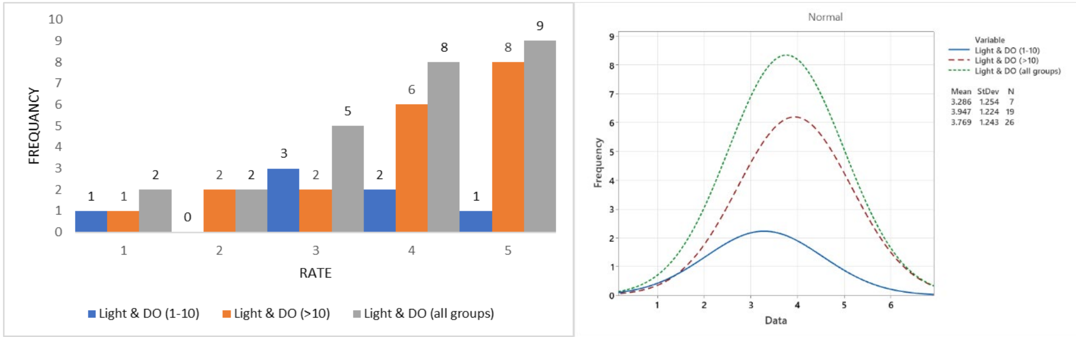

Figure 5-23 Light on dissolved oxygen (DO)

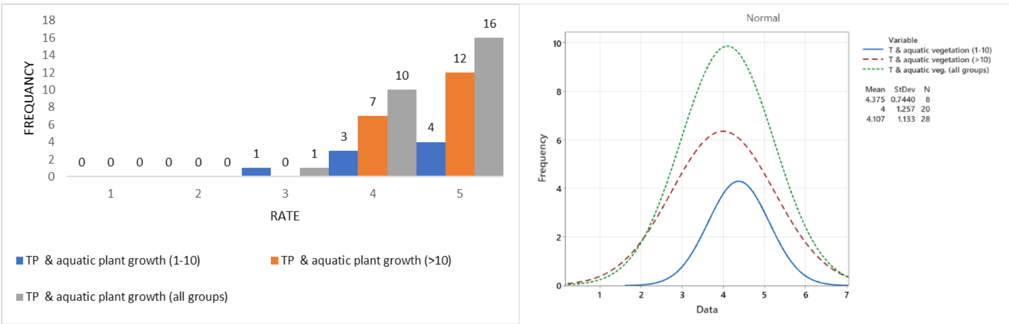

Figure 5-25 Total phosphorous (TP) on plant growth

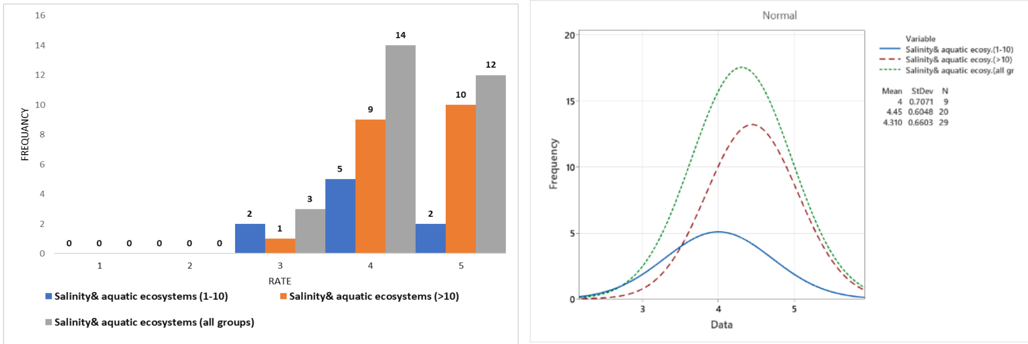

Figure 5-24 Salinity on aquatic ecosystem

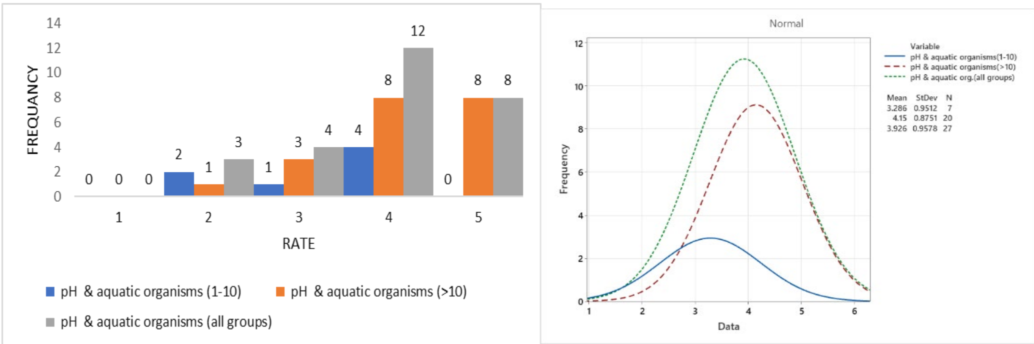

Figure 5-26 pH on aquatic organisms

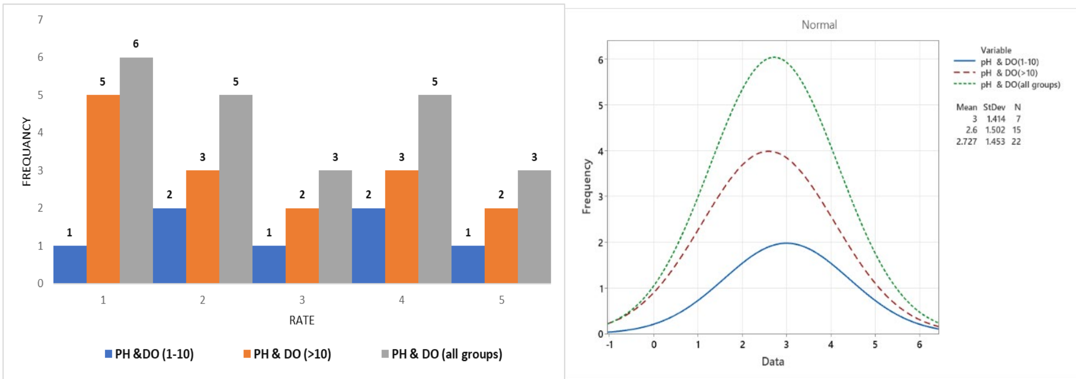

Figure 5-27 pH on dissolved oxygen (DO)

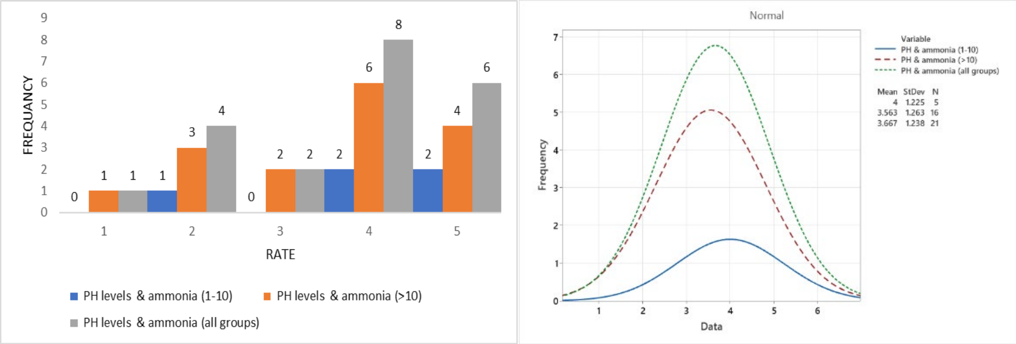

Figure 5-28 pH level on ammonia

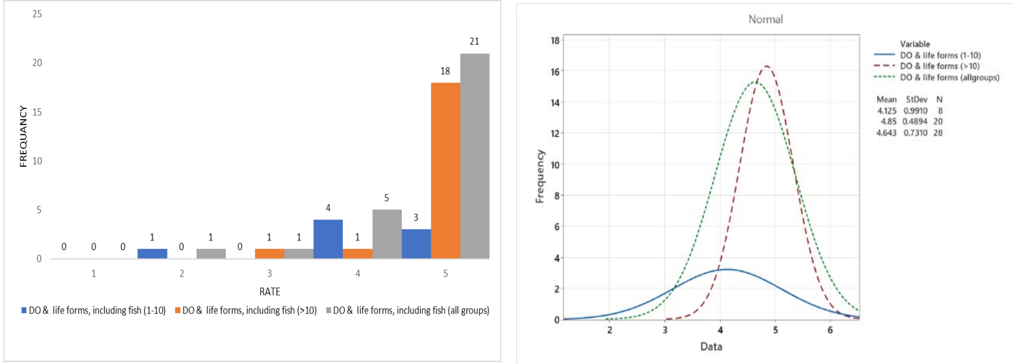

Figure 5-29 Dissolved oxygen (DO) on life forms including fish

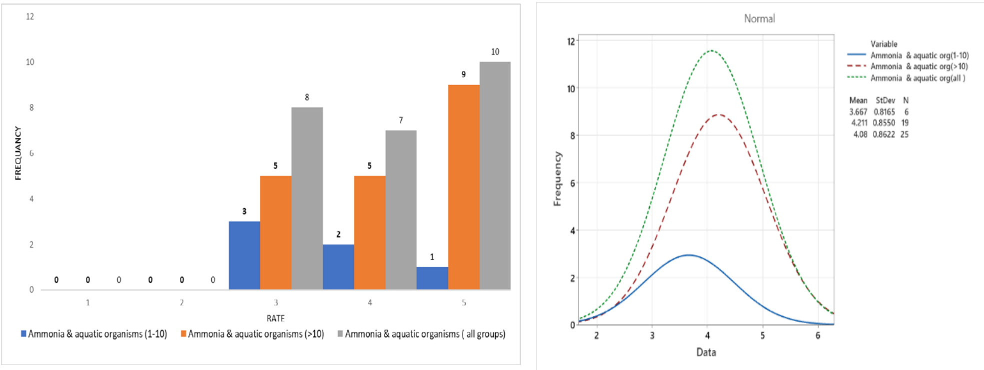

Figure 5-30 Ammonia on aquatic organisms

5.3.2.2 Univariate Statistical Tests

For each of 21 statements for ecological criteria, a one-way ANOVA test was used to investigate the differences between the three groups of experience (<10 years, >10 years and all groups). This method is useful to determining whether each of the 21 statements varies between three groups. The one-way ANOVA test was used to examine the following hypotheses:

H0: There are no differences among the three groups.

Ha: There is at least one difference between the three groups.

The 90% confidence interval (CI) was used with a significance level of $\alpha = 0.1$.

The analysis indicated that most p-values were not statistically significant as shown in Table 5-1, except for two statements: Statement 8 (Temperature on saline level) and Statement 21 (Dissolved oxygen on life forms), with p-values of 0.08 and 0.054, respectively, both of which are statistically insignificant. However, three other statements—Statement 10 (pH level on aquatic organisms), Statement 11 (pH level on the survival of aquatic species), and Statement 17 (Nitrogen on aquatic vegetation)—had p-values of 0.115, 0.107, and 0.101, respectively. These values are close to the α level, suggesting potential differences between the groups. Notably, these differences were observed in the group of experts with less than 10 years of experience see Figure 5-9. Consequently, this group was excluded from the survey to ensure more accurate weightings.

Table 5-1 Comparisons between three groups of experience (<10years, >10years and all groups).

Statements	P-value	Significance	Experience groups, 90% (CI)		
			<10 years	>10 years	All groups
1- pH level on Dissolved oxygen	0.838	No	(2.068, 3.932)	(1.964, 3.236)	(2.202, 3.253)
2- Light on ammonia	0.592	No	(2.751, 4.249)	(2.408, 3.467)	(2.693, 3.557)
3- Light on pH	0.949	No	(1.833, 3.834)	(2.478, 3.633)	(2.500, 3.500)
4- Temperature on pH	0.205	No	(2.005, 3.995)	(1.963, 2.984)	(2.755, 3.645)
5- Temperature on total phosphorus (TP)	0.267	No	(2.699, 4.901)	(1.947, 3.178)	(2.320, 3.395)
6- pH level on ammonia	0.792	No	(3.061, 4.939)	(3.037, 4.088)	(3.208, 4.125)
7- Temperature on Nitrogen retention	0.444	No	(3.293, 4.707)	(3.016, 3.761)	(3.192, 3.851)
8- Temperature on saline level	0.08	Yes	(1.802, 3.309)	(3.283, 4.451)	(2.913, 3.837)
9- Ammonia level on fish and other aquatic organisms	0.404	No	(3.081, 4.252)	(3.882, 4.540)	(3.793, 4.367)
10- pH level on aquatic organisms	0.115	No	(2.699, 3.873)	(3.803, 4.497)	(3.627, 4.225)
11- pH level on survival of aquatic species	0.107	No	(2.699, 3.873)	(3.803, 4.497)	(3.627, 4.225)
12- Light on bacteria growth	0.911	No	(2.962, 4.371)	(2.946, 3.943)	(3.112, 3.925)
13- Light on aquatic organisms	0.996	No	(3.498, 4.752)	(3.749, 4.584)	(3.806, 4.501)
14- Light on dissolved Oxygen (DO)	0.486	No	(2.502, 4.070)	(3.472, 4.423)	(3.362, 4.176)
15- Temperature and aquatic vegetation	0.734	No	(3.702, 5.048)	(3.574, 4.426)	(3.747, 4.467)
16- Temperature on bacteria growth	0.901	No	(4.354, 5.075)	(4.387, 4.813)	(4.446, 4.813)
17- Nitrogen on aquatic vegetation	0.101	No	(4.394, 5.106)	(3.975, 4.425)	(4.167, 4.547)
18- Salinity on aquatic ecosystem (aquatic organisms)	0.234	No	(3.638, 4.362)	(4.207, 4.693)	(4.109, 4.512)
19- Salinity on aquatic vegetation	0.874	No	(3.649, 4.601)	(3.999, 4.601)	(3.995, 4.505)
20- Total phosphorus (TP) on aquatic plant growth	0.576	No	(4.033, 4.717)	(4.410, 4.853)	(4.370, 4.741)
21- Dissolved oxygen on life forms	0.054	Yes	(3.712, 4.538)	(4.589, 5.111)	(4.422, 4.864)

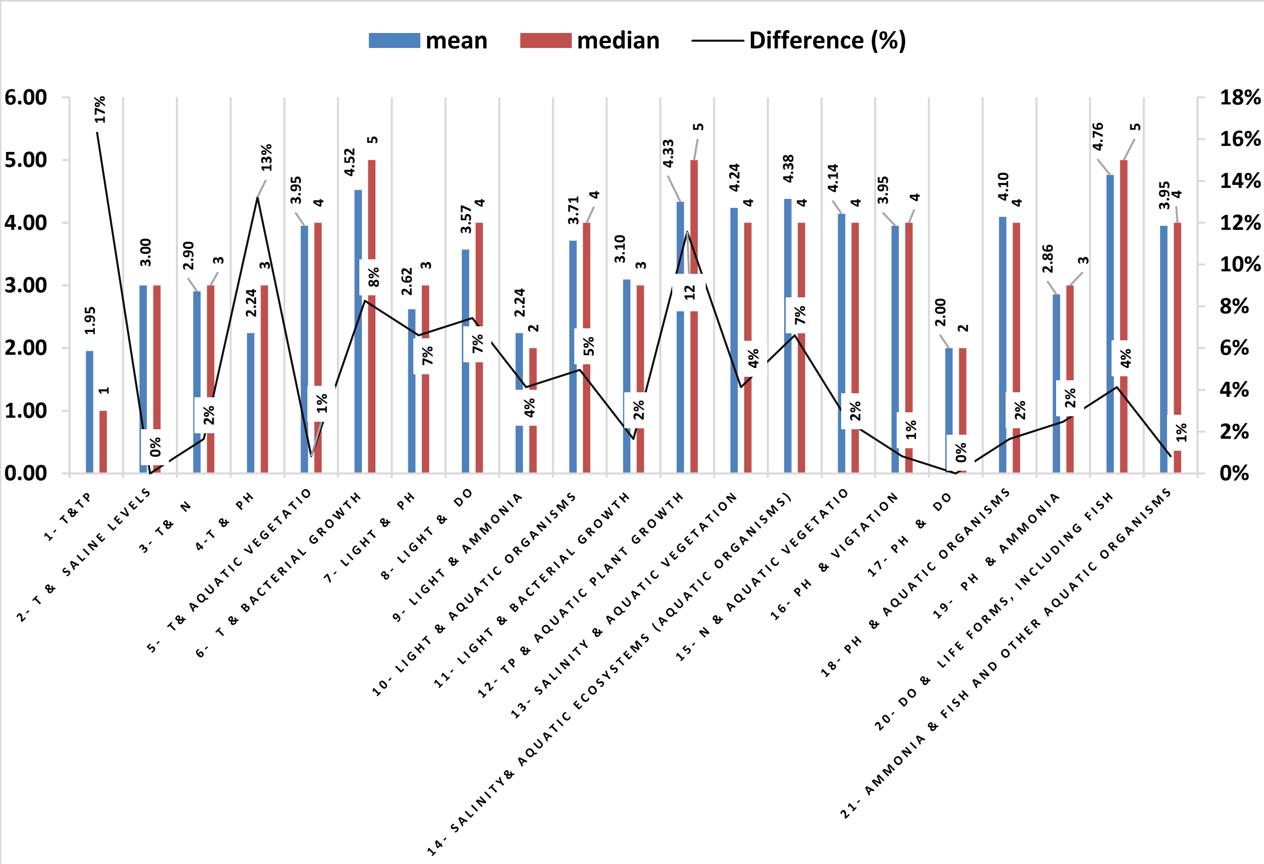

Figure 5-31 Mean and median for data collected from experts (more than 10 years of experience).

The Figure 5-31 illustrates the differences between mean and median of expert responses who are experts with more than 10 years. Notably, the statement 1 (temperature (T) & total phosphorus (TP)) exhibited the largest disparity followed by the statement 4 (temperature &pH), statement 12 (total phosphorus (TP) & aquatic plant growth), statement 6 (temperature & bacteria growth), statement 7 (light & pH), statement 8 (light and dissolved oxygen (DO)),statement 14 (salinity & aquatic ecosystem), statement 10 (light & aquatic organisms), statement 9 (light & ammonia), statemen13 (salinity & aquatic vegetation), statemen20 (dissolved oxygen (DO) & life form including fish), statemen 3(temperature & nitrogen), statemen11 (light & bacteria growth), statemen15 (nitrogen & aquatic vegetation), statemen18 (pH and aquatic vegetation), statemen 19 (pH and ammonia), statemen5 (temperature & aquatic vegetation), statemen16 (pH & vegetation), statemen21 (Ammonia & fish and other aquatic organisms). The differences between mean and median for these criteria were 17%, 13%, 12%, 8%, 7%,7%, 7%, 5%, 4%, 4%,4%, 2%, 2%, 2%, 2%,2%, 1%, 1% and 1%.

Conversely, Statements 2, and 17 exhibited no differences between the mean and median values, indicating that there was no skewness.

Determine the total effect of the independent criteria (temperature and light) on the dependent criteria (vegetation and organisms). The mediation analysis reveals intriguing insights into the normalization of the total effects of temperature on both vegetation and aquatic organisms when mean values were employed, exhibiting a normalization rate of 49%. Furthermore, the normalization of the total effect of light on vegetation and aquatic organisms was noted to be 51%.

In contrast, when median values were utilized, the normalization of the total effect of temperature on vegetation and aquatic organisms displayed a marginally higher rate of 51%. Conversely, the effect of light under these conditions exhibited a normalization rate of 49%.

As a result, The examination of differences between mean and median holds significance within the context of mediation analysis. It is essential to assess the effects of individual criteria by maintaining all other variables at their mean values, except for one criterion where the median is applied. This procedure should be iterated for each criterion (has gap between mean and median), facilitating a detailed exploration of each criterion's specific influence on the outcomes of the mediation analysis.

