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WATER HARVESTING STRUCTURE SUSTAINABILITY

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DECLARATION

I, RAMADAN MARNE, hereby declare that this thesis represents my personal work, realized to the best of my knowledge, without plagiarism. I also declare that all information, material and results from third parties have been fully cited and referenced according to the academic rules and regulations.

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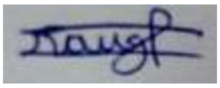

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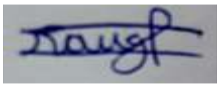

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ABSTRACT

WH comprises all forms of activities where water is collected, stored and used either in the blue or green form. It involves the direct collection of rain that falls onto the roofs, grounds and runs off, as well as floodwater harvesting. Abougoudam District in Chad has been characterized by irregularities in the rainfall intensities with short duration. The district has a long period of the dry season with only four months of rain. The rainfall is unevenly distributed spatially and temporally, therefore, affecting water availability for humans, livestock consumption and off-season irrigation. Water harvesting structures have been proven to provide a cost-effective, environmentally friendly, affordable and relatively simple solution to supplement water for the intended use. The adaptability of sustainable WHSs may increase adoption rate in areas with chronic water shortages through a public-private partnership. The objective of this study was to analyse various water harvesting practices in arid regions and propose sustainable structures that incorporated the technical feasibility, economic and socio-cultural acceptability to be implemented in Abougoudam district, Chad and other arid regions of Africa. The probability analysis was used to design rainfall for WH and ArcGIS 10.5 was used to generate the soil map in order to avoid soils that are not suitable for WH. 150 sample questionnaire was administered to the local community of Abougoudam district to assess their willingness to adopt WH. A field survey in Chad and literature review were conducted to assess the best practices. The results from the rainfall analysis revealed that rain with a probability of more than 50% might be considered to supplement water for the intended use. The soil map showed 40 to 60% of vertisols to be avoided for WH. 100% of the local community were ready to adopt WH. The results from the field survey and literature review revealed that water spreading weirs, Hafir system, Sand dam, permeable rock dam, rooftop, Zai pit and Stone lines are the best practices that could be adaptable in Chad and most specifically in Abougoudam District but water spreading weir, Sand dam and combination of the zaï pit and stones lines were more preferable. This was because of their capacity to regenerate degraded lands in valley regions, reduce evaporation and recharge groundwater. Hafir system is also considered because of their potential to provide water both for human and livestock. The sustainability of these structures could be addressed by incorporating the policy brief developed at the end of this study into the national policy.

Key Words: Rainfall, soil map, WH, policy brief, water spreading weirs, Hafir systems, Sand dam, permeable rock dam, rooftop, Zai pit and Stone lines