See Table 5-2 illustrates the effect of the exchange mean to median for each criterion on mediation analysis (taking into consideration the other criteria have mean values for each statement). Notably, statements 1, 4, 12, and 7 exhibit differences of 17%, 13%, 12%, and 7%, respectively, in mediation analysis outcomes when transitioning from mean to median for each statement, the mediation analysis results for temperature and light (T, L) for these statements were (48%, 52%), (53%, 47%), (50%, 50%), and (47%, 53%), respectively. These values differ from those obtained using the mean (49%, 50%).

Conversely, despite an 8% difference between mean and median for statement 6, there was no discernible change in mediation analysis results for temperature and light when employing the median instead of the mean. This is attributed to statement 6 representing a direct effect, necessitating a higher percentage difference between mean and median to exert an impact on the outcomes of the mediation analysis.

These findings highlight the sensitivity of mediation results to central tendency indicators. The differences in normalisation rates highlight the importance of methodological concerns in interpreting temperature and light impacts on the examined ecological components. This sophisticated perspective adds to the wider discussion of statistical methodologies in ecological research by emphasising the need of meticulously considering statistical choices in mediation analyses for robust and correct interpretations.

According to this analysis, data with percentage differences between mean and median levels ≤ 7% exhibit consistent outcomes in mediation analysis. Therefore, the mean is considered the optimal choice for representing the central tendency of the data, except for statement 7 (Light & pH). In this case, where there is a difference in mediation analysis between mean and median, the median is preferred to better handle outliers.

Conversely, for data with percentage differences between mean and median levels ≥ 8%, variations in outcomes of mediation analysis are observed. In such instances, the median is recommended for accurately representing the centre of the data, except for statement 6 (Temperature & Bacteria Growth). Here, despite the percentage difference, the mean is favoured as it yields similar outcomes in mediation analysis.

Table 5-2 Mediation analysis exploring the impact of differences between mean and median.

NO.	Statement number	Criteria	Mean	Median	Differences between mean and median (%)	Mediation analysis %			
						Based on Mean values		Based on Median value for one statement for each trail.	
						Temperature	Light	Temperature	Light
1	1	T on TP	1.95	1	17	49	51	48	52
2	4	T on PH	2.24	3	13	49	51	53	47
3	12	TP & aquatic plant	4.33	5	12	49	51	50	50
4	6	T on bacterial growth	4.52	5	8	49	51	49	51
5	7	Light on pH	2.62	3	7	49	51	47	53
6	8	Light on DO	3.57	4	7	49	51	49	51
7	14	Salinity on aquatic ecosystems (aquatic organisms)	4.38	4	7	49	51	49	51
8	10	Light on aquatic organisms	3.71	4	5	49	51	49	51
9	9	Light on ammonia	2.24	2	4	49	51	49	51
10	13	Salinity on aquatic vegetation	4.24	4	4	49	51	49	51
11	20	DO on life forms, including fish	4.76	5	4	49	51	49	51
12	3	T on N	2.9	3	2	49	51	49	51
13	11	Light on bacterial growth	3.10	3	2	49	51	49	51
14	15	N on aquatic vegetation	4.14	4	2	49	51	49	51
15	18	pH on aquatic organisms	4.10	4	2	49	51	49	51
16	19	PH on ammonia	2.86	3	2	49	51	49	51
17	5	T on aquatic vegetation	3.95	4	1	49	51	49	51
18	16	PH & vegetation	3.95	4	1	49	51	49	51
19	21	Ammonia & fish and other aquatic organisms	3.95	4	1	49	51	49	51

Chapter 6: A Novel, Ecology-Inclusive, Hybrid Framework for Rainwater Harvesting Site Selection in Arid and Semi-Arid Regions

This chapter has been submitted as a paper to the journal. It aims to combine the current structural criteria used for rainwater harvesting (RWH) site selection with new ecological criteria to create a comprehensive, hybrid framework for achieving a sustainable system. The proposed framework was validated through questionnaires sent to experts, and their responses were analysed in depth in Section 5.3.2. Subsequently, the framework was applied in a case study in Section 6.5.

This chapter has been submitted as "A Novel, Ecology-Inclusive, Hybrid Framework for Rainwater Harvesting Site Selection in Arid and Semi-Arid Regions." The first author conducted the foundational research for the paper, wrote the initial draft, and revised in response to feedback from other authors.

This paper has been accepted as:

Ahmed, S., Jesson, M., & Sharifi, S. (2025). A Novel, Ecology-Inclusive, Hybrid Framework for Rainwater Harvesting Site Selection in Arid and Semi-Arid Regions. Water Resources Management, https://link.springer.com/article/10.1007/s11269-024-04073-7

6.1 ABSTRACT:

The water crisis is a critical issue, particularly in arid and semi-arid regions where rainfall is limited. Rainwater harvesting systems have been introduced in many locations to capture what rainfall does occur, but selection of the optimum site is vital to ensure efficient capture and storage. Over the past few decades, a range of frameworks for assessing the suitability of rainwater harvesting sites have been suggested. These frameworks were designed using what are termed structural criteria (biophysical and socio-economic) to rank potential sites. However, existing frameworks do not account for ecological criteria, which are essential for ensuring environmental protection, maintaining biodiversity, water quality improvement, climate resilience, regulatory compliance and sustainability of the system. In this paper, this deficiency is addressed by the development of a hybrid framework which combines structural criteria with important ecological criteria. The inter-relationships of ecological criteria are complex, with "independent" criteria affecting the "mediator" criteria (e.g. dissolved oxygen, phosphorous concentration) which directly impact on ecological standards, i.e. the "dependent" criteria such as number of aquatic organisms. This study focuses on the key independent criteria of temperature and light, though the hybrid framework could easily be expanded to include additional ecological criteria, dependent on the region it is applied to. The temperature of water affects the levels of total dissolved solids, nitrogen, Chlorophyll-a, turbidity, and bacterial growth. As the temperature rises, dissolved oxygen decreases. Higher temperatures also increase microbial activity and photosynthesis. Light intensity directly affects pH, dissolved oxygen, and ammonia levels, but has an inverse impact on bacteria, nitrite, total phosphorus, and transparency. The framework encompasses independent, mediator and dependent ecological criteria identified from the literature, and the importance of each (represented as weightings in the framework) have been quantified through a robust combination of data analysis and expert opinion. The importance of the inclusion of the ecological criteria is demonstrated through a case study of Erbil Province in Iraq, where both climate change and human actions have seriously reduced water supplies in the past twenty years. A number of proposed rainwater harvesting sites are assessed via a structural framework and the new hybrid framework. The hybrid framework was implemented in two scenarios: one incorporating biophysical, socio-economic, and ecological criteria, and the other only biophysical and socio-economic criteria. The results show that inclusion of these ecological criteria changes the ranking of the sites.

6.2 INTRODUCTION

Water is a crucial and precious natural resource (Al-Adamat, 2008). Water scarcity is a prevalent issue in numerous regions across the globe, with more than two billion people predicted to live in areas with severe water scarcity by 2050 according to the United Nations Environment Program (Field & Barros, 2014; Sekar

& Randhir, 2007). Water resource consumption has increased due to population growth, expansion of agricultural areas, and industrial development. As a result, these actions have caused more research to focus on surface water resources (Fatima Ezzahra El Ghazali et al., 2021).

Arid and semi-arid regions cover approximately 50 million square kilometres, or 35% of the Earth's surface, and have limited water resources, which causes challenges associated with water scarcity for crop production, drinking, and other purposes (Ziadat et al., 2012). These regions are categorised based on the annual rainfall they receive, with an annual rainfall ranging from 150–350mm and 350–700 mm of rainfall annually, respectively (A. Adham et al., 2016b). In addition, in these regions with water scarcity and high humidity, solar radiation leads to high evapotranspiration and temperatures. The relationship between precipitation and evaporation is termed the aridity index. Based on this index, regions can be classified as humid, subhumid, semiarid, arid, or extremely arid (Perez-Aguilar et al., 2021).

Rainwater harvesting (RWH) is a traditional technique employed to gather and store rainwater for diverse uses such as drinking water and agricultural applications (Prinz, 1996). RWH comes in two primary forms: harvesting from rooftops and harvesting from rainfall catchments (Critchely & Siegert, 1991). Several types of rainwater harvesting systems have historically been utilised in different countries such as Libya, Yemen, Egypt, northern Mexico, and southwestern USA, including check dams, dikes, ponds, small dams, cisterns, terracing, and wadi-beds (Oweis, 2012).

The first step in constructing a rainwater harvesting system (RWH) is identifying a suitable location, based on relevant criteria. This is often done via a framework which essentially takes a numerical score for each criterion – the score represents the suitability of the site in terms of that criterion - and merges these into a single numerical score which is used to rank the sites. Criteria included in current frameworks can be classified as either biophysical or socio-economic. Biophysical criteria encompass aspects such as climate (rainfall), agronomy (crop traits), hydrology (rainfall-runoff dynamics and intermittent watercourses), topography (land slope), and soil characteristics (structure, depth, and texture). Socio-economic criteria include factors like community expertise, labour force availability, societal preferences, population density, water regulations, land ownership systems, accessibility, and associated expenses (FAO, 2003; Oweis et al., 1998). The criteria may be classified as either quantitative, which refers to measurable qualities such as slope, rainfall (mm) and runoff (m^3s^{-1}), or qualitative, which refers to criteria that rely on assessment by stakeholders and experts (Ahmed et al., 2023a). In both cases, a method for converting the measured data or expert assessment into a numerical score must be defined, which arguably results in rather subjective outcomes. Developing such a framework is a complex process that requires determining the relevant criteria based on their degree of significance, classifying and grouping them into different types (e.g. biophysical, socio-economic or ecological criteria), obtaining a score for each group and then combining the group scores to obtain an overall site rating. Each criterion may be assigned a different weighting within the framework, quantifying the relative importance of each; similarly, each group may have a different weighting in the calculation of the final score (see Section 6.3.2). The relationships between criteria may be complex and may be application specific. For example, different catchment slopes are suitable for different types of RWH system: terracing is used for higher slopes of 5–30%, bunds are used for small flat areas with slopes less than 5%, percolation tanks are used for moderate slopes of 5–10%, and check dams are appropriate for slopes of 15% (Ammar et al., 2016; Krois & Schulte, 2014; Ramakrishnan et al., 2009). The weighting for the slope criterion may therefore differ according to the planned RWH structure type. Additionally, the existence of various methods for measuring the slope adds to the complexity.

To-date, frameworks for RWH site selection have taken into account only biophysical and socio-economic criteria, with ecological criteria ignored, as detailed by Ahmed et al. (2023a) . Incorporating ecological criteria into the decision-making process enhances its robustness by increasing the objectivity of the outcomes. Rainwater harvesting system which have been constructed without accounting for ecological criteria have been seen to be highly affected by microbial assembly in the stored water and consequent potential health risks (Liu et al., 2024). For example**,** in semi-arid regions of Brazil, around 65 patients have died due to cyanobacterial toxins present in drinking water reservoirs. The proliferation of these bacteria is influenced by factors such as the nitrogen-to-phosphorus (N:P) ratio, evaporation, temperature, and electrical conductivity (Barros et al., 2019).

Therefore, the knowledge gap addressed by this study is how to include, and the importance of including, ecological criteria with the currently-used biophysical and socio-economic criteria to achieve a sustainable system. Its aim is to develop a hybrid framework that integrates structural and ecological criteria for selecting rainwater harvesting sites in arid and semi-arid regions.

The paper is divided into seven parts. Following this introduction, Section 6.3 describes the Methodology. Section 6.4 briefly outlines the analysis of the results of the expert survey (full details are available as a supplementary file). In Sections 6.5,6.6 and 6.7 the case study is introduced, the framework applied and a sensitivity analysis presented, respectively, along with discussion of the important findings. Finally, key conclusions are drawn and summarised in Section 6.8.

6.3 METHODOLOGY

The framework presented in this paper has been developed through a combination of grey literature (secondary data) and consultation with a range of experts in the field via questionnaire. The relevant biophysical and socioeconomic criteria, and their respective weightings in the framework, were identified through the systematic review detailed in the authors' previous paper (Ahmed et al., 2023a). Separately, the important ecological criteria were determined by an additional literature review, and the weightings of these ecological criteria were then determined through expert consultation. The complex relationships between the ecological criteria were modelled using mediation analysis. Specifically, ecological criteria have complex interrelationships which must be accounted for in a robust framework. The criteria which are a direct measure of ecological health of a system (e.g. the diversity of aquatic life and water quality) are often not measured but are inferred through our understanding of the relationship between, for example, phosphorous concentration and aquatic life. The *direct* criterion (phosphorous) is what is measured and included in the framework. There may be more complex relationships, with one indirect criterion affecting another which, in turn, affects the direct criterion, quantified using mediation analysis. In the language of mediation analysis, the indirect criteria are *independent*, the ecosystem criteria are *dependent*, and any intermediate criteria are *mediators* (Carrión et al., 2017), as illustrated in Figure 6-1**.** Following the notation in this figure**,** the total effect of X on Y is quantified by its *weighting*, C, in the absence of mediators (Figure 6-1a), but an additional effect occurs when X also affects mediator M, which affects Y in turn (Figure 6-1b) (Carrión et al., 2017). The total direct effect of X on Y can be quantified as the total weighting, C, using:

$$C = C' + (a \times b) \quad (6\text{-}1)$$

where C' is the weighting for the effect of X on Y, a is the weighting of X's effect on M and b is the weighting for the effect of M on Y.

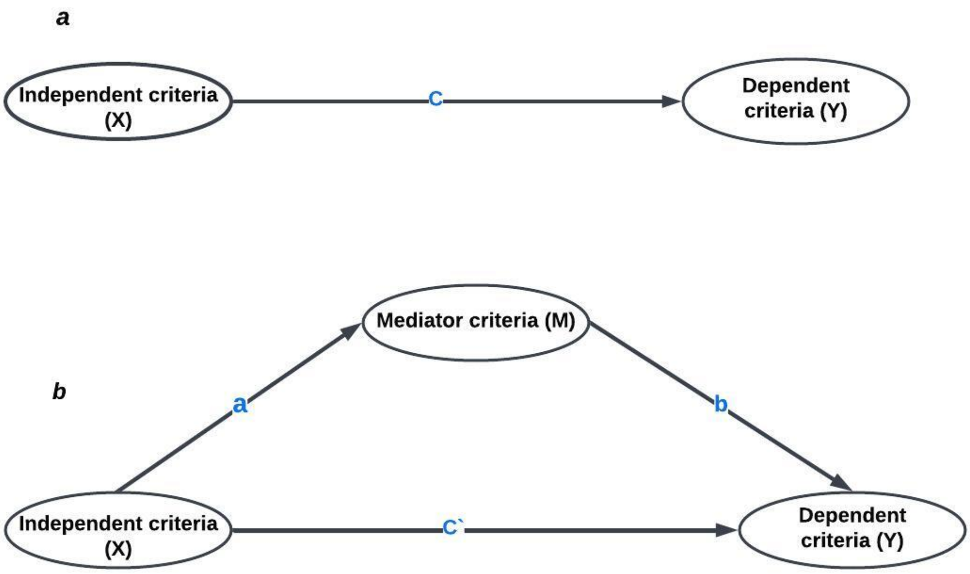

Figure 6-1 a) Cause-and-effect relationship and b) general mediation model (Carrión et al., 2017)

The consultation of experts took the form of an online survey which required the participants to assess and evaluate the specified criteria. The survey was divided into different sections and consisted of a total of 32 questions. The first seven questions were designed to collect general demographic information and background details such as experience and years of involvement. The following, main, section included 21 questions asking the experts to rate the importance of various parameters on ecological criteria, for example "*On a scale of 1 to 5, how important is the temperature in affecting pH levels in water bodies?*" These criteria included both direct and indirect criteria related to ecological concerns or practices. In addition, the respondents were asked to rank these criteria, which provided insight into their prioritisation and validation of their previous responses. Finally, the survey concluded with several questions aimed at gathering feedback from the respondents, which could help refine future iterations of the survey. A number of postgraduate students were asked to complete a draft version of the survey questionnaire in order to obtain feedback on the questions and format, and to estimate the time needed to complete it. The time taken to complete the survey was kept to a minimum (approximately 15 minutes) to maximise the likelihood of the experts approached responding.

The communication with prospective participants was conducted based on electronic media (i.e., ResearchGate, direct email and LinkedIn) which targeted different groups of participants, such as academics at universities and academic investigators at research institutions, with different specialisms such as ecologists, hydrologists and environmentalists. The experts were selected based on their institutional profiles, LinkedIn biographies, and their publications on ResearchGate and Google Scholar.

In the first round, the questionnaire was sent to 249 experts, 149 by direct email, 94 via ResearchGate and 9 via LinkedIn. Responses were received from 33 experts (13 hydrologists, 12 civil engineers specialising in water resources, and 8 environmentalists). The questionnaire underwent further minor revision based on their feedback. This feedback included a number of remarks that their field of expertise was not well-aligned with the questionnaire and that participants with a more specialist background in the ecology of water should be recruited, rather than from the broader water resources fields.

The second-round survey was distributed to a total of 454 participants, comprising 359 individuals contacted via direct email and an additional 95 through ResearchGate. These participants were specialists in the ecology of water hailing from various countries. Of those contacted, 30 responses were received.

Based on the formula for the prevalence study provided by the online Raosoft calculator (Raosoft, 2004), the required sample size for statistical validity of the survey was estimated. A 90% confidence level and a 10% margin of error were used. The required number of responses is dependent on the skewness of the responses for each question, increasing with increased skewness. with the two highest skewness being 17% and the second highest 13%. The associated calculated required sample sizes were 36 and 29. Clearly, the 30 responses received is an adequate sample size based on this analysis for all but one question, for which it is slightly smaller than would be ideal.

6.3.1 Included Ecological Criteria

Rainwater harvesting systems that incorporate ecological requirements are guaranteed to be environmentally friendly and support the health of the surrounding ecosystem. This strategy contributes to biodiversity preservation. Furthermore, it improves water quality in ecologically sound systems, making the gathered water safer for use in a variety of applications. All things considered, it harmonizes rainwater collection techniques with more general environmental preservation objectives, cultivating a more robust and sustainable ecosystem. Applying a hybrid framework with ecological criteria has a significant long-term impact on water quality, biodiversity, and community resilience. It protects habitats, supports diverse ecosystems, and reduces long-term maintenance costs for RWH structures.

Ecological criteria relevant to the health of the ecosystem of an RWH system include temperature, light, wind speed, wind direction, lagged wind speed, humidity, and evaporation (El-Jabi et al., 2014b). In this paper, temperature and light are prioritised, based on the findings of the analysis of literature, which has shown them to be the most influential factors affecting water quality criteria.

Water temperature can significantly influence various water quality criteria, impacting the solubility of contaminants, pH, electrical conductivity, and chemical toxicity of gases. Several studies have demonstrated that water temperature has a direct correlation with total dissolved oxygen (TDS), nitrogen (N), Chlorophyll-a concentration (Chlo-a), turbidity, specific bacteria growth, and an inverse relationship with dissolved oxygen (DO) (Das et al., 2020; Dhaka & Wang, 2021; El-Jabi et al., 2014b; Elçi, 2008; Tomaszek & Koszelnik, 2003; White et al., 1991). Additionally, higher temperatures stimulate microbial metabolic activity and photosynthesis, which impact the growth and functioning of living communities (Bonacina et al., 2023). Temperature also plays a crucial role in the vulnerability of aquatic plants to pests and illnesses. Warmer temperatures can increase the risk of disease outbreaks and infestations in aquatic plant populations by favouring the growth and spread of diseases and pests (Qu et al., 2022).

According to El-Jabi et al. (2014b), the air temperature and water temperature are directly proportional, with the water temperature being approximately 0.25-0.4 less than the air temperature. The average yearly air temperature serves as an indicator of the overall climatic conditions in the study area.