Résumé

La récupération d'eau comprend toute forme d’activité dans laquelle l'eau est collectée, stockée et utilisée sous forme bleue ou verte. Cela implique la collecte directe des précipitations sur les toits, les sols et les écoulements, ainsi que la récupération des eaux de crue. Le district d'Abougoudam au Tchad a été caractérisé par des irrégularités d'intensité des précipitations de courte durée. La région est marquée par une longue période de saison sèche avec seulement quatre mois de pluie. La pluviosité est inégalement répartie dans le temps et dans l'espace, affectant par conséquent la disponibilité d’eau pour les Hommes, la consommation du bétail et l'irrigation des cultures pendant la saison sèche. Il a été prouvé que les systèmes de collecte d’eau constituaient une solution rentable, écologique, abordable et relativement simple pour augmenter la disponibilité en eau afin d’atteindre la demande. L'adaptabilité des systèmes durable dans la collecte d’eau peut augmenter le taux d'adoption dans les zones de pénurie chronique d'eau grâce à un partenariat public-privé. L'objectif de cette étude était d'analyser les diverses pratiques des systèmes de collecte d’eau dans les régions arides et de proposer des systèmes durables intégrant la faisabilité technique et la conception, l'acceptabilité économique et socioculturelle à réaliser dans le district d'Abougoudam, au Tchad et dans d'autres régions arides d'Afrique. L'analyse de la probabilité a été utilisée pour calculer la précipitation qui pourrait être choisie pour la collecte d’eau afin d’atteindre les besoins en eau et ArcGIS 10.5 a été utilisée pour générer la carte du sol afin d'éviter les sols qui ne conviennent pas au stockage de l’eau collectée. Une enquête de 150 questionnaires a été administrée à la communauté locale du district d'Abougoudam afin d'évaluer leur volonté d'adopter les systèmes de collecte d’eau. Une enquête sur le terrain au Tchad et des revues de la littérature ont été menées pour évaluer les meilleures pratiques des systèmes de collecte d’eau. Les résultats de l'analyse des précipitations ont révélé que l'on pouvait considérer que les précipitations avec une probabilité supérieure à 50% pour augmenter la disponibilité en eau afin d’atteindre les besoins en eau. La carte du sol a montré que 40 à 60% des argiles noires devaient être évités. 100% de la communauté locale avait exprimé leur volonté d’adopter les systèmes de collecte d’eau. Les résultats de l'enquête sur le terrain et de l'analyse de la littérature ont révélé que les seuils d'épandage, le système d’Hafir, le barrage en sable, les digues filtrantes, le toit, la fosse de Zaï et les cordons pierreux sont les meilleures pratiques pouvant être adaptées au Tchad et plus particulièrement dans le district d'Abougoudam. Le seul d’épandage, le barrage en sable et la combinaison de la fosse de zaï et les cordons pierreux étaient plus préférables. Cela était dû à leur capacité de régénérer les terres dégradées dans les vallées, à réduire l'évaporation et à recharger les eaux souterraines. Le système d’Hafir a été également pris en compte en raison de son potentiel d'approvisionner l’eau pour les Hommes et le bétail. La durabilité de ces systèmes pourrait être abordée en incorporant la note politique à la fin de cette étude dans la politique nationale.

Mots clés: Précipitation, carte du sol, collecte d’eau, note politique, seuil d'épandage, système d’Hafir, digues filtrantes, toit, fosse de Zaï et cordons pierreux

DEDICATION

I dedicate this work to my late father in the person of MARNE SALEH and my mother who has always been there to ensure that I progress with my education.

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LIST OF ABBREVIATIONS

AfDB	African Development Bank
AGH	Action Against Hunger
DWR	Directorate of Water Resources
FAO	Food and Agriculture Organisation
FEWS NET	Famine Early Warning Systems Network
FIDA	Fonds International de Développement Agricole Fonds
FWH	Floodwater Harvesting
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GWH	Groundwater Harvesting
ha	Hectare
IsDB	Islamic Development Bank
JRC	Joint Research Centre
KfW	Kreditanstalt für Wiederaufbau
LDP	Local Development Plan
m	Meter
MEWAF	Ministry of Environment, Water and Fisheries
NGOs	Non-Government Organisations
NISEDS	National Institute of Statistics, Economic and Demographic Studies
O&M	Operation and Maintenance
OCHA	United Nations Office for the Coordination of Humanitarian Affairs
RWH	Rainwater Harvesting
SDGs	Sustainable Development Goals
UN	United Nations
UNDP	United Nations Development Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNICEF	United Nations Children’s Fund
USAID	United States Agency for International Development
WH	Water Harvesting
WHO	World Health Organisation
WHSs	Water Harvesting Structures
WHTs	Water Harvesting Techniques
WMO	World Meteorological Organization
US$	United Nations Dollar

CHAPTER ONE

1.0 INTRODUCTION

1.1 BACKGROUND

Over the last decade, climate change has influenced changes in the frequency of droughts and precipitation trends in arid and semi-arid areas of Africa(Awojobi and Tetteh 2017). The impact is expected to increase over the content in the future (WMO 2018). On the other hand, it is common that precipitation is more intense than before, which limits the infiltration process and encourages the development of infrastructure to store and retain runoff. Seasonal occurrence of flooding and drought have already been observed and are expected to become more apparent in the coming future; however, their prediction is complex and hard(Gemeda and Sima 2015). African countries are more affected by climate change because of their reliance on agriculture as well as their lower financial, technical, and institutional capacity to adapt (Signgh and Purohit 2014). Sahelian countries such as Senegal, Mauritania, the Gambia, Guinea Bissau, Mali, Burkina Faso, Niger, Chad, Sudan, and Eritrea depend mainly on subsistence and small-scale farming, temperature and erratic rainfall pose considerable risks to their livelihoods (Hummel, 2015).