Light intensity is a very important factor which affects water properties, with an optimal light intensity enhancing water quality, degrading pollutants and being necessary for life (Espinosa, Abril et al. 2020, Qu, Zhao et al. 2022). Qu et al. (2022) have investigated the effects of light intensity on direct criteria finding a direct relationship between light intensity and pH, DO, and ammonia. There is also an inverse relationship with bacteria, nitrite, total phosphorus, and transparency (Qu et al., 2022).

Figure 6-2 shows the relationships between independent (temperature and light) and dependent (ecosystem criteria) through mediator criteria (TP, salinity, N, PH, DO, and ammonia), where lowercase "*a*"s represent the weightings for the effects of temperature on the mediator criteria, "*b*"s represent the weighting for the effects of light on the mediator criteria, "*c*"s represent the direct relationship between the independent and dependent criteria, "*d*"s are the weightings between mediators and dependent criteria, and "*e*"s are the weightings for the effects between mediator criteria. The total weighting for temperature, C_T, and light, C_L, are therefore given by eq.(6-2) and eq.(6-3) respectively, following the principles of mediation analysis discussed in Section 6.3:

$$\boldsymbol{C_T = a_1 d_1 + a_2 d_2 + a_2 d_5 + a_3 d_3 + a_4 d_4 + a_4 d_6 + a_4 e_2 d_7 + a_4 d_4 + a_4 d_6 + a_4 e_1 d_8 + C_1 + C_3} \quad (6\text{-}2)$$

$$\boldsymbol{C_L = b_1 d_6 + b_1 e_2 d_7 + b_1 e_1 d_8 + b_2 d_7 + b_3 d_8 + C_2 + C_3 + C_4 + C_5} \quad (6\text{-}3)$$

It is these weightings which have been determined via the consultation with experts in the field.

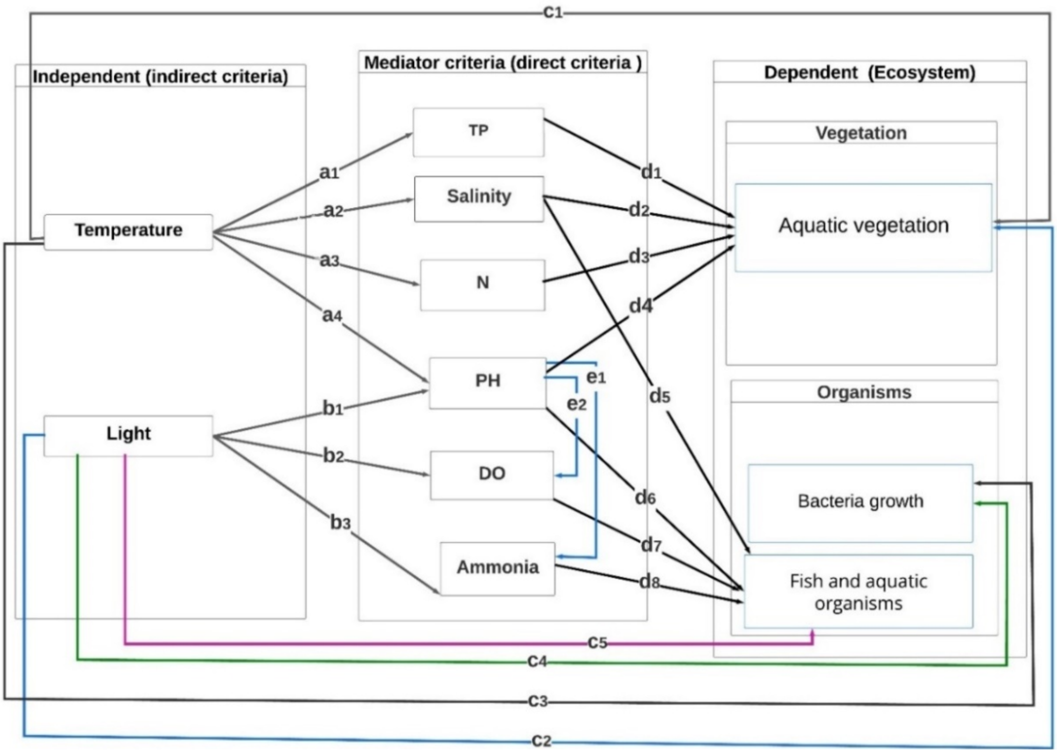

Figure 6-2 Shows the relationships between direct and indirect criteria constructs based on literature review.

6.3.2 Calculation of Site Suitability

The hybrid framework includes three groups of criteria: the biophysical and socioeconomic criteria used in existing frameworks and the newly incorporated ecological criteria. The score, *S*, for each of these *n* groups are combined to give the overall site score (S_O), taking into account weightings (*W*) which represent the relative importance of each group, following:

$$S_O = \sum_{i=1}^{n} S_i \times W_i \tag{6-4}$$

An equivalent formula is used to determine *S*, the group score, from the scores (*s*) and weightings (*w*) of the *N* criteria within that group:

$$S = \sum_{i=1}^{N} s_i \times w_i \tag{6-5}$$

The weighting of criteria for biophysical and socioeconomic factors was calculated through a systematic literature review conducted by Ahmed et al. (2023). However, for the ecological criteria each criterion was ranked via the expert opinion questionnaire, and this was converted to a weighting, the results of which are summarised in the next section.

6.4 SURVEY RESULTS

For the sake of brevity, a full analysis of the survey results is not included here but is available as a supplementary document file. As well as a full breakdown of the rankings from the experts and quantification of the overall weighting for the independent criteria light and temperature, this analysis included the impact of using mean versus median rankings, variation in response due to amount of relevant experience of the respondent and skewness of the response distributions. The mean and median rankings for each criterion are shown in Figure 6-3. The overall weightings for temperature and light were 0.49 and 0.51 respectively.

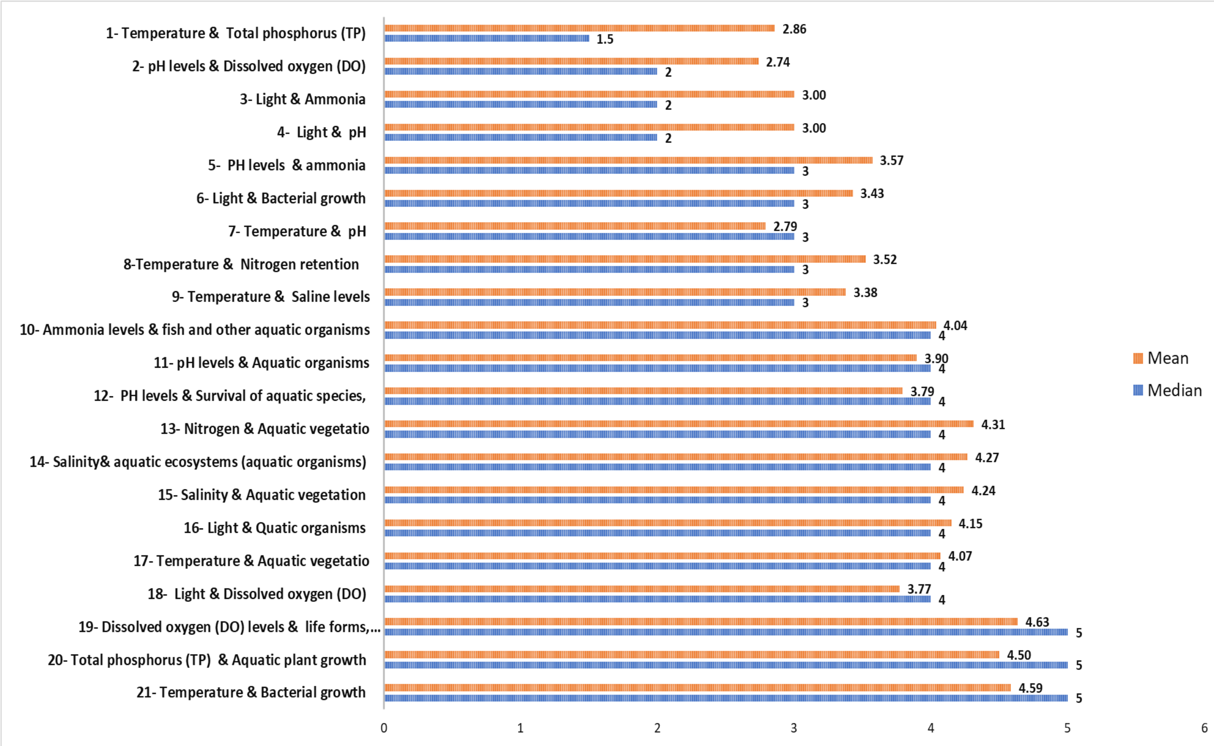

Figure 6-3 Mean and median rankings of each criterion based on experts' opinion.

6.5 CASE STUDY OVERVIEW – HYBRID FRAMEWORK APPLICATION TO (ERBIL PROVINCE)

To demonstrate the impact of including ecological criteria, the framework was applied both with and without the inclusion of ecological criteria to a representative semi-arid catchment area, Erbil Province in northern Iraq. Erbil Province lies between 44° to 45° east longitude and 36° to 37° north latitude with an area of approximately 14,837 km^2 and a population of ~2.25 million and comprises six administrative districts (Ahmed et al., 2023b) see Figure 6-4. Over the last twenty years, Erbil has suffered from water shortages due to drought. This has caused wells used for drinking and irrigation to dry up completely as the groundwater level has dropped by over 54% (Ahmed et al., 2023b). Villagers who raised animals faced additional difficulties due to a lack of water, leading some of them to migrate. Consequently, in light of these difficulties, it is important to utilise appropriate water resource management strategies aimed at increasing water retention and reducing outflow (Hämmerling et al., 2020).

Four potential RWH sites (Figure 6-4b) were chosen based on the literature review by Ahmed et al. (2023b) and Hameed (2013). The potential locations for rainwater harvesting (RWH) in these regions are illustrated in Table 6-1. The authors of the original papers have previously applied other frameworks to these sites, so the relevant data are available and have been used in this paper.

Table 6-1 potential location for rainwater harvesting

site	Latitude	Longitude
1	35.90128	44.75567
2	36.30324	44.13427
3	36.43	44.32
4	36.95956	44.34863

6.5.1 Study Area Characteristics

The region includes mountains, hills, and fertile plains, with the highest point (known as the Zagros) at 3607m above sea level and elevations gradually declining towards the central areas before reaching the plains in the southern regions, which constitute the majority of the agricultural land (Ahmed et al., 2023b).

The weather in this region is characterised by damp, coolness during winters and very hot and dry experienced in the summer months. The mean temperature in March's high temperature is 13–18°C, while May's ranges from 27–32°C. Summers (June to September) are quite hot and dry, with mean highs in July and August reaching 39–43°C, sometimes even close to 50°C (Nanekely, 2020).

In the northern regions, the soil is shallow to medium chestnut soil, formed from the underlying rocks (Ahmed et al., 2023b). The plain areas in this region are excellent for agriculture because of their considerable depth, favourable texture, and high organic matter content (Hameed, 2013). Wheat and barley are dominant during winter, relying on rainfall, while other crops thrive in summer using subsurface water (Fadhil, 2011).

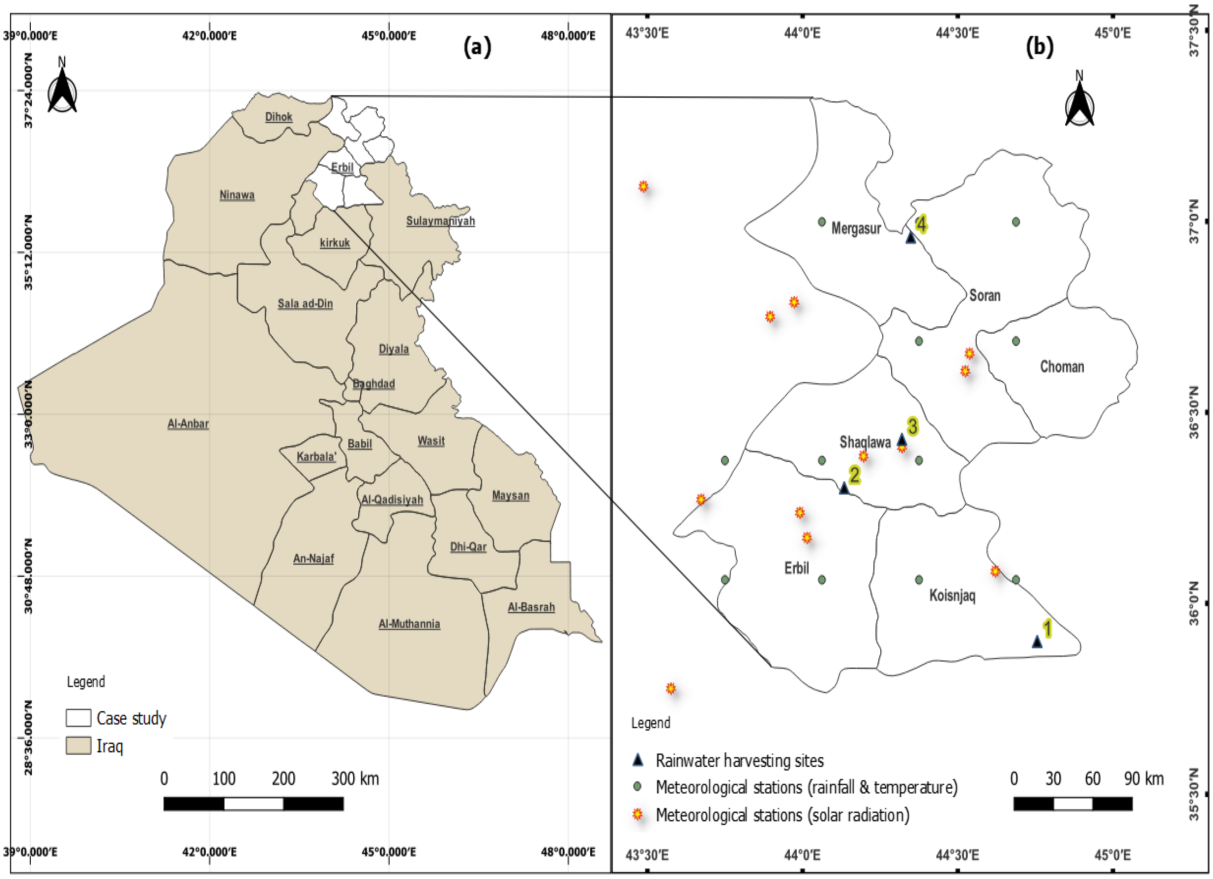

Figure 6-4 (a) The province boundaries in Iraq, and (b) Displays the study area and sites selection for case study.

6.5.2 Data Sources and Preparation

The data for the criteria in each of the three groups (biophysical, socioeconomic, and ecological) were obtained from existing literature and satellite images. These data were imported into QGIS (Version 3.22.11), where the Inverse Distance Weighted (IDW) functionality was used for interpolation. The data included a Digital Elevation Model (DEM) acquired from the Shuttle Radar Topography Mission (SRTM) with a resolution of 30 meters, and a satellite image from Landsat 8 Operational Land Imager (OLI), available from United States Geological Survey (USGS) (*USGS.* , 2024). The data for rainfall (Figure 6-5a) and temperature (Figure 6-5b) came from twelve meteorological stations located across Erbil city (see Figure 6-4b), with daily rainfall records covering 35 years (1980-2014), as reported by Nanekely (2020). The data on soil (Figure 6-5c) were obtained from the Digital Soil Map of the World (DSMW), which was developed jointly by the Food and Agriculture Organization (FAO) and the United Nations Educational, Scientific, and Cultural Organization (UNESCO) in 2008 (FAO. FAO-UNESCO Digital Soil Map of the World (DSMW).Food and Agriculture Organization of the United Nations., 2008). The data for light (Figure 6-5d) were from twelve meteorological stations (note that these were not the same stations as for rainfall - see Figure 6-4b) reported by Keya et al. (2023). Figure 6-5e shows land use and land cover for the study area, the data for land use and land cover were obtained from FAO. FAO-UNESCO Digital Soil Map of the World (DSMW).Food and Agriculture Organization of the United Nations. (2008). Figure 6-5f demonstrates the population density of the study area, the data as reported by Sissakian (2023) and Ayoob Khaleel and Ngah (2011). Run-off was calculated using the Soil Conservation Service Curve Number (SCS-CN) method. The Curve Number (CN), created by the United States Department of Agriculture, has a numerical range of 0 to 100 which depends on the soil type/land use (Ibrahim et al., 2022). Runoff is estimated by Equations (6-6) and (6-7) (Ibrahim et al., 2022; Sayl, 2017).

$$Q = \frac{(P - O.2S)^2}{(P + 0.8S)} \qquad (6\text{-}6)$$

$$S = \frac{25400}{CN} - 254 \qquad (6\text{-}7)$$

where P is the amount of rain in millimetres, S is the maximum retention after runoff begins in millimetres, and Q is the runoff depth in millimetres (Sayl, 2017). Table 6-2 illustrates the calculation of runoff for sites selection.

Table 6-2 Runoff calculations

Sites	**Land use**	**CN**	**Annual Rainfall (P) (mm)**	**Runoff (mm)**
1	Bare Soil	88	580.4	540.81
2	Bare Soil	88	609.9	570.22
3	Bare Soil	88	645.8	606.02
4	Bare Soil	88	622.8	583.08

The biophysical and socio-economic criteria used in existing frameworks are detailed in (Ahmed et al., 2023a). The scale used for weightings in each within those frameworks were different and hence the published weighting values have been normalised by division by the sum of weights for all criteria used in the same framework (see Table *6-3*).

Table 6-3 Normalised maximum, minimum and average weights of the existing criteria (Ahmed et al., 2023a).

Criteria		Max. Weight (%)	Min. Weight (%)	Average (%)	Standard Deviation (%)	Relative Standard Deviation (RSD)	Frequency of Criteria in Existing Frameworks
1-	Rainfall	45.7	6	23.2	10.5	45.26	44
2-	Runoff	53	5.5	32	12.8	40.00	42
3-	Slope	35.4	6	19.8	8.3	41.92	60
4-	Soil	42.6	3.2	18.9	10	52.91	55
5-	Land use/land cover (LULC)	35.5	4	11.7	8.6	73.50	48
6-	Drainage density	41.6	4.1	14	9.9	70.71	47
7-	Hydrological losses	13.3	4.8	8	3.4	42.50	6
8-	Catchment area	22.2	9.81	14.8	6.5	43.92	3
9-	Distance to wadis	19	17	18	1.4	7.78	2
10-	Distance to faults	13.6	4.6	4.6	2.8	60.87	13
11-	Distance to water source	19.8	5	11.4	5.9	51.75	9
12-	Distance to roads	25	1.63	7.6	7.4	97.37	22
13-	Distance to agricultural area	21.3	4.07	10.4	8.1	77.88	4
14-	People's priorities	64.4	9.6	30	30	100.00	3
15-	Population density	4.3	2.77	3.5	1.1	31.43	2
16-	Distance to urban area	13	2.3	7.2	4	55.56	12

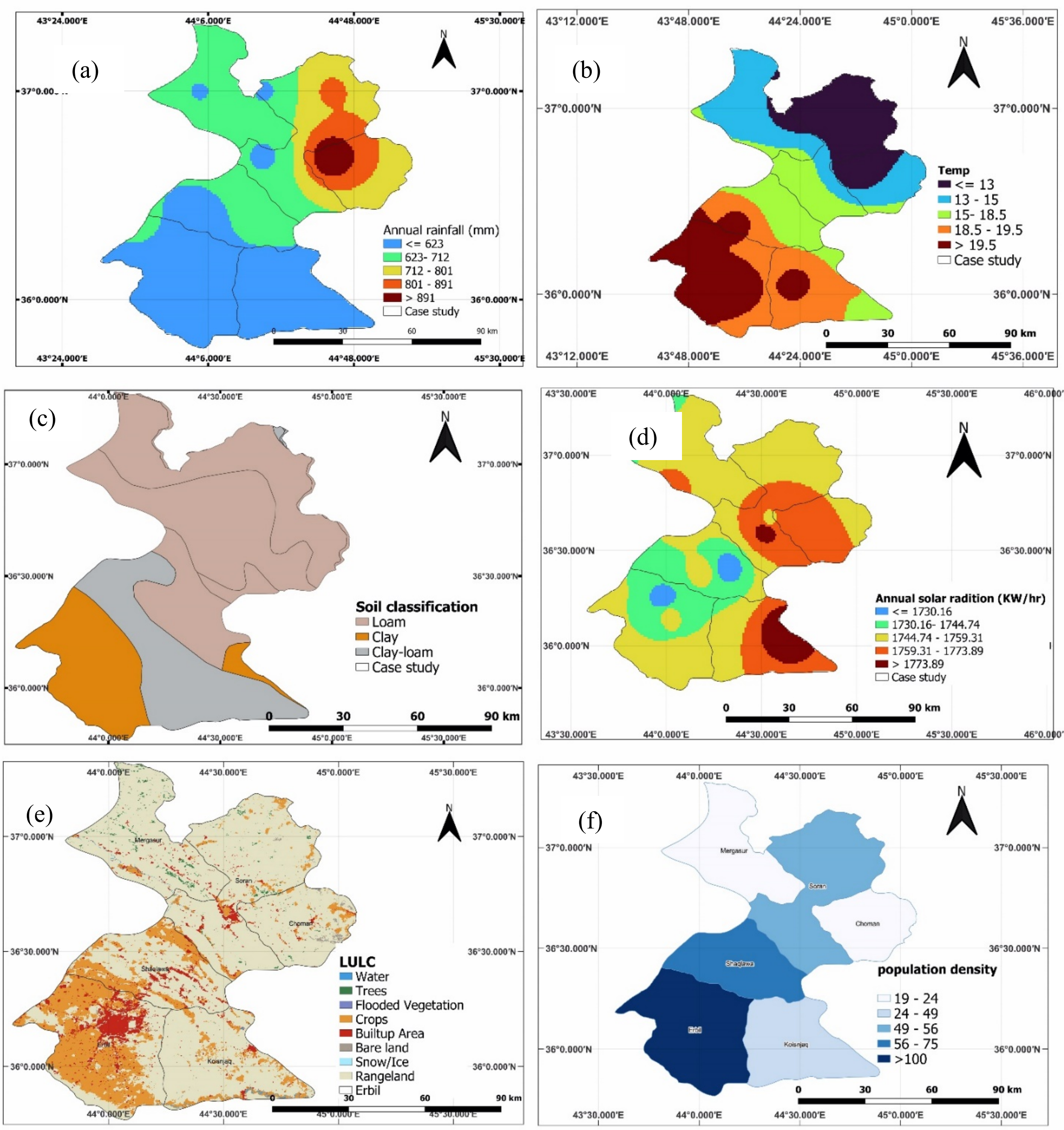

Figure 6-5 Maps showing regional variation of criteria. (a) Annual rainfall; (b) Annual temperature; (c) Soil texture ;(d) Annual solar radiation; (e) Land use/land cover (LULC); (f) Population density

6.6 CASE STUDY RESULTS

Each of the criteria was given an integer score from 0 to 4, with 0 representing complete unsuitability of the site for RWH and 4 signifying very high suitability (see Table 6-4). The average weights of the biophysical and socio-economic criteria utilised in eq. (4-5) are shown in Table 6-3. The weightings for the ecological criteria, temperature and light, were determined through mediation analysis, as detailed in Section 6.3.1. The results of this mediation analysis are presented in Table 6-5. The data for each criteria for each of the four proposed RWH sites in Erbil Province is shown in Table 6-6.

Table 6-4 The scoring system for the criteria

Rank / Criteria	0	1	2	3	4	**References**
Rainfall (P) (mm)	-	P<100	100≤P<300	≥ 300 P<500	P >500	(Al-Adamat et al., 2010)
Runoff (R) (mm)	-	R<100	100≤R<300	≥ 300 R<500	R >500	(Al-Adamat et al., 2010)
Slope (S) (%)	-	S>10	5 ≤S< 10	3≤ S < 5	S <3	(Al-Adamat et al., 2010)
Soil	-	Loam	Sandy Clay Loam, silty Loam	Silty clay	Clay Loam	(Ahmed et al., 2023b)
Land use/land cover (LULC)	Urban/Built-Up Area Water Bodies	Forest	Cultivated Land	Grassland	Bare soil	(Ahmed et al., 2023b)
Drainage density ($\frac{km}{km^2}$)	0-0.21	0.212-0.33	0.34-0.46	0.47-0.61	>0.62	(Khalid Mahmood et al., 2020)
Hydrological losses (%)	-	75-100	50-75	25-50	0-25	Normalisation
Catchment area (Km^2)		9.33–84.71	84.72-226.51	226.52–527.70	>527.2	(Ezzeldin et al., 2022)
Distance to wadis (D) (m)	< 50	D ≥1000	2000>D ≥1000	1000>D ≥500	51>D<500	(Al-Adamat et al., 2010)
Distance to faults (m)		500-2000	2000-10000	10000-20000	>20000	(Noori et al., 2019)
Distance to water source (m)	< 1500	1500-2000	2000-2500	2500-3000	≥ 3000	(Matomela et al., 2020)
Distance to roads (m)	<250	>2000	1500-2000	1000-1500	250-1000	(Faisal & Abdaki, 2021)
Distance to agricultural area (m)	<250	>700	500 –700	300–500	250-300	(Alem et al., 2022)
People's priorities	<250	>700	500 –700	300–500	250-300	Suggestion
		Agriculture	Agriculture	Agriculture	Agriculture	
Population density	-	0-10	10-20	20-40	>40	(Faisal & Abdaki, 2021)
Distance to urban area (m)	<250	500-1000	1000- 1500	≥ 1500 < 3000	≥ 3000	(Matomela et al., 2020)
Temperature (°C)	-	20_25	15_20	10_15	5_10	Equal interval
Light (kWh/yr)	-	1700_1720	1720_1740	1740_1760	1760_1780	Equal interval

Table 6-5 Mediation analysis calculation of ecological effect weightings based on mean ranking values.

Mediation Analyses (mean)						
Independent	Effect	Dependent	Effect	Dependent	Effect	Ecosystem
Temperature	a_1	TP	d_1			Aquatic Vegetation (a_1 x d_1)
	1.95		4.33			8.4435
	a_2	Salinity	d_2			Aquatic vegetation (a_2 x d_2)
	3		4.24			12.72
			d_4			Fish and Aquatic organisms (a_2 x d_4)
			4.38			13.14
	a_3	N	d_3			Aquatic vegetation (a_3 x d_3)
	2.9		4.14			12.006
	a_4	PH	d_5			Fish and aquatic organisms (a_4 x d_5)
			4.1			9.184
			d_8			Aquatic vegetation (a_4 x d_8)
			3.95			8.848
			e_2	DO	d_6	Fish and Aquatic organisms (a_4 x e_1 x d_6)
	2.24		2		4.76	21.3248
			e_1	Ammonia	d_7	Fish and Aquatic organisms (a_4 x e_1 x d_7)
			2.86		3.95	25.30528
	c_1					Aquatic Vegetation (c_1)
	3.95					3.95
	c_3					Bacteria growth (c_3)
	4.52					4.52
	The total effect of temperature on ecosystems					119.44158
Normalised effect of temperature on ecosystems						49%
Light	b_1	PH	d_5			Fish and aquatic organisms (b_1 x d_5)
			4.1			10.742
			d_8			Aquatic vegetation (b_1 x d_8)
			3.95			10.349
			e_1	DO	d_6	fish and aquatic organisms (b_1 x e_6 x d_7)
			2.86		4.76	35.667632
			e_2	Ammonia	d6	fish and aquatic organisms (b_1 x e_2 x d_6)
	2.62		2.86		4.04	30.272528

	b_2	DO	d_6			Fish and Aquatic organisms (b_2 x d_6)
	3.52		4.76			16.7552
	b_3	Ammonia	d_7			Fish and aquatic organisms (b_3 x d_7)
	2.24		3.95			8.848
	c_2					Aquatic vegetation (c_2)
	3.71					3.71
	c_4					Bacteria growth(c_4)
	3.1					3.1
	C_5					Fish and aquatic organisms(C_5)
	3.71					3.71
	The total effect of light on ecosystems					123.15436
Normalised effect of light on ecosystems						51%

Table 6-6 Data extraction for four sites in Erbil city

Criterion	Site	1	2	3	4
Biophysical criteria	Annual Rainfall (mm)	580.4	609.7	645.8	622.8
	Runoff (mm)	540.81	570.22	606.02	583.08
	Hydrological losses (mm)	39.59	39.68	39.78	39.72
	Slope (%)	1.51	4.1	1.57	1.8
	Soil	Clay-loam	Clay-loam	Loam	Loam
	Land use/land cover.	Bare soil	Bare soil	Bare soil	Bare soil
	Drainage density (Average) (m/km^2)	1.47	1.63	3.45	1.12
	Catchment area (km^2)	118.9	3.5	154.2	887.3
	Distance to wadis (m)	79	346	43	18
	Distance to faults (m)	1273	3862	2200	1320
	Distance to water source (m)	2923	3690	82	23
Socio-economic Criteria	Distance to roads (m)	1549.5	132	93	474
	Distance to agricultural area (m)	3126	1195	1692	1107
	People's Priorities	Agriculture	Agriculture	Agriculture	Agriculture

	Population Density	49	75	75	24
	Distance to Urban Area (m)	2176	65	868	813
Ecological criteria	Temperature (c)	18.2	19.26	17.84	12
	Light (kw/hr/year)	1773.22	1743	1717.5	1766.2

The final results of the framework for Erbil Province are summarised in Table 6-7, which presents suitability based on two scenarios: one considering biophysical and socioeconomic criteria, and the other considering biophysical, socioeconomic, and ecological criteria. Site 4 showed the highest suitability in both scenarios, with scores of 3.03 and 3.31, respectively. Conversely, Site 3 had the lowest suitability in both cases, scoring 2.26 and 2.13. The rankings differed slightly between the two scenarios. In the scenario considering only existing criteria, Site 2 ranked second with a suitability of 2.62, while in the scenario including ecological criteria, Site 1 took the second spot with a suitability of 2.71. Similarly, Site 1 ranked third in the existing criteria scenario with a suitability of 2.53, while Site 2 ranked third in the scenario with ecological criteria, scoring 2.52.

Table 6-7 Suitability of sites for rainwater harvesting in Erbil city.

Biophysical and Socioeconomic criteria			Biophysical, Socioeconomic and Ecological criteria		
Rank	Site name	Suitability	Rank	Site name	Suitability
1	4	3.03	1	4	3.31
2	2	2.62	2	1	2.71
3	1	2.53	3	2	2.52
4	3	2.26	4	3	2.13

6.7 CASE STUDY - SENSITIVITY ANALYSIS

Sensitivity analysis is a method used to evaluate the effectiveness of implementing a decision model to establish the ranking of potential rainwater harvesting sites (Sayl, 2017). This analysis examines the degree to which the ranking of alternatives is affected by changes in the ecological criteria while keeping the other criteria constant.

The model was applied using hypothetical site temperatures of 9°C, 12°C, 17°C, and 25°C, while keeping other criteria constant. Respective suitability scores for each site were (Figure 6-6a):

- Site 1: 3.03, 2.87, 2.71, and 2.54.
- Site 2: 2.84, 2.68, 2.52, and 2.35.
- Site 3: 2.45, 2.29, 2.13, and 1.96.
- Site 4: 3.47, 3.31, 3.15, and 2.98.

Site 4 consistently scores the highest, indicating strong suitability across various temperature ranges. The scores decrease as temperatures rise, with Site 4 showing the smallest decline.

Separately, the model was applied for hypothetical site light values of 1710, 1735, 1755, and 1770 kw/year, again keeping other criteria constant. The respective suitability scores for each site were (Figure 6-6b):

- Site 1: 2.2, 2.37, 2.54, and 2.71.
- Site 2: 2.18, 2.35, 2.52, and 2.69.
- Site 3: 2.13, 2.3, 2.47, and 2.64.
- Site 4: 2.80, 2.97, 3.14, and 3.31.

Site 4 shows the most improvement with increased light, while all sites maintain their rankings.

In general, appropriateness rises with increasing light and falls with increasing temperature. With its ability to withstand changes in temperature and its greatest advantage from increased light, Site 4 is always ranked best.

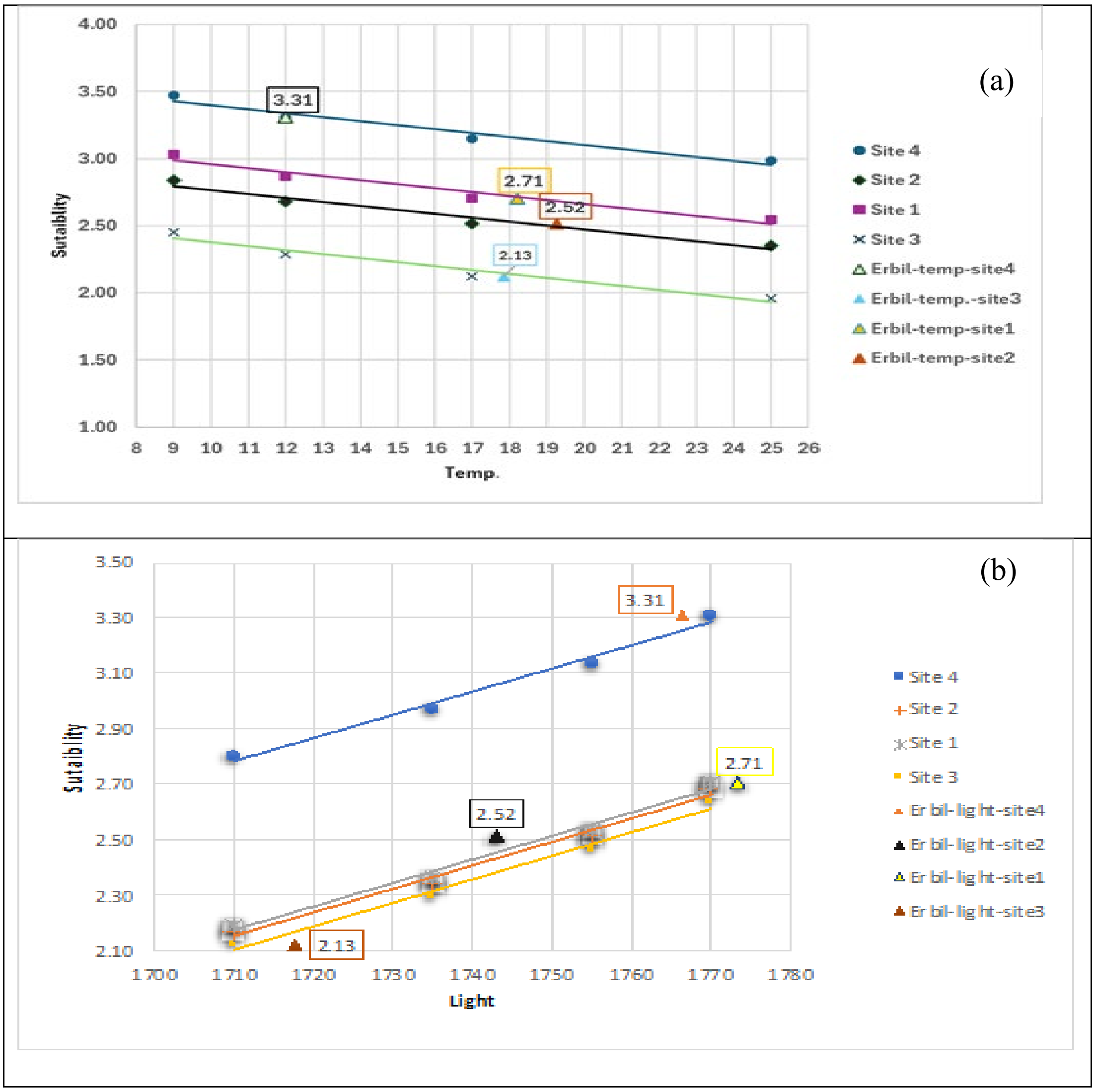

Figure 6-6 Effect of (a) Temperature and (b) Light.

6.8 CONCLUSIONS

In this paper, a novel hybrid framework for rainwater harvesting site selection in arid and semi-arid regions is presented. This framework expands existing frameworks, which are generally based on biophysical and socio-economic criteria, to include ecological criteria, thus ensuring sustainability of the region. This framework has been applied in a case study of Erbil Province, Iraq. The following important conclusions have been drawn from this work:

- Inclusion of ecological criteria in the framework is a complex process due to the interdependencies and complex relationships between environmental factors and their ecological impacts.

- Temperature and light have been identified as two of the most important factors, and their impact on the ecological criteria has been quantified using mediation analysis to establish the final weights. These weights were found to be 0.49 for temperature and 0.51 for light, as illustrated in Table 6-5.
- Additional ecological factors can be included in the framework following a similar procedure as detailed in this paper.
- The case study demonstrates that including the ecological criteria in the framework can lead to changes in the suitability ranking of proposed rainwater harvesting sites. The hybrid framework implemented on these sites encompasses two distinct scenarios. The first scenario incorporates three key components: biophysical, socio-economic, and ecological criteria. In contrast, the second scenario integrates two components: biophysical and socio-economic criteria. The suitability of the sites for the first scenario was as follows: 3.31, 2.71, 2.52, and 2.13 for sites 4, 1, 2, and 3, respectively. Meanwhile, the suitability of sites for the second scenario was: 3.03, 2.62, 2.53, and 2.26 for sites 4, 2, 1, and 3, respectively.

6.9 FUTURE WORK

The strategies and tools presented in this study are an effective improvement over existing procedures for identifying rainwater harvesting (RWH) locations. For future research, various recommendations and suggestions are made to further enhance and advance the approach for rainwater harvesting (RWH) site selection, as detailed below:

- Incorporating additional ecological criteria, such as wind speed, wind direction, humidity, and evaporation, into the site selection process may help identify suitable, sustainable sites for rainwater harvesting.
- Incorporating the other biophysical characteristics of rainwater harvesting sites, such as depth and surface area, should be added to the next version of the framework, which could have additional effects on water ecology and, consequently, influence site selection for rainwater harvesting.
- The lack of data in arid and semi-arid regions necessitated the use of QGIS for data interpolation. However, more data is needed, particularly regarding light, outlet discharge of catchment, and soil.

- It is recommended to use a soil sampling test to classify the soil for different regions accurately.
- This framework needs to be applied to more case studies, and further analysis should be conducted on arid and semi-arid regions to improve this study.
- Efforts should be made to find a larger pool of experts to obtain more accurate data, which can improve the final weights of the criteria.
- The framework is recommended for application in regions with significant variations in temperature and light. This approach will help identify suitable sites in terms of ecological, biophysical, and socioeconomic aspects.

Chapter 7: Conclusions and Recommendations

7.1 CONCLUSION

This study introduces a novel hybrid framework designed to identify potential rainwater harvesting sites in arid and semi-arid regions, emphasising the integration of ecological criteria, previously overlooked in current methodologies. The integration of ecological aspects with existing biophysical and socioeconomic factors in this research represents a significant advancement towards developing sustainable rainwater harvesting systems.

The effectiveness of a rainwater harvesting system relies on finding an appropriate site. The study findings presented here are essential, demonstrating new methodologies and instruments to be employed in planning effective and environmentally conscious rainwater harvesting (RWH) systems.

This study was founded on the five objectives outlined in Section 1.3. While these goals have been met, there remains scope for further improvement given adequate time and resources; this recommended future work is detailed in Section 7.2. In summary, the research yielded the following outcomes:

7.1.1 Structural criteria (biophysical and socioeconomic criteria)

An extensive systematic review of existing studies was conducted to identify knowledge gaps regarding rainwater harvesting sites in arid and semi-arid regions. After the screening process, 68 papers met the inclusion criteria. This achieves Objective 1, detailed in Chapter 3: .The key outcomes of the review were:

- Identifying the core components of the framework and investigating methods of data collection. In addition, the comparison between different frameworks and the identification of the similarities and differences between them helped identify the gap in knowledge.