Arid and semi-arid regions around the world are continuously facing problems of water scarcity, both drinking and agriculture water as well as the ecosystem. Arid and semi-arid represents 35% of Earth's land, about 50 million km^2 (Adham et al. 2016). Water Harvesting (WH) has played an important role in ancient civilizations, especially in drylands. In recent years, it has been promoted in many regions to address the increasing water supply pressures associated with population growth, urbanization, industrial development and climate changes(Amos, et al. 2016; Campisano et al. 2017). Countries like Australia, China, and Jordan have mandated the implementation of WH in new buildings (Jing et al. 2017). Countries like Brazil, Germany, France, Italy, South Korea, UK, and the USA are also promoting WH to increase the water sufficiency of their cities (Palla et al. 2017).

In Africa, Water harvesting technology started in northern Egypt where storage tanks between 200 and 2,000 m3 were used for at least 2,000 years and most of which are still operational today(Al-Abyadh 2017). Water harvesting techniques have been in use in many regions of sub-Sahara Africa (Critchley et al., 1992), like the caag and the Gawan in Somalia; Haffirs in Sudan and the Zai system in West Africa. A wealth of experience and various locally well-adapted runoff farming were found in Morocco's Anti Atlas region (Prinz 1996). Traditional runoff farming such as lacs collinaires, rainwater storage ponds are used for agriculture and open ponds are mainly used for livestock. The largest tank in the world is likely the YerebatanSarayi in Istanbul, Turkey which was constructed during the time of Caesar Justinian (AD 527- 565). The size of the tank was estimated about 9800 m2 with a capacity of 80,000 m3. The ruins of dams and storage tanks were found in Yemen in Yemen and the country's spectacular mountain terraces confirm a long history of water harvesting(Al-komaim 2018). The breakdown of the Marib dam is mentioned in the Koran which is an evidence of water harvesting practices in the history of Yemen. The concentration and collection of rainfall through storage use for beneficial purposes is referred to as water harvesting (Salman 2017).

Only a few countries around the world have the natural and financial means to increase water demands or can manage the available water resources efficiently in order to address water scarcity issues and the importance of water-use efficiency increase in terms of US dollars per cubic meters (US$/$m^3$) of water(SDGs 2018). Based on the SDG report, more than 2 billion people live in countries experiencing high water stress which affects the sustainability and limits social and economic development (UN 2016). Countries living with high water stress are Northern Africa, Western, Central and Southern Asia as well as Sub-Saharan Africa(UNESCO 2019).

With the increase in population and the effects of climate change, the water stress is likely to affect the demands for domestic water supply, livestock and agricultural production(Jayne and Yeboah 2017). 70% of available water, as well as 90% of it in arid regions, is needed in agricultural production in order to mitigate against food security and the availability of water for human consumption and livestock is also decreasing drastically(Bangira 2018). Therefore, there is a need to save a little fraction of water which can significantly alleviate water stress in arid regions(World Bank Group 2018).

This study seeks to analyse the various water harvesting design and techniques in arid regions in the light of adopting some of the techniques that have worked so far, specifically in Chad. In addition, the techniques can also be extended to other arid regions of Africa through an integrated approach.

1.2 PROBLEM STATEMENT

Climate change and aridity have affected the spatial and temporal distribution of rainfall resulting in excess runoff which is lost through the environment and disappears before it can be used (Rose 2015). Whether it is dedicated to consumption or to agriculture, the need for water is indeed, a reality that no one can challenge. Millions of Sahelian still lack access to water even though the Sahel has remarkable potential for water resources (Bewket, 2012). The pastoral situation was characterized by very low availability of natural pastures in pastoral areas of Sahelian countries. Livestock continues to feed with the residual forage mass-produced during the rainy season(Zalagou, Binta and Abdoul Aziz 2018).