- This study showed that the criteria used in existing frameworks were biophysical and socioeconomic criteria, which were insufficient to achieve the pillars of the sustainability system. Forty frameworks (59 percent of the total) were founded on biophysical criteria, whereas twenty-eight frameworks (41 percent of the total) were founded on both biophysical and socioeconomic factors. In addition, "slope" was the most common criterion, followed by "soil", "LULC", "drainage density", "rainfall", "runoff", and "distance to roads", with biophysical criteria representing 80% of the weight, and socioeconomic criteria 20%. The biophysical and socioeconomic criteria were weighted based on an analysis of the weights of criteria in existing frameworks.

- These frameworks for rainwater harvesting (RWH) are developed without fully considering how the location of the structures and the duration of their use might affect ecological factors such as water quality and the surrounding living organisms. While rainwater is initially free from microbial contamination, it can become polluted due to human and animal activities. Improper storage conditions can further promote the growth of pathogens, increasing the risk of infectious disease outbreaks.

- In light of these challenges, it is essential to develop more comprehensive rainwater harvesting (RWH) framework that prioritize sustainability by conserving natural resources and minimizing water contamination. Such frameworks should align with the core principles of sustainability, particularly ecological considerations. Therefore, integrating ecological aspects into the design of RWH systems is critical to ensure their long-term effectiveness and environmental compatibility.

7.1.2 Ecological criteria (direct and indirect criteria)

Ecological criteria are essential for sustainability, ensuring long-term watershed health, biodiversity, and resilience. Incorporating ecological criteria into the framework presents a significant challenge due to the intricate interdependencies and complex relationships between various environmental factors and their resulting ecological impacts. Through this study, temperature and light have been identified as two of the most critical factors influencing these criteria. This conclusion is made through a review of the literature related to evaluating the water ecology of water bodies. By employing mediation analysis as detailed in Section 4.6, the impact of these factors on the ecological criteria has been effectively quantified, providing a clearer understanding of their roles. Moreover, the hybrid framework is adaptable, allowing for the inclusion of additional ecological factors by following the same detailed procedures outlined in this study. This achieves Objective 2, detailed in Sections 4.5 and 4.6.

7.1.3 Weights of ecological criteria

The weights for ecological criteria were determined based on a questionnaire that was sent to experts in the field. The main purpose of the questionnaire was to gather expert opinions and practical insights from individuals with expertise in ecological and environmental aspects. The questionnaire aimed to evaluate the suitability of selected components and indicators, which were derived from existing literature and tailored to fit the unique characteristics of arid and semi-arid regions. The responses were thoroughly analysed to accurately determine the final weights for the ecological criteria, which were 49% for temperature and 51% for light. This achieves Objective 3, detailed in Section 5.3.

7.1.4 Novel hybrid framework

To identify the score of the sites, criteria from three groups—biophysical, socioeconomic, and ecological—are combined. The score for each criterion is multiplied by the weight of that criterion to obtain the criterion's weighted score. The scores for each group are then summed, and finally, the scores of the three groups are aggregated to derive the overall score of the site. The weighted score for each group was used equally, at 33.33%. The normalised average weights for the biophysical criteria were 4.38% for rainfall, 6.05% for runoff, 1.51% for hydrological losses, 3.74% for slope, 3.57% for soil, 2.21% for land use/land cover, 2.65% for drainage density, 2.8% for catchment area, 3.4% for distance to wadi, 0.87% for distance to water source, and 2.15% for distance to the water source. The normalised average weights for the socioeconomic criteria were 4.32% for distance to roads, 5.91% for distance to agricultural area, 17.03% for people priority, 1.99% for distance to urban area, and 4.09% for distance to urban area. The normalised average weights for the ecological criteria were 16.33% for temperature and 17% for light. This achieves Objective 4, detailed in Section 6.3.2.

7.1.5 Case Study

Erbil Province is a relevant case due to its pressing water scarcity, climate change impacts, and reliance on rainwater harvesting, making it an ideal context to demonstrate the framework's application. The case study conducted illustrates the practical implications of integrating ecological criteria, revealing that their inclusion can significantly alter the suitability rankings of proposed rainwater harvesting sites. This underscores the importance of considering ecological impacts in environmental planning and decision-making processes, ensuring that sustainability and ecological integrity are prioritised.

Four different sites for rainwater harvesting (RWH) were chosen within Erbil province, each identified by its specific geographic coordinates.

The hybrid framework implemented on these sites encompasses two distinct scenarios. The first scenario incorporates three key components: biophysical, socio-economic, and ecological criteria. In contrast, the second scenario integrates two components: biophysical and socio-economic criteria.

The suitability of the sites for the first scenario was as follows: 3.31, 2.71, 2.52, and 2.13 for sites 4, 1, 2, and 3, respectively. Meanwhile, the suitability of sites for the second scenario was: 3.03, 2.62, 2.53, and 2.26 for sites 4, 2, 1, and 3, respectively.

The importance of these findings lies in the fact that the order of site suitability has changed between the two scenarios. In the first scenario, Site 4 was the most suitable due to its superior scores and rankings in both biophysical and socioeconomic criteria compared to the other sites, making it the most favourable option, followed by Sites 1, 2, and 3. However, in the second scenario, while Site 4 remained the most suitable, the rankings for the remaining sites shifted: Site 2 became more suitable than Site 1, and Site 3 improved slightly in its relative position compared to Site 1. This change in ranking highlights how the specific criteria or conditions of each scenario influence the suitability of the sites differently, which may impact decision-making based on the chosen scenario. This achieves Objective 5, detailed in Section 6.5. The framework is transferable, especially to arid and semi-arid regions, as it uses adaptable biophysical, socioeconomic, and ecological criteria. However, outside these regions, modifications may be needed to adjust the weights of the criteria depending on the aim of the RWH.

7.2 LIMITATIONS AND RECOMMENDATIONS FOR FUTURE WORK

The strategies and tools presented in this study are an effective improvement over existing procedures for identifying rainwater harvesting (RWH) locations. For future research, various recommendations and suggestions are made to further enhance and advance the approach for rainwater harvesting (RWH) site selection, as detailed below:

- Incorporating additional ecological criteria, such as wind speed, wind direction, humidity, and evaporation, into the site selection process may help identify suitable, sustainable sites for rainwater harvesting.
- Incorporating the other biophysical characteristics of rainwater harvesting sites, such as depth and surface area, should be added to the next version of the framework, which could have additional effects on water ecology and, consequently, influence site selection for rainwater harvesting.
- The lack of data in arid and semi-arid regions necessitated the use of QGIS for data interpolation. However, more data is needed, particularly regarding light, outlet discharge of catchment, and soil.
- It is recommended to use a soil sampling test to classify the soil for different regions accurately.
- This framework needs to be applied to more case studies, and further analysis should be conducted on arid and semi-arid regions to improve this study.
- Efforts should be made to find a larger pool of experts to obtain more accurate data, which can improve the final weights of the criteria.
- The framework is recommended for application in regions with significant variations in temperature and light. This approach will help identify suitable sites in terms of ecological, biophysical, and socioeconomic aspects.

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Appendices

APPENDIX A. The papers selected for the systematic review

This appendix contains details of the papers selected for the systematic review

Table A 1 Summary and comparison of the key components of current frameworks

No	Reference	Country and Year	Criteria	Tools	Keywords	Catchment Area km²	Annual Rainfall (mm)	Range of Index Value	Temp °C	Methods for Weighting	Criteria Selection and Score
1-	(Albalawneh et al., 2015)	Jordan, 2015	Edge, Edge Contrast Proximity Index, class area proportion, class area, patch size, radius of gyration, number of patches, shape and neighbour distance (10)	(AHP)	Rainwater harvesting, analytic hierarchy process, landscape metrics	21,565	250 150	0–1	12–23 °C	Nonequal	Biophysical criteria
2-	(S. H.	Saudi Arabia, 2015	slope, rainfall, runoff, soil	GIS-based (DSS)	Geographic information system,		200–600	(1–5)	12–23 °C	Nonequal	Biophysical

	Mahmoud & A. A. Alazba, 2015)		texture, and land use/land cover (5)		in situ water harvesting, remote sensing, decision support system						criteria
3-	(Elewa et al., 2016)	Egypt, Sinai, 2016	Length of overland flow, drainage density stream frequency, infiltration number, bifurcation ratio, drainage texture (6)	RS and GIS techniques	Runoff water harvesting, remote sensing, GIS weighted spatial probability modelling, watershed morphometry	23,380.93	95 mm (Weather &Climate, 2019)	(1–4)	23.2 °C (Weather&Climate, 2019)	Equal and nonequal weights	Biophysical criteria
4-	(Jamali & Ghorbani Kalkhajeh, 2020)	Iran, 2020	Proximity to qanat, slope, geomorphology, climate, land use, rainfall, geology, distance to rock source, fault, stream, well, water spring, proximity to road, proximity to village	DSS, Boolean and fuzzy logic	Water harvesting, cross section, valley's profile, check dam, satisfaction, rural		345	0–1	11 °C	Nonequal	Biophysical and socioeconomic criteria

			(14)								
5-	(Ezzeldin et al., 2022)	Northern China, 2020	Streams, roads, lake area, roads and railway, lake area or reservoir, built-up areas, rainfall runoff, drainage density, slope (10)	Remote sensing–based MCA, (WLC), combination with the Boolean approach in a GIS	Water management, geographic information system, rainwater harvesting, multi-criteria analysis, analytical hierarchy process (AHP)	744.57	325.8	(0–1)	5.2 °C	Nonequal	Biophysical and socioeconomic criteria
6-	(Mugo & Odera, 2019)	Kenya, 2019	Drainage density, lineament density, runoff density, runoff depth, slope, land use/land cover, soil texture (6)	GIS and remote sensing, use of SCS-CN for runoff	Weighted overlay analysis, runoff depth, rainwater harvesting structures, SCS-CN method		699 mm to 1058 mm	1–5	26 °C (Wikipedia, 2022c)	Nonequal	Biophysical and socioeconomic criteria
7-	(K. Mahmood et al., 2020)	Pakistan, 2020	Slope, drainage density, geological setup, soil texture and drainage stream characteristics, runoff, land use/land cover (7)	GIS, conservation service (SCS)	Rainwater harvesting Remote sensing, GIS, site suitability	2987	580	1–3	5–41 °C	Nonequal	Biophysical criteria

8-	(Sayl et al., 2017)	Iraq, 2017	Slope, land use, rainfall, geological, soil type, condition, road, vegetation, village, sediment, evaporation (10)	RS, MCA fuzzy, AHP	GIS. Multi-criteria decision techniques, rainwater harvesting structure, remote sensing	13,370	115	(0–1)	2.6–42.8 °C	Equal, and nonequal weights	Biophysical and socioeconomic criteria
9-	(Mahmoud et al., 2016)	Egypt, 2016	land use, land cover, slope, runoff coefficient precipitation, soil type (5)	GIS and (DSS) and remote sensing	Normalized difference, drought management, decision support system (DSS), geographic information system, vegetation index (NDVI), multi-criteria evaluation, rainwater harvesting, analytical hierarchy process (AHP)	10,130	110	1–5	32 °C	Nonequal	Biophysical criteria
10-	(Karani et al., 2019)	India, 2019	Stream networks, digital elevation, soil quality (3)	GIS and digital elevation model (DEM), ArcGIS	Rainwater harvesting, DEM, India, drought			None	26.98 °C (National Informatics Centre, 2022)	Nonequal	Biophysical
11-	(Faisal &	Iraq	Land use/land	GIS, multi-	Water harvesting,	6135.77	350	1–5	7.8—33.9	Nonequal	Biophysi

	Abdaki, 2021)		cover, slope, stream orders, rainfall, soil, elevation, runoff, roads and settlements, agriculture density, livestock water demand, population and rural density (13)	criteria model, (AHP)	Iraq, GIS, multi-criteria, AHP				°C		cal and socioeco nomic criteria
12-	(Harka et al., 2020)	Ethiopia, 2020	Soil texture, runoff, slope, stakeholders' priorities, land use/land cover (5)	(SWAT), RS, MCA	Rainfall runoff, geographic information system, the Dawe River watershed, rainwater harvesting, the Wabe Shebelle River basin, soil and water assessment tool (SWAT)	368	723.36–534	1–3	27.14 °C	Nonequal	Biophysi cal and socioeco nomic criteria
13-	(Tahvili et al., 2021)	Iran, 2021	Evaporation, rainfall, soil depth, permeability of soil, organic matter of soil, soil texture,	Geographic Information System.	Rainwater harvesting, Shannon, TOPSIS, geographic information system, entropy	83,000	115	1–4	19.17 °C (Weathe r&Clima te, 2018)	Nonequal	Biophysi cal and socioeco nomic criteria

			electrical EC of soil,vegetation condition, vegetation types, percentage of vegetation, fault density, slope aspect, EC of water, groundwater, groundwater drop transport capability, drainage density, stream order, runoff, discharge management, land use, participation, alluvium thickness, distance from water resources, distance from a road, population density								
14-	(Elewa	Egypt, 2021	Flood,	WMS and	Runoff water	3515	54.87	0–100	23.2 °C	Equal and	Biophysi

	et al., 2021)		maximum flow distance, drainage density, infiltration, slope, watershed length, watershed area, flow distance (8)	remote sensing techniques, (MPDSM)	harvesting (RWH), remote sensing, analytical hierarchy process (AHP), multi-parametric spatial model (MPDSM), dry regions, decision				(Weather &Climate, 2019)	nonequal weights	cal criteria
15-	(Karimi & Zeinivand, 2021)	Iran, 2021	Temperature, precipitation, discharge, soil texture, land use, discharge density, slope, evapotranspiration (8)	GIS, (AHP), (WLC), multi-criteria decision analysis	AHP,WetSpa model, GIS, WLC, RWH	1132	528.3	0–1	4.85–25.16 °C	Nonequal weights	Biophysical criteria
16-	(Al-Ghobari & Dewidar, 2021)	Saudi Arabia, 2021	Rainfall, soil, slope, land use/land cover, drainage network (5)	GIS, MCDA, SCS-CN	GIS, MCDA, rainwater harvesting, suitability SCS-CN, AHP	681	197	1–3	29 °C	Nonequal	Biophysical criteria
17-	(Aghad et al., 2021)	Morocco, 2021	Soil texture, drainage density, slope, land use/land cover, runoff	GIS-based fuzzy (FAHP), remote sensing, (DEM)	RWH Suitability, SCS-CN, FAHP, RS, GIS, Kenitra province	3052	450	0–1	13.1–20.1 °C	Nonequal	Biophysical criteria

			(5)								
18-	(Aghaloo & Chiu, 2020)	Iran, 2020	Rainfall, Spatial Geographic Information, Slope, Land use/cover, Soil texture, Drainage network, Basin/sub basin, River, Road and railway, Fault, City. (10)	Best-Worst Method and fuzzy logic in a GIS-based decision support system	RWH, BWM, agriculture, decision support system	12,981	125–700	1–5	15.6 °C (Wikipedia., 2022)	None	Biophysical and socioeconomic criteria
19-	(Zheng et al., 2018a)	China, 2018	Slope and hydrological soil groups, land use, hydrological soil groups (4)	ArcGIS, SCS-CN model	---------	90,021	370 mm (Wikipedia., 2022)	1–4	0–7 °C	None	Biophysical criteria
20-	(Sayl et al., 2019a)	Iraq, 2019	Lineament frequency, drainage frequency density, slope, maximum flow distance, stream order, flood, basin area,	GIS techniques, (DEM), remote sensing, (SRTM)	Barrages, reservoirs, dams, hydrology, water resource, environment	13,370	115	0–1	2.6–42.8 °C	Equal weight and nonequal	Biophysical and socioeconomic criteria

			geological condition, distance from villages, distance from main roads, geometric and morphometric, basin length, vegetation index, land use (14)								
21-	(Rejani et al., 2017)	India, 2017	Soil texture, rainfall, soil depth, land use/land cover, slope	GIS, Google Earth, remote sensing	water-harvesting runoff, remote sensing, GIS, structures' potential	16,600	735 mm	NA	11–45 °C	None	Biophysical criteria
22-	(El-Awar et al., 2000b)	Lebanon, 2000	Slope, permeability, runoff coefficient, stream order, watershed area, soil type, rainfall (7)	Hydrologic modelling, (AHP)	Hydrologic modelling, geographic information systems, water harvesting, Lebanon, analytic hierarchy process		300 mm	0–1	16.23 °C (Climate change knowledge portal, 2022)	Nonequal	Biophysical criteria
23-	(Tiwari et al., 2018)	Rajasthan/India, 2018	Soil map, rainfall, drainage network, land	MCAintegrated with RS and GIS	GIS rainwater harvesting, DEM, suitable location, surface runoff	162	234.88	1–3	31.9–18.8 °C (Wikipedia, 2022b)	None	Biophysical criteria

			use/land cover, depth of depression, slope, runoff (7)								
24-	(Mbilinyi et al., 2007)	Tanzania, 2007	Drainage, slope, land use/land cover, soil texture, soil depth, rainfall (6)	(DSS), remote sensing	Remote sensing, rainwater harvesting, geographic information systems, decision support system, technologies		400–700	0–100	26.55 °C (World climate guide, 2020)	Nonequal	Biophysical criteria
25-	(Sayl et al., 2020)	Iraq, 2020	Soil texture, drainage, land use/land cover, rainfall, slope (5)	RS, MCD		452.6	116	1–5	8–33 °C	Nonequal	Biophysical
26-	(Abdeladhim et al., 2022)	Tunisia, 2022	Economic, social, environmental indicators, land use, slope, stream network, road network (6)	Geographic information systems	Spatial multi-criteria, rainwater harvesting, indicator, analysis, Tunisia, composite sustainability	361	157 mm.	0–10	−3–48 °C	Nonequal	Biophysical and socioeconomic
27-	(Doulabian et al., 2021)	Iran, 2021	Soil type, soil depth, rainfall, land use, slope (5)	GIS, SWAT, (WLC), multi-criteria decision analysis	SWAT model, geospatial techniques, arid and semi-arid regions, rainwater harvesting, multi-criteria	9762	303	1–4	11.6–26.7 °C	Nonequal	Biophysical criteria

					decision analysis						
28-	(F. E. El Ghazali et al., 2021)	Morocco, 2021	Land use/land cover, soil type, lithology, rainfall, hydrographic typology, slope, lineament density (7)	RS and GIS data	Remote sensing, geographic information system water harvesting structures, multi-criteria analysis, dam	20,500	300	0–10	20 °C	None	Biophysical criteria
29-	(Balkhair & Ur Rahman, 2021)	Saudi Arabia, 2021	Slope, alluvial, drainage density, rainfall distribution, runoff depth, soil, closeness to streams, curve number (8)	AHP, GIS, RS.	AHP, rainwater harvesting, pairwise comparison, arid regions, suitability map	572.17	95	1–5	30.8 °C (wikipedia, 2022a)	Nonequal	Biophysical criteria
30-	(Kumar et al., 2008)	India, 2008	Geomorphology, land use/land cover, road, drainage and lineaments (5)	Remote Sensing and GIS	Rainwater harvesting site suitability	560	747.52	0–100 Rank 1–4	32.1 °C	Nonequal	Biophysical and socioeconomic
31-	(Mahmoud, Mohammad, et	Saudi Arabia, 2015	Slope, runoff, rainfall, soil texture, land use/land cover (5)	GIS, DSS	Rainwater harvesting, GIS, multi-factor evaluation (MFE), analytical hierarchy	12,000	600	1–5 suitability	12–23 °C	Nonequal	Biophysical

	al., 2015)				process, decision support system (DSS)						
32-	(Farooq et al., 2022)	Punjab, Pakistan, 2022	Slope, runoff depth, land use/land cover, drainage density (4)	MCA, GIS, AHP	HEC-GeoHMS, rainwater harvesting, SCS-CN modification, satellite, multi-criteria analysis, water resource management, remote sensing	300	781.4	0–100	21.5 °C (Wikipedia, 2022d)	Nonequal	Biophysical criteria
33-	(Al-Adamat et al., 2010)	Northern Jordan, 2010	Distance to international borders, distance to roads, Distance to wells, distance to wadis, distance to roads, distance to urban centres, distance to faults, soil, rainfall, slope (12)	GIS, Boolean	WLC, GIS, Jordan, ponds, Boolean, harvesting	2611	600	(1–4)	20.36 °C (climate Weather and portal, 2021)	Nonequal	Biophysical and socioeconomic criteria
34-	(Alem et al., 2022)	Northern Ethiopia, 2022	Land use/land cover, soil texture, project, workforce and	GIS-, MCA, hydrological model	Catchment multi-criteria analysis, SCS curve number, water harvesting	1797	610	1–5	17 °C (World climate	Nonequal	Biophysical and socioeconomic

			people's priorities and water laws, rainfall, slope, runoff, implementation costs, accessibility (8)		techniques, Werie, analytical hierarchy process, surface runoff				guide, 2022)		criteria
35-	(Al-Khuzaie et al., 2020)	Al-Qadisiyah, Iraq, 2020	Runoff, soil, rainfall (3)	Geographical information system techniques, multi-criteria evaluation techniques	GIS multi-criteria, clean water quality, rainwater harvesting, runoff, remote sensing, water availability.	8957.682	180	(1–4)	25 °C	Nonequal	Biophysical criteria
36-	(Shadmehri Toosi et al., 2020)	Iran, 2020	Roads, faults, rainfall, land use, slope, soil depth, drainage density, drainage networks, RWH zones, soil type, farms and wells, urban areas (11)	MCA, hydrological models	Rainwater harvesting, decision support system, geospatial techniques, water conservation	9762	262	0–1	11.6–26.7 °C	Nonequal	Biophysical and socioeconomic criteria
37-	(Al-	Iraq, 2017	Land cover, surface distance	GIS, fuzzy, AHP,	Analytic hierarchy process, system, Iraq,	2098	190	(1–5)	23.74 and 26.43 °C	Nonequal	Biophysical

	Abadi et al., 2017)		to river, slope, soil, runoff (5)		water harvesting, fuzzy logic, geographical information						criteria
38-	(Nyirenda et al., 2021)	Malawi, 2021	Land use, soil type, slope, runoff, environmental factors, rainfall, socioeconomic factors (6)	RS, number (SCS-CN)	Harvesting technologies, rainwater, geographic information systems, service contour-tied ridging soil mulching, soil conservation	343.1	700–900	1–5	12–30 °C	Nonequal	Biophysical, socioeconomic
39-	(Grum et al., 2016)	Northern Ethiopia, 2016	Soil data, drainage network, slope map, land use map, rainfall, stream order (6)	GIS-based multi-criteria analysis	Decision support suitability approach, multi-criteria analysis, indicators selection, suitability maps, participatory	2380	520–680	1–10	16–20 °C	Nonequal	Biophysical criteria
40-	(Al-Adamat, 2008)	Jordan, 2008	Distance to international borders, distance to Agricultural areas, distance to roads, distance to urban areas, distance to	GIS layers, Boolean logic to find combinations of layers	Jordan, basalt, harvesting, ponds, GIS	56,930	100–300	0–1 (suitability)	35–40 °C (max annual 2–9 °C (min	Equal weights	Biophysical and socioeconomic criteria

			wells, soil, slope, rainfall, distance to wadi, distance to water pipeline (10)								
41-	(Ochir et al., 2018)	Mongolia, 2018	Runoff, forest land, mining area, agricultural land, road, soil type, surface slope, precipitation, catchment slope, drainage density, settlement area, water catchment area, lake (14)	GIS, AHP, spatial multi-criteria analysis	Analytic hierarchy process, water harvesting pond, spatial multi-criteria analysis, error matrix, proper sink	1850.09	250 mm	0–1	0–25 °C	Nonequal	Biophysical and socioeconomic criteria
42-	(Yegizaw et al., 2022)	Northwest Ethiopia, 2022	Soil depth, slope, rainfall, distance from settlement, lineament density, soil, land use, distance from	AHP and combined in a GIS environment	Drought-prone area, rainwater harvesting, site suitability	7073.79	620 mm	(1–4)	27 °C	Nonequal	Biophysical criteria

			road (8)								
43-	(Shadeed et al., 2020)	West Bank, Palestine, 2020	{Agricultural water poverty index (AWPI)}: (agricultural access, citizens above poverty line, illiteracy, agricultural extension, agricultural resources, drainage network, irrigated areas to governorate area), rainfall, curve number, surface slope, soil texture, evapotranspiration (ET), electrical conductivity, land use (14)	GIS environment, analytical hierarchy process (AHP)	Agricultural rainwater harvesting, GIS agricultural, rainwater suitability, sustainable agriculture, water poverty, harvesting	5860	153–698	1–10	23.44 °C (weather and climate, 2010)	Nonequal	Biophysical criteria
44-	(A. Adham	Wadi Oum Zessar, Tunisia, 2016	Climate and drainage (rainfall–	Analytical hierarchy process (AHP)	RWH suitability, AHP, approach, GIS	367	150–230	(1–5)	19–22 °C	Nonequal	Biophysical criteria

	et al., 2016b)		drainage length), structure design (storage capacity–structure dimensions ratio –CCR ratio), site characteristic (soil depth–soil texture– slope), socioeconomic (distance to settlements), structure reliability (reliability ratio), demand and supply (10)	supported by a geographic information system						
45-	(Ziadat et al., 2012)	Mharib, Jordan, 2012	Soil depth, soil texture, land tenure, slope, stoniness (5)	GIS	Socioeconomic and biophysical benchmark suitability, watershed, land tenure, participatory approach multidisciplinary, GIS, suitability	60	100–150	none	Nonequal	Biophysical and socioeconomic criteria

46-	(Ezzeldin et al., 2022)	Sinai Peninsula, Egypt, 2022	Slope, land use/land cover, runoff depth topographic wetness index, drainage density, distance to roads, basin area, lineament frequency density, infiltration number, flow distance, distance to built-up areas, Bedouin community, distance to roads (12)	GIS, RS, MCA, hydrological modelling	Boolean analysis, multi-criteria analysis, remote sensing, sustainable development goals	3580	55.86	0–1		Nonequal	Biophysical and socioeconomic
47-	(Darabi et al., 2021)	Maharloobakhtegan basin, Fars province, southern Iran, 2021	Distance from road, slope, temperature, land use, soil type, population density, distance from lakes, elevation,	GIS and remote sensing techniques	Planning AIAs, optimum range artificial intelligence algorithms (AIAs), water scarcity, RWH, probability curve (PC)	31,511	350–390 mm	(0–1)	12.80–15.16 °C	None	Biophysical and socioeconomic criteria

			precipitation, curve number (CN), geology, distance from river (13)								
48-	(Yousif & Bubenzer, 2015)	Northwestern Coast of Egypt, 2015	Landform, watershed area, rainfall amounts, geologic setting drainage lines, surface runoff, flow accumulation, flow direction, slope, morphometric parameters (10)	GIS and remote sensing	Geomorphology, rainwater harvesting, remote sensing, runoff, GIS	770	164 mm	(1–5)	22–31.6 °C 7.2–23.7 °C	None	Biophysical criteria
49-	(Alkaradaghi et al., 2022)	Qaradaqh basin, Sulaimaniyah city, Iraq, 2022	Stream, geology, rain lineament, DEM, CN, land use/land cover, soil, villages, slope (10)	GIS, MCDM, AHP, sum average weighted method SAWM, fuzzy-based index (FBI) techniques	Drought crisis, water shortage, AHP, sustainable water development	605	650 mm	(1–10)	18 °C to 40 °C	Nonequal	Biophysical and socioeconomic
50-	(Mahmo	Egypt, 2015	Slope, soil texture runoff,	(AHP), (DSS)	Decision support system (DSS),	556,961	100–200	(1–5)		Nonequal	Biophysical

	ud, Alazba, et al., 2015)		land use/land cover, rainfall (5)	2 level (2,5)	geographic information system, rainwater harvesting, analytical hierarchy process (AHP), multi-criteria evaluation, (RWH)					criteria
51-	(Mbiliny i et al., 2005)	Makanya catchment, Kilimanjaro region, Tanzania, 2005	Production (ndiva), near water sources, e.g., stream, sloping terrain, shallow water table, Charco Dam (lambo), soils with good flat area, far from settlement, presence of conveyance system, non-saline soils, diversion canal (sasi), hard stable soils, water holding capacity, gentle slope, no rocks, ridges and border soils,	Geographic information system decision-making process, tow level (4,15)	Rainwater harvesting, indigenous knowledge, agriculture	300	250 and 400 mm	(1–3)	None	Biophysi cal criteria

			water storage structure for crop slopes, soil type runoff (location of the farm) (15)								
52-	(Khudhair et al., 2020b)	Iraq, Anbar Province, Al-Muhammadi Valley, 2020	Soil texture, drainage density, slope, vegetation cover, distance to the roads. (5)	Remote sensing, GIS		5332	115 mm	1–4	0–52 °C	Nonequal weight	Biophysical and socioeconomic criteria
53-	(Ouali et al., 2022)	Toudgha watershed, Morocco, 2022	Slope, drainage density, permeability, runoff depth, fracture density, rainfall, groundwater depth, closeness to stream (8)	MCDM coupled with GIS techniques, 2 level (2,8)	GIS, remote sensing, water management, rainwater harvesting, MCDM	2296	40 to 345 mm	1–5	18 °C	Nonequal	Biophysical criteria
54-	(Alwan et al., 2020)	Maysan Province, Iraq, 2020	Stream order, roads, soil type, evaporation, slope, NDVI, precipitation (7)	GIS, Multi-Criteria Evaluation RHHS = Wci × Rsc 2 level (3, 7)	GIS, MCE, water harvesting catchment, spatial analysis, fuzzy model	16,072	rainfall range (14_39) mm/month	(0–1)	23.74–26.43 °C	Nonequal	Biophysical and socioeconomic criteria

55-	(Shalamzari et al., 2019)	Kavir Area of Iran, 2019	Soil texture, slope and drainage network, rainfall, infiltration (5)	Multi-criteria techniques	Suitability, GIS, arid land, fuzzy, AHP, runoff harvesting, MCDM	680,000 hectares	240 mm	(1–5)	Annual temperature of 19 °C in	Nonequal	Biophysical criteria
56-	(Aly et al., 2022)	Wadi Hodein Basin, Red Sea, Egypt, 2022	Drainage density, infiltration number, basin area, max. flow distance, flood volume, basin length, basin slope, flow distance (8)	Integration between watershed modelling and remote sensing	Remote sensing, (RWH), arid and semi-arid, rainwater harvesting regions, spatial probability model (WSPM), weighted	11,600		0–1	37.5–14 °C	Two scenarios Equal and nonequal weights	Biophysical criteria
57-	(Radwan & Alazba, 2022)	Saudi Arabia, Riyadh, 2022	Land use/land cover, slope, precipitation, potential runoff coefficient , soil texture (5)	Multi-criteria DSS, AHP	GIS, RST, arid climate, spatial distribution PRWH, MCDSS, AHP	8500	150 mm	(1–5)	(28–46 °C) (15–35 °C)	Nonequal	Biophysical
58-	(Zheng et al., 2020)	Xinjiang, China, 2020	Runoff, slope, crop characteristics, soil, rainfall, land use/land	GIS, MCA	Runoff potential, ecological restoration, gully erosion, rainwater harvesting		400 mm	(1–5)	10 °C	Nonequal	Biophysical criteria

			cover (5)								
59-	(Makhamreh, 2011)	Mediterranean region in northern Jordan, 2011	Type of soil, vegetation, land use types, geometric, slope, sub-catchments, water drainage (6)	GIS, DEM and remote sensing technique	Management of watershed, landsat organic carbon colour, soil	1000	150–650 mm	NA	5.2–22.0 °C 2.5–28 °C	None	Biophysical criteria
60-	(Hadadin et al., 2012)	Northeastern desert, Jordan, 2012	Drainage networks, slope, drainage network, flow direction, runoff (5)	GIS	Flow discharge, harvesting, unit hydrograph, watershed models		200 mm	NA		None	Biophysical criteria
61-	(Ahmed et al., 2007)	Oasis zone, Mauritania, 2007	Land cover, drainage, geomorphology, slope, geology, lineament (6)	Landsat image and GIS based on AHP	Water harvesting, GIS, remote sensing	455,745 hac	Arid land	NA		Nonequal	Biophysical criteria
62-	(K. Sayl et al., 2020)	Wadi Horan, Iraq, 2020	Sediment index, cost–benefit index, hydrology index, evaporation index (4)	GIS-based multi-criteria analysis, the analytic hierarchy process (AHP), fuzzy	Harvesting, GIS, AHP, rainwater, fuzzy		115 mm	1–10		Nonequal	Biophysical criteria

63-	(Adham et al., 2022)	West Bank, Palestine, 2022	Runoff, rainfall, slope, soil texture, land use (5)	Analytical hierarchy process (AHP) methods and GIS techniques	Technique (RWH), analytical hierarchy process, the West Bank, Palestine, rainwater harvesting method (AHP), GIS	5860	450	0–100		Nonequal	Biophysical criteria
64-	(Hashim & Sayl, 2021)	Western Desert of Iraq, 2021	Irrigated lands, slope, land use/land cover, residential areas, distance from roads, runoff, soil texture (7)	Boolean, (WLC)	Rainwater harvesting, earthen dam, GIS, WLC, Boolean	1953.1	115	(1–4)	40–2.6 °C	Nonequal	Biophysical and socioeconomic criteria
65-	(Khan et al., 2022)	Ghazi Tehsil, Khyber Pakhtunkhwa, Pakistan, 2022	Elevation, land cover, rainfall, drainage and various land uses (such as roads, settlements), surface slope, geology, soil (7)	Geospatial Approach, GIS, arc GIS	SCS-CN, HMS, geospatial technology, method, harvesting, HEC-geo-weighted overlay analysis, rainwater	348	Semi-arid	(1–3)	4.8–44 °C	Nonequal	Biophysical and socioeconomic criteria
66-	(Manaouch et al., 2021)	Morocco, 2021	Drainage density, slope, runoff, land use/land cover, soil texture	GIS, FAHP	Fuzzy AHP, GIS, rainwater harvesting, SCS-CN, WaTEM/SE, DEM	4435	119 to 377 mm	1–4	20 °C	Nonequal	Biophysical

			(5)								
67-	(Buraihi & Shariff, 2015)	Kirkuk, Iraq, 2015	Runoff depth, slope, drainage, land use/land cover (4)	RS, GIS,	Rainwater harvesting, remote sensing and geographic information system, multi-criteria decision analysis	4875	360 mm	1–3		Nonequal	Biophysical criteria
68-	(Aklan et al., 2022)	Sana'a Basin, Yemen, 2022	Slope, soil type, land use/land cover, precipitation, proximity to urban areas, water wells, dams, roads, open sewage passage, wadis, drainage networks (11)	Multi-criteria analysis, analytical hierarchy process	RWH, spate, indigenous, multi-criteria, socioeconomic criteria, dry areas, systems analysis irrigation systems, limited data	3200 km²	240 mm	1–5	20 °C	Nonequal	Biophysical and socioeconomic criteria

Table A 2 Summary of advantages and disadvantages of existing criteria.

Reference	Selection Process for Criteria	Advantage	Disadvantage
(Albalawneh et al., 2015)	Experts and stakeholders	1- The analytical hierarchy process (AHP) was used for questionnaire output weighting. 2- Engagement of stakeholders—included them for	1- Socioeconomic and ecological criteria were not included. 2- The range of suitability (0–1) indicates no flexibility in

		indicator choice and participation in weightings.	choices.
(S. H. Mahmoud & A. A. Alazba, 2015)	Literature	1- The range of suitability (1–5) gives flexibility in choices. 2- The analytical hierarchy process (AHP) was used for questionnaire output weighting.	1- Socioeconomic and ecological criteria were not included. 2- There is no mention of the number of experts.
(Elewa et al., 2016)	Literature	1- Applied three scenarios of weighting, which caused the differences between the results.	1- Socioeconomic and ecological criteria were not included. 2- Stakeholders and experts were not engaged.
(Jamali & Ghorbani Kalkhajeh, 2020)	Literature	1- The satisfaction of stakeholders, rural residents, and people. 2- The analytical hierarchy process (AHP) was used for questionnaire output weighting.	3- Socioeconomic and ecological criteria were not included. 4- The range of suitability (0–1) indicates no flexibility in choices.
(Ezzeldin et al., 2022)	Literature	1- The analytical hierarchy process (AHP) was used for questionnaire output weighting. 2- This is a cost-effective and low-data-intensive strategy. 3- RWH structure types were taken into consideration.	1- Ecological criteria were not included. 2- The range of suitability (0–1) indicates no flexibility in choices. 3- There was no field investigation to ensure there is no other land use conflict.
(Mugo & Odera, 2019)	Availability of data	1- The range of suitability (0–5) indicates flexibility in choices.	2- Ecological criteria were not included. 3- Stakeholders and experts were not engaged.
(K. Mahmood et al., 2020)	Literature	1- RWH structure types were taken into consideration.	1- Socioeconomic and ecological criteria were not included. 2- Stakeholders and experts were not engaged.
(Sayl et al., 2017)	Literature	1- The analytical hierarchy process (AHP), fuzzy AHP, and ROM were used for questionnaire output weighting. 2- Four scenarios of weighting were applied to determine the differences between the results.	1- Ecological criteria were not included. 2- The range of suitability (0–1) indicates no flexibility in choices. 3- Stakeholders and experts were not engaged.
(Mahmoud et al., 2016)	Strategy of selecting criteria unclear	1- The range of suitability (0–5) indicates flexibility in choices. 2- The analytical hierarchy process (AHP) was used for questionnaire output weighting. 3- Two scenarios of weighting were applied to determine	4- Socioeconomic and ecological criteria were not included. 5- The method of weighting was unclear.

		the differences between the results.	
(Karani et al., 2019)	None		1- Socioeconomic and ecological criteria were not included. 2- The method of weighting was unclear.
(Faisal & Abdaki, 2021)	Literature reviews	1- The analytical hierarchy process (AHP) was used for questionnaire output. 2- Experts, local authorities, and the literature were used to identify the weight of the criteria. 3- The range of suitability (1–5) indicates flexibility in choices.	1- Ecological criteria were not included. 2- The number of experts and stakeholders is unknown.
(Harka et al., 2020)	Literature reviews	1- Experts and the literature were used to identify the weight of the criteria. 2- The analytical hierarchy process (AHP) was used for questionnaire output.	1- Ecological criteria were not included. 2- The number of experts and stakeholders is unknown.
(Tahvili et al., 2021)	Experts' opinions	1- Experts were engaged to determine the weights of the criteria. 2- The range of suitability (1–4) indicates flexibility in choices.	1- The number of criteria is too large to be implemented in a practical way. 2- The number of experts is unknown. 3- Ecological criteria were not included.
(Elewa et al., 2021)	Literature	1- The analytical hierarchy process (AHP) was used for questionnaire output. 2- The range of suitability (0–5) indicates flexibility in choices. 3- Experts were hired to determine criteria weights.	1- Socioeconomic and ecological criteria were not included. 2- The number of experts is unknown.
(Karimi & Zeinivand, 2021)	None	1- The analytical hierarchy process (AHP) was used to weight output. 2- Experts were engaged to determine the weights of the criteria.	1- Strategy of selecting criteria unclear. 2- The number of experts and stakeholders is unknown. 3- The range of suitability (0–1) indicates no flexibility in choices. 4- Socioeconomic and ecological criteria were not included.
(Al-Ghobari &	Literature	1- The analytical hierarchy process (AHP) was used for	1- Socioeconomic and ecological criteria were not

Dewidar, 2021)		weights output.	included. 2- Stakeholders and experts were not engaged.
(Aghad et al., 2021)	Literature	1- The analytical hierarchy process (AHP) was used for weights output.	1- Socioeconomic and ecological criteria were not included. 2- The range of suitability (0–1) indicates no flexibility in choices.
(Aghaloo & Chiu, 2020)	Literature	1- The range of suitability (1–5) indicates flexibility in choices. 2- The analytical hierarchy process (AHP) was used for decision making, or experts' questionnaire output.	1- Ecological criteria were not included. 2- The number of experts is unknown.
(Zheng et al., 2018a)	None	1- The range of suitability (1–4) indicates flexibility in choices.	1- Socioeconomic and ecological criteria were not included. 2- Stakeholders and experts were not engaged.
(Sayl et al., 2019a)	None	1- The ranking process was performed based on the analytical hierarchy process (AHP), fuzzy AHP, rank order method (ROM), and variance inverse (VI). 2- Decision makers were engaged to identify the weighting of criteria. 3- Area–volume curve was used for geometric properties.	1- Ecological criteria were not included. 2- The range of suitability (0–1) indicates no flexibility in choices. 3- The number of decision makers is unknown.
(Rejani et al., 2017)	None	1- RWH structure types were taken into consideration.	1- Socioeconomic and ecological criteria were not included. 2- Stakeholders and experts were not engaged. 3- There is no mention of weights for the criteria.
(El-Awar et al., 2000b)	Experts and literature	1- Experts were engaged to identify the weighting of criteria. 2- The analytical hierarchy process (AHP) was used for questionnaire output.	1- Socioeconomic and ecological criteria were not included. 2- The range of suitability (0–1) indicates no flexibility in choices. 3- The number of experts is unknown.
(Tiwari et al., 2018)	None	1- This strategy saves time, reduces earthwork, and may be used for water resource management planning.	1- Socioeconomic and ecological criteria were not included.