The growing shortage affecting the most valuable resource of our planet is brutally reminded by Cape Town, South Africa, which made the headlines by declaring to be preparing for “Day Zero", that day when the tap of the city will be dried(Nissen-petersen 2010; J R C 2018).

For instance in Chad, areas with high agricultural potential suffer from a delay in the onset of the rainy season or sequences of a long dry period which affects the agricultural production(FEWS NET 2018). Due to partial overwintering and poor rainfall distribution, plantings to date are estimated at only 10 to 15 percent versus 25 to 30 percent in a normal year. Poor households will not be able to meet their basic food needs. Water is scarce and animals travel 5-10 km to reach pastoral wells. The lack of pasture that resulted in high forage deficit would continue to degrade the physical condition of the livestock. This situation affects the economy and the social activities of the population(USAID 2019). However, there is a need to promote technology that will improve ways to increase drinking water supply, pastoral water and improve the climate resilience of agricultural production systems.

In view of the current situation which affects most of the arid regions of Africa, It is strongly felt that Water harvesting structures are the solution to overcome such water shortages in regions with inadequate water by considering the feasibility studies.

1.3 Objectives of the study

1.3.1 Main Objectives

The main objective of this study is to analyse the various water harvesting practices in arid regions and propose sustainable structures that incorporated the technical feasibility, economic and socio-cultural acceptability to be implemented in Chad and other arid parts of Africa.

1.3.2 Specific objectives

The specific objectives of the study were to:

1) Assess the technical specification and design of WHSs,and identify best practices in arid regions;
2) Assess both the institutional and beneficiaries' financial capacity on proper Operation and Maintenance (O&M) activities of the water harvesting structures;
3) Propose best practices of WHSs that is economically and financially affordable, and socio-culturally acceptable in arid regions;
4) Develop a policy brief on WHSs sustainability in Chad and other arid regions of Africa.

1.4 Research Questions

1. What are the best practices of WHSs, design, techniques that have performed well to meet water demand for humans, livestock and agricultural production?
2. What is the effective mechanism to enhance the institutional and beneficiaries' financial capacity on O&M to ensure the sustainability of WHSs?
3. Does the current WHSs consider the technical and economic feasibility and the acceptability by the users?
4. What are the effective guidelines on water policy to ensure the sustainability of WHSs?

1.5 Hypothesis

1. There is now several good practices and experiences of WHSs and design that provide water for the intended uses during the dry seasons.
2. Stakeholder participation in the planning, design, implementation, and O&M will increase the effectiveness and assure sustainability of the WHSs.
3. Incorporating water harvesting techniques, cost-benefit and socio-cultural acceptability will ensure sustainability.
4. Guidelines will serve as a means to ensure the sustainability of WHSs.

1.6 SCOPE OF THE STUDY

The ever-increasing pressures on water resources and chronic shortages that affect water demand for food, humans, and livestock, water harvesting techniques can be employed as a solution to increase the required water supply.

This study is restricted to the design and assessment of water harvesting techniques that have performed well in arid regions, proper Operation and Maintenance of the techniques to ensure capacity building of the Institutions, Water User Associations and the Beneficiaries, the proposition of some of the techniques to be adopted in Chad and other arid regions of Africa. It will also provide brief policy guidelines that will ensure the sustainable management of the structures. This research will be conducted for a period of five to six months.

1.7 RELEVANCE OF THE STUDY

The population of the African continent is expected to increase from 1 billion to 3 billion by 2050 and 1 billion Africans already live under extreme poverty (Christopher 2016). The population in Africa that suffers from a chronic shortage of water is estimated to 200 million, one-quarter lack food and two-thirds of the population live in a rural area and depend on rainfed agriculture which is limited by erratic water resources (UNDP 2018). Ninety-five percent of the agriculture depends on rainfall but most of it is lost through evaporation and runoff without being captured for use (Falkenmark 2016). Due to the current increase in temperature and rainfall variability, the ever-increasing pressure on water resources will affect water needed for agriculture growth, human beings, and livestock (UN-Water 2018).

Moreover, It will not be possible to achieve the SDGs (end hunger, food, poverty, health, water, and sanitation) without an African water revolution (green water) (World Bank Group 2018). Water harvesting innovation techniques under pan-Africanism ownership are proposed to coordinate investments between private and public, funded by national and international resources (Bangira 2018). As a strategy for African Green Water Plan, a minimum of USD 100 billion investments in green water will be needed to build resilience for food security and human well-being.

However, it is clear that Africa has a vast untapped potential in water harvesting investments. This study will provide a practical approach that will be needed to attract water harvesting investments in Chad. In addition to that, the study will propose sustainable Water harvesting structures to supplement water needed for agricultural growth, humans, and livestock, Improve the socio-economic activities leading to job creation for African youths and women and develop a policy brief that will enable the sustainability of water harvesting structures.

1.8 STRUCTURE OF THE THESIS

This research consisted of 5 chapters.

Chapter one gave a broad introduction to some key features of the study. It began with a background overview of the impacts of climate change in Arid and Semi-arid regions, the traditional use of water harvesting in arid and semi-arid regions and the regions facing water stress. It also includes the problem statement, the objectives, research question, the hypothesis, the rationale of the study and ended up with the structures of the thesis.

Chapter 2 reviewed the definitions of water harvesting, components of water harvesting systems, classifications of water harvesting systems, types of water harvesting in Arid Regions, the economic viability of water harvesting structures, O&M of water harvesting structures and the benefits of water harvesting including policy on water harvesting structures.

Chapter 3 outlined the data and methods employed for the research and It also described the geographical location, Vegetation and Flora, Climate, Hydrography of the study area and the Legal Framework on Chadian's Water Regime.

Chapter 4 presented the results obtained from the field survey and desk study, the discussion of results analyses of the study area and the brief policy developed for the sustainability of the structures.

Chapter 5 concluded the study and recommended the way forward for future prospects of water harvesting structures in Chad and other arid regions of Africa.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Definitions of Water Harvesting

Water harvesting (WH) is the collection and storage of rainwater and runoff in a natural or artificial storage facility to be used instantly or before the beginning of next season(Tobin and Asogun 2013) to provide water needs for humans and livestock consumption, the irrigation of annual crops, pastures and trees and for groundwater recharge(Bunclark et al. 2018).WH comprises all forms of activities where water is harnessed, stored and used either in the blue or green form. It involves the direct collection of rain that falls onto the roofs, grounds and runs off, as well as floodwater harvesting(Haile and Merga 2002). There are many ways in which WH can be achieved, and the collected water is stored in cisterns, micro-catchment, macro-catchment or use for groundwater recharge(FAO 2015). However, there is a difference between rainwater harvesting and water harvesting: rainwater harvesting is harnessing and storing runoff water on the surfaces that rain has directly fallen onto while WH is the gathering and concentration of any form of water, which can be runoff or creek flow for multiple usages. WH is also known as the process of collecting and storing runoff water for productive and beneficial use with different types of techniques and structures to increase the availability of surface water and recharge groundwater in dry areas(Ziadat et al. 2012).

2.2 Components of Water Harvesting Systems

Water harvesting systems (WHSs) consist of a catchment area, storage facility and the target area or application area(Dwiratna et al. 2018). Sometimes a conveyance system is needed to move the water from the catchment area to the storage facility and then the target area(HARB 2015). They may be cases where the components are made adjacent to each other or conveyance is needed in other cases (Figure 1)(Prinz 2013). The storage facility and the target area may be the same in the case where water is stored in the soil profile for direct uptake by the plants.

The Catchment area also called runoff area: it is an area of land where runoff is stored and flowed downstream in regions or locations where the runoff is needed for use or where the slope is fit for the runoff to be carried(Tasawwar 2018). It is also referred to as the portion of land where all or part of the precipitation runs off to the limits of an area. It varies from micro-catchment (a few square meters) to macro-catchment (as large as several square kilometers).

The limit of the land can be a rooftop, paved road, agricultural and non-agricultural land, complex basement, natural slopes or even a marginal land(Hamid and Nordin 2011).