			2- Stakeholders and experts were not engaged. 3- There is no mention of weight for the criteria.
(Mbilinyi et al., 2007)	Not mentioned	1- The range of suitability (0–100) gives flexibility in choices. 2- Employing decision support systems (DSS) to adjust suitability levels and weights based on the research area.	1- Socioeconomic and ecological criteria were not included. 2- There is no specific number for decision makers.
(Sayl et al., 2020)	Literature	1- The range of suitability (0–100) gives flexibility in choices. 2- The analytical hierarchy process (AHP) was used for questionnaire output. 3- Area elevation curve to estimate the best site for a dam.	1- Socioeconomic and ecological criteria were not included. 2- Stakeholders and experts were not engaged.
(Abdeladhim et al., 2022)	Literature and experts	1- Stakeholders and experts were engaged in identifying criteria and weights. 2- The number of stakeholders and experts was determined. 3- The range of suitability (0–10), gives flexibility in choices.	1- Ecological criteria were not included.
(Doulabian et al., 2021)	Literature	1- The analytical hierarchy process (AHP) was used for questionnaire output. 2- RWH structure types were taken into consideration. 3- Stakeholders and experts were engaged to identify the weighting of criteria.	1- Socioeconomic and ecological criteria were not included. 2- The number of experts is unknown.
(F. E. El Ghazali et al., 2021)	Literature	1- The range of suitability (0–10) gives flexibility in choices. 2- Experts were engaged to identify the weighting of criteria.	1- Socioeconomic and ecological criteria were not included. 2- The number of experts is unknown.
(Balkhair & Ur Rahman, 2021)	Literature	1- The analytical hierarchy process (AHP) was used for questionnaire output. 2- The range of suitability (1–5) gives flexibility in choices. 3- Experts were engaged to identify the weighting of criteria.	1- Socioeconomic and ecological criteria were not included. 2- The number of experts was unknown.

(Kumar et al., 2008)	Data availability	1- The range of suitability (0–10) gives flexibility in choices. 2- RWH structure types were taken into consideration as criterion.	1- Ecological criteria were not included. 2- Stakeholders and experts were not engaged.
(Mahmoud, Mohammad, et al., 2015)	None	1- The range of suitability (1–5) gives flexibility in choices. 2- The analytical hierarchy process (AHP) was used for questionnaire output. 3- Decision makers were involved in the weighting of criteria.	1- Socioeconomic and ecological criteria were not included. 2- The number of decision makers is unknown.
(Farooq et al., 2022)	Literature	1- Weights were assigned based on the literature. 2- The analytical hierarchy process (AHP) was used for weight output.	1- Ecological criteria were not included. 2- Stakeholders and experts were not engaged.
(Al-Adamat et al., 2010)	Literature	1- Weights were assigned based on the literature.	1- Ecological criteria were not included. 2- Stakeholders and experts were not engaged.
(Alem et al., 2022)	Literature	1- The range of suitability (1–5) gives flexibility in choices. 2- The analytical hierarchy process (AHP) was used for weights output. 3- RWH structure types were taken into consideration.	1- Ecological criteria were not included. 2- Stakeholders and experts were not engaged.
(Al-Khuzaie et al., 2020)	None	1- The range of suitability (1–4) gives flexibility in choices.	1- Socioeconomic and ecological criteria were not included. 2- Stakeholders and experts were not engaged.
(Shadmehri Toosi et al., 2020)	Literature	1- The analytical hierarchy process (AHP) was used for questionnaire output. 2- Experts were involved in the weighting of criteria.	1- The range of suitability (0–1) indicates no flexibility in choices. 2- Ecological criteria were not included. 3- The number decision makers was unknown.
(Al-Abadi et al., 2017)	Literature review and available data	1- The analytical hierarchy process (AHP) was used for questionnaires' output. 2- Experts were involved in the weighting of criteria. 3- The range of suitability (1–5) gives flexibility in choices.	1- Socioeconomic and ecological criteria were not included. 2- The number of decision makers is unknown.
(Nyirenda et al.,	Literature	1- The analytical hierarchy process (AHP) was used for	1- Ecological criteria were not included.

2021)	review	weights output. 2- The range of suitability (1–5) gives flexibility in choices.	2- Stakeholders and experts were not engaged.
(Grum et al., 2016)	Stakeholder workshop	1- The analytical hierarchy process (AHP) was used for weights output. 2- Experts were involved in the weighting of criteria. 3- The range of suitability (1–10) gives flexibility in choices.	1- Socioeconomic and ecological criteria were not included. 2- The number of stakeholders is unknown.
(Al-Adamat, 2008)	Literature	1- Weights of criteria were equally distributed in order to promote respect in all areas	1- The range of suitability (0–1) indicates no flexibility in choices. 2- Ecological criteria were not included. 3- Stakeholders and experts were not engaged.
(Ochir et al., 2018)	Literature	1- The analytical hierarchy process (AHP) was used for weights output.	1- The range of suitability (0–1) indicates no flexibility in choices. 2- Ecological criteria were not included. 3- Stakeholders and experts were not engaged.
(Yegizaw et al., 2022)	Literature	1- The analytical hierarchy process (AHP) was used for weights output. 2- The range of suitability (1–4) gives flexibility in choices.	1- Socioeconomic and ecological criteria were not included. 2- Stakeholders and experts were not engaged.
(Shadeed et al., 2020)	Literature	1- The analytical hierarchy process (AHP) was used for weights output. 2- The range of suitability (1–10) gives flexibility in choices. 3- The weights of the criteria were based on the literature.	1- Socioeconomic and ecological criteria were not included. 2- Stakeholders and experts were not engaged.
(A. Adham et al., 2016b)	Literature	1- The analytical hierarchy process (AHP) was used for weights output. 2- The range of suitability (1–5) gives flexibility in choices. 3- Stakeholders and experts were involved in the weighting of criteria. 4- The number of stakeholders and experts was determined.	1- Ecological criteria were not included.
(Ziadat et al., 2012)	Literature	1- Discussions with owners and people to see the requirements and land tenure information.	2- Ecological criteria were not included. 3- The criteria were limited.

(Ezzeldin et al., 2022)	Literature	1- The analytical hierarchy process (AHP) was used for weights output. 2- The weights were determined by the literature. 3- RWH structure types were taken into consideration.	1- The range of suitability (0–1) indicates no flexibility in choices. 2- Ecological criteria were not included. 3- Stakeholders and experts were not engaged.
(Darabi et al., 2021)	Literature	1- Used remote sensing for locating RWH sites.	1- Ecological criteria were not included. 2- The range of suitability (0–1) indicates no flexibility in choices. 3- Stakeholders and experts were not engaged.
(Yousif & Bubenzer, 2015)	Literature	1- The range of suitability (1–5) gives flexibility in choices.	1- Socioeconomic and ecological criteria were not included. 2- Stakeholders and experts were not engaged.
(Alkaradaghi et al., 2022)	Literature and experts	1- The analytical hierarchy process (AHP) was used for questionnaire output. 2- Stakeholders and experts were involved in the weighting of criteria. 3- The range of suitability (1–10) gives flexibility in choices.	1- Ecological criteria were not included. 2- The number stakeholders and experts is unknown.
(Mahmoud, Alazba, et al., 2015)	Literature and experts' opinions	1- The range of suitability (1–5) gives flexibility in choices. 2- The analytical hierarchy process (AHP) was used for questionnaire output. 3- Stakeholders and experts were involved in the weighting of criteria.	1- Socioeconomic and ecological criteria were not included. 2- The number stakeholders and experts is unknown.
(Mbilinyi et al., 2005)	Literature and experts' opinions	1- Stakeholders and experts were involved in the weighting of criteria. 2- The number of stakeholders and experts was determined.	1- Socioeconomic and ecological criteria were not included.
(Khudhair et al., 2020b)	Literature	1- The range of suitability (1–5) gives flexibility in choices. 2- Weights depend on the literature.	1- Ecological criteria were not included. 2- Stakeholders and experts were not engaged.
(Ouali et al., 2022)	Literature and experts	1- The analytical hierarchy process (AHP) was used for questionnaire output. 2- The range of suitability (1–5) gives flexibility in choices.	1- Ecological criteria were not included. 2- The number stakeholders and experts is unknown.

		3- Stakeholders and experts were engaged to determine criteria and weights.	
(Alwan et al., 2020)	Literature	1- Money and time needed to select the best RWH sites was saved, based on DEM and remote sensing.	1- Socioeconomic and ecological criteria were not included. 2- The range of suitability (0–1) indicates no flexibility in choices. 3- Stakeholders and experts were not engaged.
(Shalamzari et al., 2019)	Literature and experts' opinions	1- The analytical hierarchy process (AHP) was used for questionnaire output. 2- The range of suitability (1–5) gives flexibility in choices. 3- Stakeholders and experts were involved in identifying the criteria and weighting. 4- The number of stakeholders and experts was determined. (5 experts)	1- Socioeconomic and ecological criteria were not included.
(Aly et al., 2022)	Literature	1- Analysis Of Variance (ANOVA) for justifications of parameters weights	1- Socioeconomic and ecological criteria were not included. 2- The range of suitability (0–1) indicates no flexibility in choices. 3- Stakeholders and experts were not engaged.
(Radwan & Alazba, 2022)	Literature	1- The range of suitability (1–5) gives flexibility in choice. 2- The analytical hierarchy process (AHP) was used for weights output.	1- Socioeconomic and ecological criteria were not included. 2- Stakeholders and experts were not engaged.
(Zheng et al., 2020)	Literature	1- The range of suitability (1–5) gives flexibility in choice. 2- The analytical hierarchy process (AHP) was used for weights output. 3- Stakeholders and experts were involved in weighting of criteria.	1- Socioeconomic and ecological criteria were not included. 2- The number of stakeholders and experts is unknown.
(Makhamreh, 2011)	Non	1- It addresses landscape surface qualities and how built-up regions, and human building items affect surface	1- Socioeconomic and ecological criteria were not included.

		drainage and water flow.	2- Stakeholders and experts were not engaged.
(Hadadin et al., 2012)	Non	1- Using DEM to assess rainwater harvesting's potential.	1- Socioeconomic and ecological criteria were not included. 2- Stakeholders and experts were not engaged.
(Ahmed et al., 2007)	Not mentioned	1- The analytical hierarchy process (AHP) was used for weights output.	1- Socioeconomic and ecological criteria were not included. 2- Stakeholders and experts were not engaged.
(K. Sayl et al., 2020)	Not mentioned	1- AHP, fuzzy-AHP, ROM, and VI methods were used for weights output. 2- area–volume curve to find height of the structure. 3- The range of suitability (1–10) gives flexibility in choices.	1- Socioeconomic and ecological criteria were not included. 2- Stakeholders and experts were not engaged.
(Adham et al., 2022)	Literature and experts	1- The range of suitability (1–100) gives flexibility in choices. 2- The analytical hierarchy process (AHP) was used for questionnaire output. 3- Stakeholders and experts were involved in weighting of criteria.	1- Socioeconomic and ecological criteria were not included. 2- The number stakeholders and experts were unknown.
(Hashim & Sayl, 2021)	Literature	1- The range of suitability (1–4) gives flexibility in choices. 2- Area–volume curve used to find height of the structure.	1- Ecological criteria were not included. 2- Stakeholders and experts were not engaged.
(Khan et al., 2022)	Literature	1- RWH structure types of criteria were taken into consideration.	1- Ecological criteria were not included. 2- Stakeholders and experts were not engaged.
(Manaouch et al., 2021)	Literature	1- The analytical hierarchy process (AHP) was used for weights output. 2- The range of suitability (1–4) gives flexibility in choices.	1- Socioeconomic and ecological criteria were not included. 2- Stakeholders and experts were not engaged.
(Buraihi & Shariff, 2015)	Available data	1- The analytical hierarchy process (AHP) was used for weights output.	1- Socioeconomic and ecological criteria were not included. 2- Stakeholders and experts were not engaged.
(Aklan et al., 2022)	Literature	1- The analytical hierarchy process (AHP) was used for weights output. 2- Stakeholders and experts were involved in identifying the	1- Ecological criteria were not included. 2- The range of suitability (0–1) indicates no flexibility in choice.

	criteria and weighting.

APPENDIX B. Questionnaire form

Introduction and consent form

I am a PHD candidate in the Department of Civil Engineering at the University of Birmingham, UK.

My research is about **Ecological Considerations in the Selection of Rainwater Harvesting Sites in Arid and Semi-Arid Regions.**

I kindly request your participation in the following survey, which will take **10 to 15 minutes** of your valuable time. By answering the following questions, your opinion as an expert (and most probably a stakeholder) will help to refine my framework, which would enhance the performance of water in arid and semiarid regions.

All information in this questionnaire is confidential and will only be used for the purpose of scientific research. Thank you very much in advance for your time and assistance.

* Indicates required question

Do you agree to complete the survey? *

Mark only one oval.

- ( ) Yes
- ( ) No — *Skip to section 8 (**Participation Declined**)*

Pilot Study (a survey by questionnaire to* develop *the framework for identifying sites for rainwater harvesting in arid and semi-arid regions based on ecological criteria)

This survey is related to my PhD research and is an essential step in refining and validating hypotheses and criteria for an **Ecological Considerations in the Selection of Rainwater Harvesting Sites in Arid and Semi-Arid Regions.** The main aim of conducting this survey is to derive the final version of the RWH framework from the opinions of participants. Consequently, the utilisation of this framework in case studies is likely to assist decision- makers in identifying suitable sites for RWH in arid and semi-arid regions, which can help the communities in these regions manage rainwater and use it for different purposes.

The purpose of this questionnaire is to solicit the expert opinion or practical insights of individuals with expertise in ecological and environmental aspects , particularly in the context of arid and semi-arid regions. The questionnaire aims to assess the suitability of selected components and indicators, which have been derived from existing literature as well as tailored to cater to the unique characteristics of arid and semi-arid regions.

These components and indicators are intended to be integrated into a Rainwater Harvesting site selection framework. The questionnaire seeks to gather feedback on the appropriateness and relevance of these components and indicators, with the ultimate goal of developing a comprehensive and effective RWH framework for arid and semi-arid regions by integration of ecological criteria.

The structure of the questionnaire is as follows:

- A brief set of questions to capture some general background information and your level of expertise in this field.
- A visual illustration shows the mechanism of the framework.
- A series of questions to determine your expert perspective on the proposed framework components and indicators.

General questions

Q1/ Which classification aligns closest with your area of expertise and *

professional work?

Please select the most appropriate response that pertains to your current occupation.

Mark only one oval.

- Academia
- Consultant
- Government official
- Community or Non-profit organization representative
- Water company
- Technical expert Practitioner
- or Engineer Policymaker
- Policymaker
- Other: ______________________

Q2/ Where do you live (country)? *

____

Q3/A/ Are you engaged with issues related to water or involved in any of the listed

cohorts? If so, we'd greatly appreciate your insights on the subsequent questions. If not, please know that we're sincerely grateful for your time and willingness to participate.

Mark only one oval.

- Civil Engineers
- Environmentalists
- Ecologists
- Hydrologists

Q3/B/ How much experience do you have in the water sector? *

Mark only one oval.

- No experience
- 1 to 5 years
- 6 to 10 years
- 11 to 15 years
- more than 20 years

Q4/ On a Likert scale of 1 to 5, how much do you agree with the statement *

"scarcity of water is a severe problem in the 21st century"?

Mark only one oval.

- 1 = Strongly disagree
- 2 = Disagree
- 3 = Neither agree nor disagree
- 4 = Agree
- 5 = Strongly agree

Q5/ Do you believe rain water harvesting (RWH) is beneficial? *

Mark only one oval.

- Yes
- Maybe
- Unsure
- N/A

Q6/ How would you rate your level of understanding of rainwater harvesting on a scale of 1 to 5? *

Mark only one oval.

- ◯ 1 = Very little
- ◯ 2 = little
- ◯ 3 = Moderate
- ◯ 4 = good
- ◯ 5 = Excellent

Q7/ Have you utilised or do you presently employ any framework for the identification of suitable sites for rainwater harvesting in arid and semi-arid regions? *

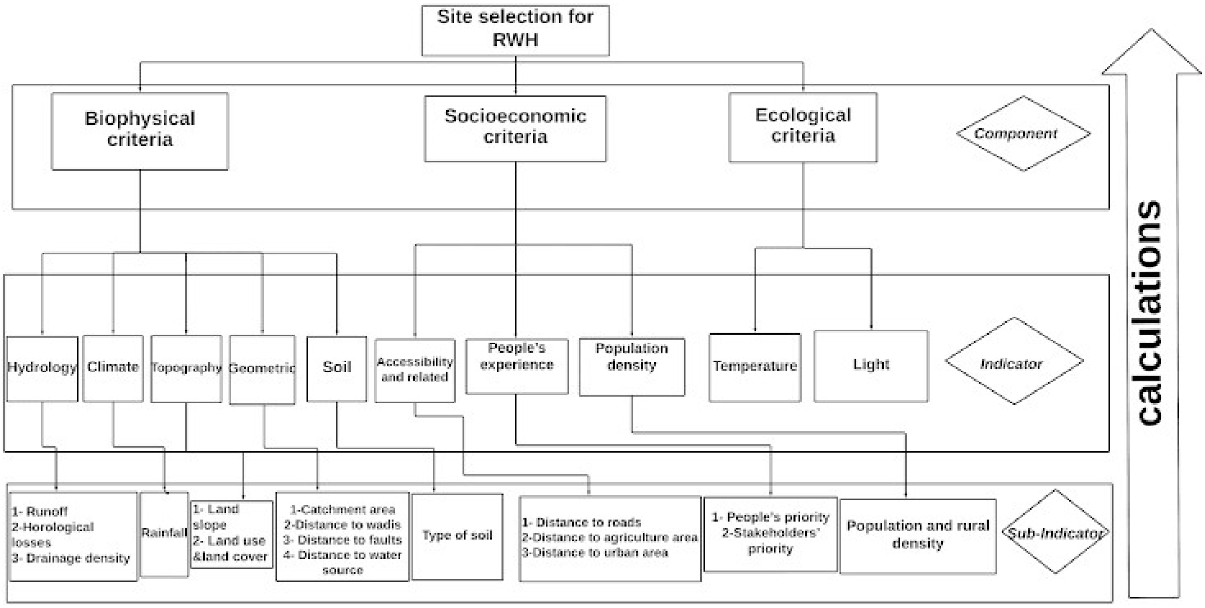
Mark only one oval.