The storage facility is the most expensive component of a water harvesting system(Lee and Kim 2013). Therefore, careful design analysis is preferred to choose an optimal capacity of a storage surface adapted to the local conditions of the area (availability of materials and skills) with the cheapest possible cost(Lade 2013). It is defined as the place where runoff is harnessed and held from the catchment area at the time when it occurs until it is made available for potable and non-potable uses. It can be used for human and animal consumption, agricultural production as well as other uses. The Storage system can be surface tanks, jars, dams, reservoirs or ponds; underground reservoirs as cisterns, groundwater recharge ponds and water storage in the soil profile as soil moisture (Gould and Nissen-Petersen, 2003).

Target area: This is the place where the harvested water is made available either for domestic use (human consumption and other domestic uses), for livestock consumption and agricultural production including supplemental irrigation(Malesu 2006).

Conveyance system: In the case of overland flow, runoff is transported through rill, gully, and natural channel, an artificial channel which is stored in the soil or into specifically designed storage systems. However, for rooftop WH, runoff is conveyed through gutters and pipes(Mati et al. 2005).

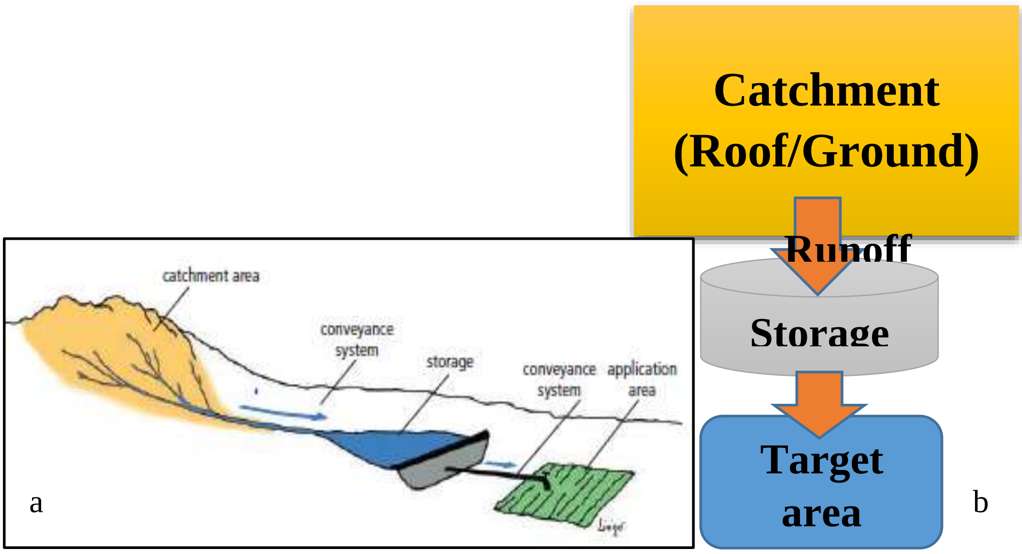


Figure 2. 1 the components of two water harvesting systems: a) catchment area, storage facility and application area are linked by a conveyance system) catchment area, storage and target area. (source: Prinz 2013; Dwiratna et al. 2018)

2.3 Classification of water harvesting systems

The criteria mostly used to classify water harvesting systems (WHSs) are the runoff generating process, catchment area and size, and the type of water storage facility. Rainfall, rivers and lakes are considered as the runoff generating processes (Oweis et al. 2012; Tuinhof et al. 2012). The storage facility could be within a soil profile, a cistern or a reservoir and the size of the water storage determines whether the system is a micro or macro scheme. There are mainly three (3) categories of WHSs that have been developed and practiced over the years. The categorization of each WHSs depends on the method and technique employed to supplement water needs for the intended use (Mekdaschi and Liniger 2013). The catchment size, the method of the water storage system and the final use are taken into account to categorize the WHSs. Hence, the three (3) classes of WHSs include Floodwater Harvesting (FWH), Rainwater Harvesting (RWH) and the Groundwater Harvesting (GWH)(Bunclark et al. 2018).

2.3.1 Floodwater harvesting

The collection and storage of temporary channel flow for irrigating crops, fodder, and trees, and for groundwater recharge are referred to as floodwater harvesting (FWH). Water spreading or spate irrigation is the term used instead of FWH. The main characteristics of FWH are the concentration of a turbulent ephemeral channel flow either by diverting spate flow from rivers and large gullies or using natural flooding or impounding water within valley floor/Channel bed (Pereira et al. 2002). Generally, the annual rainfall ranges from 100-700 mm. FWH is an option to provide optimal water use during flood events in areas where the evaporation rate exceeds the annual rainfall (Van Steenbergen et.al. 2010). The catchment area varies from 2 to 50 km^2 in size and the catchment area ratio is 100:1 to 10,000:1. There are two (2) types of FWH systems which are: FWH diversion system and Wadi bed system (Ratsey, 2011).

2.3.1.1 Floodwater diversion system

Spate irrigation is generally the alternative name of the floodwater diversion system. In this system, the channel water flow is either forced to leave its natural course or transported to the closed by fields or overflow the channel bank of a river or stream to flood farmlands as an irrigation method (Majdoub et al. 2014).

2.3.1.2 Wadi bed system

Wadi bed system or floodwater within a streambed is a system whereby,(Oweis, Prinz, and Hachum 2013) the water flow is blocked either on the surface to inundate the valley of a flood plain or the water is allowed to infiltrate in the soil profile and the wetted area is used for agricultural and fodder production around the wadi areas. The infiltrated water also recharges the groundwater that will later be abstracted for drinking purposes through boreholes or open wells. However, the soil built up behind the wadi bed and distributed evenly around the wadi areas can help regenerate the degraded lands(GIZ-KFW 2012).

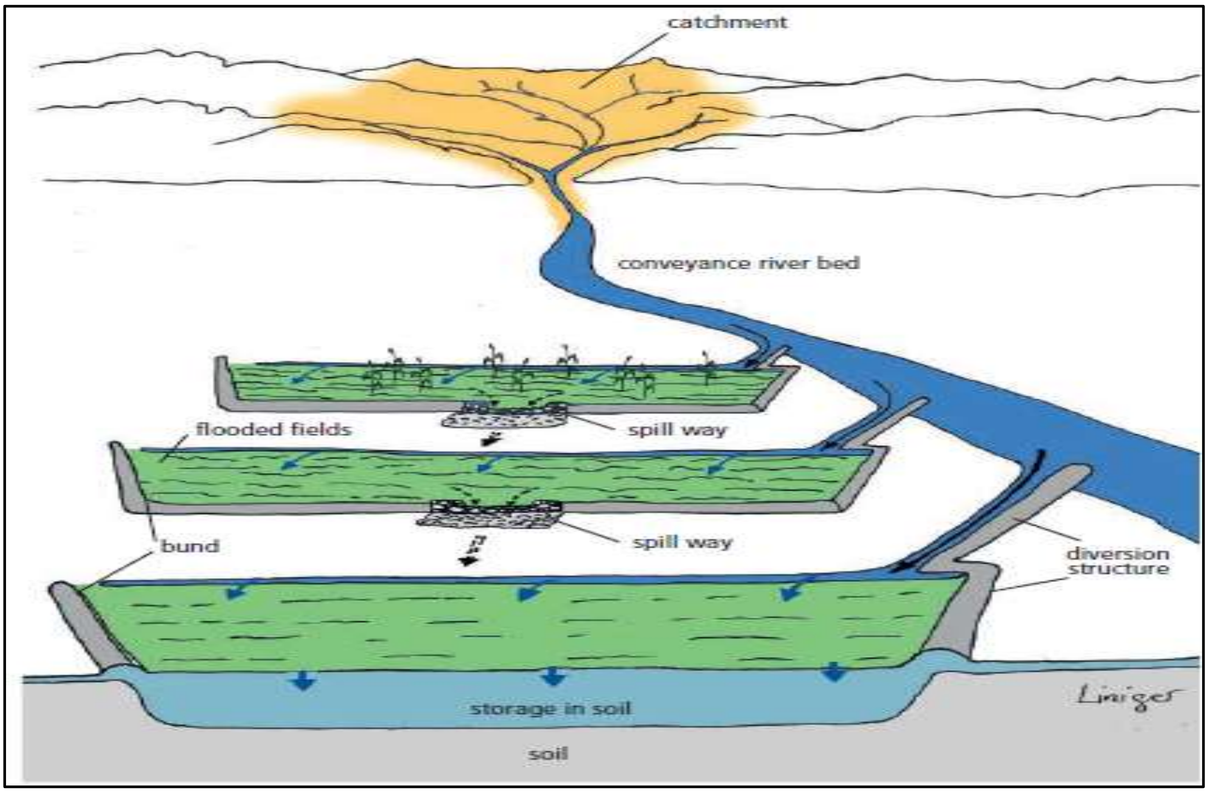


Figure 2. 2 Floodwater diversion system. (source: Oweis, Prinz, and Hachum 2013)