◯ Yes ◯ No

A brief explanation of the framework

Figure 1 shows a visual example of a **framework for the identification of suitable sites for RWH in ASARs.** The final framework value, which represents the level of suitability, is obtained through a hierarchical structure. The process of calculation proceeds in a systematic manner from lower- level components to higher-level ones and involves the integration of a normalisation procedure aimed at ensuring that all numerical values are uniformly scaled within the range of 0 to 100. In our scenario, a framework is comprised of sub-indicators that must be combined and averaged in order to obtain a value for the indicator under consideration. Indicators within the same category or component undergo the same procedure. The framework's ultimate value is determined by averaging all of its components.

Figure 1 Schematic of a framework for identifying sites for RWH in *ASARs*.



Q8/ When it comes to managing water resources in arid and semi-arid regions, **the three proposed components: biophysical, socioeconomic, and ecological criteria in our framework for identifying sites for RWH in ASARs** should be calculated with the **"same weight. Do you agree with this statement?"** *

(Weight, in this context, refers to given significance or importance in RWH site selection.)

Mark only one oval.

- 1 = Strongly disagree
- 2 = Disagree
- 3 = Neither agree nor disagree
- 4 = Agree
- 5 = Strongly agree

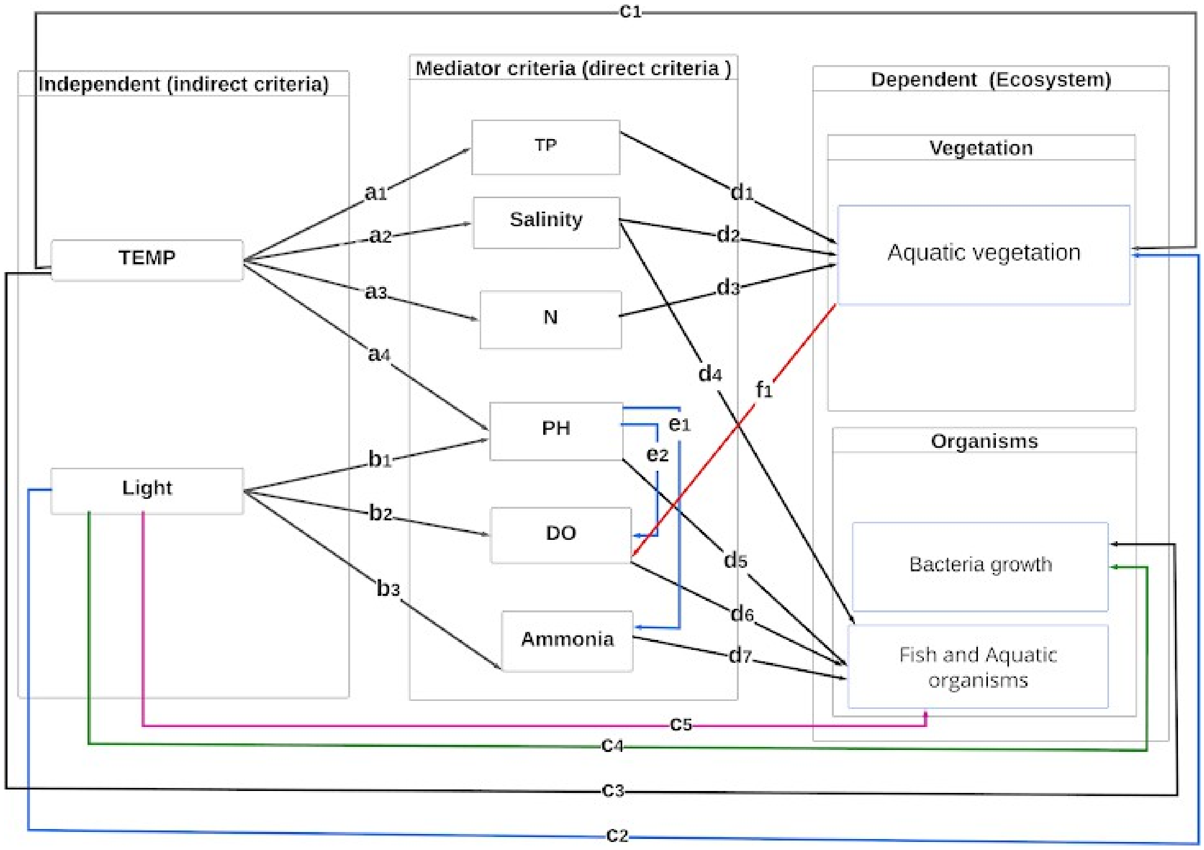
Ecological criteria.

Over the past years, much research effort has been devoted to developing methods for evaluating the ecological state of natural water bodies. The ecological health is a measure of the type and quantity of vegetation and organisms in the water body. However, these “dependent criteria” are affected by biological, chemical, and physical criteria which are often used as ecological indicators themselves (e.g. measurements of PH, DO, N, ammonia, TP, and salinity). In turn, these “mediator criteria” are affected by other “independent” criteria, such as temperature and light, in a complex system illustrated in Figure 2.

In the framework developed in this research, the relationships between independent, mediator, and dependent criteria will be found through mediation analysis. The **a, b, c, d,** and e values in Figure 2 represent the weights of the effect of each criterion on the others. **a** and **b** values show the effect of the temperature and light, respectively, on the mediator criteria; the **c** values represent direct relationships between independent and dependent criteria; **d** values are the weights of relationships between mediators and dependent criteria, and **e1, e2, e3**... represent the weights of the effects of relationships between mediator criteria, finally, **f1** represents the weight of effect dependent on mediator criteria.

The aim of this questionnaire is to gather expert opinion on the importance of each ecological parameter, allowing suitable weighting of each in the final framework.

*Figure 2 Relationships between independent (**temperature and light**) and dependent through mediator criteria*



1- Temperature effect *

Q9: On a scale of 1 to 5, how important is **temperature** in determining **total phosphorus (TP)** concentration?
(If you don't know, please choose 0)

Mark only one oval.

	0	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	◯	Very Important

Q10: On a scale of 1 to 5, how important is **temperature** in determining **saline levels and concentrations** in bodies of water such as reservoirs, ponds, etc.? *
(If you don't know, please choose 0.)

Mark only one oval.

	0	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	◯	Very important

Q11: On a scale of 1 to 5, how important is **temperature** in determining **nitrogen retention** in aquatic ecosystems? *

(If you don't know, please choose 0)

Mark only one oval.

	0	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	◯	Very important

Q12: On a scale of 1 to 5, how important is **temperature** in affecting **pH levels** in water bodies? *

(If you don't know, please choose 0)

Mark only one oval.

	0	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	◯	Very important

Q13: On a scale of 1 to 5, how important is **temperature** in affecting **aquatic vegetation** such as chlorophyll concentration, phytoplankton biomass, and so on? *
(If you don't know, please choose 0)

Mark only one oval.

	0	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	◯	Very important

Q14: On a scale of 1 to 5, how important is **temperature** in affecting **bacterial growth** rates in aquatic ecosystems? *
(If you don't know, please choose 0)

Mark only one oval.

	0	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	◯	very important

2- Light effect

Q15: On a scale of 1 to 5, how important is **light intensity** in affecting **pH** levels in aquatic environments? *

(If you don't know, please choose 0)

Mark only one oval.

	0	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	◯	Very important

Q16: On a scale of 1 to 5, how important is **light intensity** in affecting **dissolved oxygen (DO)** levels in aquatic environments? *
(If you don't know, please choose 0)

Mark only one oval.

	0	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	◯	Very important

Q17: On a scale of 1 to 5, how important is **light intensity** in affecting **ammonia** levels in aquatic environments? *
(If you don't know, please choose 0)

Mark only one oval.

	0	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	◯	Very important

Q18: On a scale of 1 to 5, how important is **light intensity** in affecting **aquatic organisms** including **fish**, and how does light stress and changes in light intensity affect bacterial growth, chlorophyll concentration, and overall aquatic ecosystem health? *
(If you don't know, please choose 0)

Mark only one oval.

	0	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	◯	very important

Q19: On a scale of 1 to 5, how important is **light intensity** in affecting **bacterial growth** levels in aquatic environments? *
(If you don't know, please choose 0)

Mark only one oval.

	0	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	◯	very important

Mediator effect

Q20: On a scale of 1 to 5, how important is **Total phosphorus (TP)** in affecting **aquatic plant growth** and its potential consequences in **aquatic ecosystems**? *
(If you don't know, please choose 0)

Mark only one oval.

	0	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	◯	Very important

Q21: On a scale of 1 to 5, how important is **salinity** in affecting **aquatic vegetation** in various aquatic ecosystems, and how do varying salinity levels affect plant biomass, species diversity, and overall plant health in wetland habitats? *
(If you don't know, please choose 0)

Mark only one oval.

	0	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	◯	Very important

Q22: On a scale of 1 to 5, how important is **salinity** in affecting *
aquatic ecosystems, including its consequences for **aquatic organisms** such as fish and its effects on species distribution and ecosystem dynamics?
(If you don't know, please choose 0)

Mark only one oval.

	0	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	◯	Very important

Q23: On a scale of 1 to 5, how important is **nitrogen** in affecting **aquatic** *
vegetation?
(If you don't know, please choose 0.)

Mark only one oval.

	0	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	◯	Very important

Q24: On a scale of 1 to 5, how important are **pH levels** in affecting the **survival of** * **aquatic species**, including potential effects on **aquatic vegetation** and changes in chemical solubility and toxicity?
(If you don't know, please choose 0)

Mark only one oval.

0		1	2	3	4	5	
Not	◯	◯	◯	◯	◯	◯	Very important

Q25: On a scale of 1 to 5, how important are **pH levels** in affecting **dissolved oxygen (DO)** concentrations in aquatic environments, including the role of algal photosynthesis? *

(If you don't know, please choose 0.)

Mark only one oval.

	0	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	◯	Very important

Q26: On a scale of 1 to 5, how important are **pH levels** in affecting **aquatic organisms?** *

(If you don't know, please choose 0)

Mark only one oval.

	0	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	◯	Very import

Q27: On a scale of 1 to 5, how important are **pH levels** in affecting **ammonia concentrations** in aquatic environments? *

(If you don't know, please choose 0)

Mark only one oval.

	0	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	◯	Very important

Q28: On a scale of 1 to 5, how important are **dissolved oxygen (DO) levels** in affecting various life forms, including **fish? (If you don't know, please choose 0)** *

Mark only one oval.

	0	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	◯	Very important

Q29: On a scale of 1 to 5, how important are **ammonia** levels in affecting **fish and other aquatic organisms.?** *

(If you don't know, please choose 0)

Mark only one oval.

	0	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	◯	Very important

Q30/ Please arrange the following criteria that impact an **ecosystem** in order of importance, with **8 indicating the most important** and **1 indicating the least important.** *

Mark only one oval per row.

	1	2	3	4	5	6	7	8
Tottall phosphorus (TP)	◯	◯	◯	◯	◯	◯	◯	◯
Saline levels	◯	◯	◯	◯	◯	◯	◯	◯
Nitrogen retention	◯	◯	◯	◯	◯	◯	◯	◯
PH	◯	◯	◯	◯	◯	◯	◯	◯
Temperature	◯	◯	◯	◯	◯	◯	◯	◯
Light	◯	◯	◯	◯	◯	◯	◯	◯
Dissolved oxygen (DO)	◯	◯	◯	◯	◯	◯	◯	◯
Ammonia	◯	◯	◯	◯	◯	◯	◯	◯

Feedback

Feedback concerning the utilisation of a framework for the identification of suitable locations for Rainwater Harvesting in arid and semi-arid regions.

Q31: Following your participation in our questionnaire, what is the likelihood of future adoption of Rainwater Harvesting frameworks in arid and semi-arid regions? *

Mark only one oval.

◯ 1 = Very unlikely

◯ 2 = Unlikely

◯ 3 = Neither likely nor unlikely

◯ 4 = Likely

◯ 5 = Very likely.

Q32: After participating in our questionnaire, how probable is it that you would support local policy or decision-makers in implementing **(RWH) frameworks**? *

Mark only one oval.

- 1 = Very unlikely
- 2 = Unlikely
- 3 = Neither likely nor unlikely
- 4 = Likely
- 5 = Very likely

Q33: Do you have any feedback about the questionnaire as a whole or any specific questions? If you have comments on a particular question, please indicate the question number.

APPENDIX C. Publications

This appendix contains the abstracts of the author's two published journal papers, which are as follows:

1- Ahmed, S., Jesson, M., & Sharifi, S. (2023). Selection Frameworks for Potential Rainwater Harvesting Sites in Arid and Semi-Arid Regions: A Systematic Literature Review. *Water*, *15*(15), https://www.mdpi.com/2073-4441/15/15/2782.

2- Ahmed, S., Jesson, M., & Sharifi, S. (2025). A Novel, Ecology-Inclusive, Hybrid Framework for Rainwater Harvesting Site Selection in Arid and Semi-Arid Regions. Water Resources Management, https://link.springer.com/article/10.1007/s11269-024-04073-7

water

MDPI

Review

Selection Frameworks for Potential Rainwater Harvesting Sites in Arid and Semi-Arid Regions: A Systematic Literature Review

Safaa Ahmed [1,2,*], Mike Jesson [1,*] and Soroosh Sharifi [1,*]

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Abstract: Water shortage is a concern in arid and semi-arid regions across the globe due to their lack of precipitation and unpredictable rainfall patterns. In the past few decades, many frameworks, each with their own criteria, have been used to identify and rank sites for rainwater harvesting (RWH), a process which is critical for the improvement and maintenance of water resources, particularly in arid and semi-arid regions. This study reviews the present state of the art in rainwater harvesting site selection for such regions and identifies areas for additional research. The results of a systematic review performed based on two major databases of engineering research, Scopus and Engineering Village, are presented. Sixty-eight relevant studies were found and critically analysed to identify patterns and unique features in the frameworks used. The results of this study show that 41% of the frameworks consider both biophysical and socioeconomic criteria, whereas the remaining 59% of the frameworks depend on biophysical criteria alone. The importance of each criterion is encapsulated through a suitability score, with 21% of the frameworks using a binary (0 or 1) indicator of whether the site matches a criterion or not and the other frameworks using graded scales of differing granularities, with 52% using a low-resolution scale of 1 to 3, 4, or 5, 7% using a medium-resolution scale of 1 to 10, and a further 7% using a high-resolution scale of 1 to 100. The remaining 13% of the frameworks did not specify the scale used. Importantly, this paper concludes that all existing frameworks for selecting RWH sites are solely based on biophysical and/or socioeconomic criteria; ecological impacts, the consideration of which is vital for building RWH systems sustainably, are currently ignored.

Keywords: rainwater management; rainwater harvesting; arid and semi-arid regions; site selection; frameworks; stakeholder; biophysical criteria; socioeconomic criteria; ecological criteria

check for updates

Citation: Ahmed, S.; Jesson, M.; Sharifi, S. Selection Frameworks for Potential Rainwater Harvesting Sites in Arid and Semi-Arid Regions: A Systematic Literature Review. *Water* **2023**, *15*, 2782. https://doi.org/10.3390/w15152782

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1. Introduction

Adequate water supply is the most important requirement for human life. The demand for water has increased due to the increase in the Earth's population, from 2.5 billion to 7.35 billion between 1950 and 2015. However, more than 40% of the earth's surface is covered by arid and semi-arid regions, defined as those that receive an average annual rainfall of only about 150–350 mm and 350–700 mm, respectively [1]. Historically, arid and semi-arid regions have contained many settlements, such as those in the Middle East, Northern Africa, and Western Asia, and it is essential that rainfall and other water sources in these areas are used efficiently.

For as long as people have engaged in agriculture, they have used water harvesting to collect rainwater, floodwaters, and groundwater. People rely on water harvesting to meet their water needs where sufficient supplies for drinking water and irrigation are not easily reached [2]. Water harvesting can be classified into one of four types: fog and dew harvesting, rainwater harvesting, groundwater harvesting, and floodwater harvesting [3]. Rainwater harvesting (RWH), the subject of this paper, is the collection or diversion of rainfall runoff for productive purposes, and its use is widespread in arid and semi-arid areas [4].

Water Resources Management
https://doi.org/10.1007/s11269-024-04073-7

A Novel, Ecology-Inclusive, Hybrid Framework for Rainwater Harvesting Site Selection in Arid and Semi-Arid Regions

Safaa Ahmed[1,2] · Mike Jesson[1] · Soroosh Sharifi[1]

Received: 26 June 2024 / Accepted: 14 December 2024

Abstract

The water crisis is a critical issue, particularly in arid and semi-arid regions where rainfall is limited. Rainwater harvesting systems have been introduced in many locations to capture what rainfall does occur, but selection of the optimum site is vital to ensure efficient capture and storage. Over the past few decades, a range of frameworks for ranking proposed rainwater harvesting sites on the basis of site suitability have been suggested. The goal of this study was to develop a robust methodology to extend these frameworks, which consider biophysical and socio-economic criteria only, to include ecological criteria in the site selection process. This is essential for ensuring environmental protection, maintaining biodiversity, water quality improvement, climate resilience, regulatory compliance and sustainability of the system. In this paper, the inter-relationships of ecological criteria are shown to be complex, with "independent" criteria affecting "mediator" criteria which then directly impact ecological standards, i.e. the "dependent" criteria such as number of aquatic organisms. It is shown how a robust combination of data analysis and expert opinion can be applied to determine relative weightings of the different ecological criteria, using temperature and light as examples of key independent criteria. The developed hybrid framework is applied to a case study of site selection in Erbil Province in Iraq, where both climate change and human actions have seriously reduced water supplies in the past twenty years, showing that inclusion of these ecological criteria changes the ranking of the sites compared to ranking without ecological considerations.

Keywords Rainwater management · Rainwater harvesting · Arid and semi-arid Regions · Site selection · Frameworks · Stakeholder

1 Introduction

Water is a crucial and precious natural resource (Al-Adamat 2008). Water scarcity is a prevalent issue in numerous regions across the globe, with more than two billion people predicted to live in areas with severe water scarcity by 2050 according to the United Nations Environment Program (Field and Barros 2014; Sekar and Randhir 2007). Water resource

Extended author information available on the last page of the article

APPENDIX D. Support letters

UNIVERSITY OF BIRMINGHAM

Dear Mike Jesson, Soroosh Sharifi, Safaa Ibrahim,

RE: Rainwater harvesting

Application for Ethical Review: ERN_1341-Jun2023

You project has been considered in line with the University of Birmingham's research ethics processes and on the basis of the information you have provided, it is understood that while your project does involve human participants, the project raises no substantial research ethics issues and therefore no further ethics review is required

Any adverse events occurring during the study should be promptly brought to the Committee's attention by the Principal Investigator and may necessitate further ethical review.

Please ensure that the relevant requirements within the University's Code of Practice for Research and the information and guidance provided on the University's ethics webpages (available at https://intranet.birmingham.ac.uk/finance/accounting/Research-Support-Group/Research-Ethics/Links-and-Resources.aspx) are adhered to.

Please be aware that whilst Health and Safety (H&S) issues may be considered during the ethical review process, you are still required to follow the University's guidance on H&S and to ensure that H&S risk assessments have been carried out as appropriate. For further information about this, please contact your School H&S representative or the University's H&S Unit at healthandsafety@contacts.bham.ac.uk.

Kind regards,

The Co-Chairs of the Science, Technology, Engineering and Mathematics Committee

E-mail: ethics-queries@contacts.bham.ac.uk

University of Birmingham Edgbaston Birmingham B15 2TT United Kingdom w: www.birmingham.ac.uk

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