Figure 2. 3 photos of Water spreading weir in AKA village, Chad. (Source: Author 2019)

2.3.2 Groundwater harvesting

Groundwater harvesting (GWH) involves the methods and techniques used to abstract water from the ground for productive and beneficial use. It encompasses all methods, traditional or contemporary of WH and has been used as a storage method for other forms of WHSs such as FWH and RWH (Rockström 2002). However, many of these techniques require a particular terrain to force the water leaves its original course and infiltrate into the soil that later will be used for crop production, human and animal consumption. Underground dams, sand dams, wells, cisterns and aquifers have been used as traditional methods for GWH. Wells such as open wells which are artificial holes dug to reach the groundwater table. This type of wells still in practice up to date. They were probably the first structures used in many regions of the world to exploit the groundwater (Van Steenbergen and Tuinhof 2009).

2.3.2.1 Dams

The abstraction of groundwater from the soil profile, either trapped in shallow layers of sand or from the water table constitutes an interesting practice of WH. Storing water beneath the ground surface is an attractive way of harnessing water (SIWI 2001). It reduces evaporation losses from the ground surface and also improves the quality of the water. Sand dams and subsurface dams where water is impounded behind a small wall in a sandy riverbed in an effective and cheap form of WH (Ibrahim 2012).

2.3.2.2 Water Wells

Water wells are artificial holes that reach the groundwater table. They were probably the first hand-dug shallow wells that were dug in the beds of temporary streams or wadi beds to tap the water from the ground to the surface (Issar 2001). The use of water wells has been practiced over many years, dating back to 8100-7500 BC. Wells are forms of WH that have employed to meet the water needs for crop production, human and livestock consumption in a particular region (Mays 2010b). Modem technologies have increased the return from wells, making it easier to obtain groundwater.

2.3.2.3 Cisterns

Cisterns are artificial underground or caves built to store water. The walls of these cisterns are always plastered to prevent evaporation, deep percolation. The underground cisterns are made to supply water for domestic and agricultural purposes in areas liable to droughts. There are two types of cisterns, one is shaped like a bottle and the other has a circular shape. The ground is excavated in a way that forms the shapes of the cisterns. The surface of the cisterns is covered with polyethylene or plastered with concrete to prevent seepage. The two (2) types of cisterns are often expensive and difficult to construct. Farmers cannot build them because of their complexity (Alem 2003).

2.3.2.4 Aquifers

Aquifers are formed when subsurface layers of water percolate into permeable rock or other materials such as gravel, sand, silt or clay (Edugreen 2007). They often occupy large spaces beneath the ground surface and are always sources of water into rivers, streams, and springs. Aquifers usually store water that can be harvested and they are often on the receiving end of WH. Depletion of aquifers have been of concern recently and there has been an increase in water harvesting techniques(WHTs) to replenish these precious resources. Several WHTs harness and store water beneath the ground surface for later use. These WHTs do not only replenish the depleting aquifers but also raise the level of the water table and increase water supply.

Qanats are techniques used to access aquifers in order to provide a freshwater supply. They are mostly used in Pakistan, Iran, North Africa and Spain (Lightfoot 1996b). The Qanat is made of a horizontal tunnel that abstract water from the underground surface in an alluvial fan, bringing it to surface due to gravitational flow (Cech 2009). Qanat tunnels are on a 1-2% incline up to 30 km long. Several are still in use to provide water for agricultural production and domestic use in many villages. In Morocco, it is called Khettara, Galleria in Spain and Felaj in Oman.

Figure 2. 4 Photo of a water well-constructed in a wadi bed, northeast of Chad

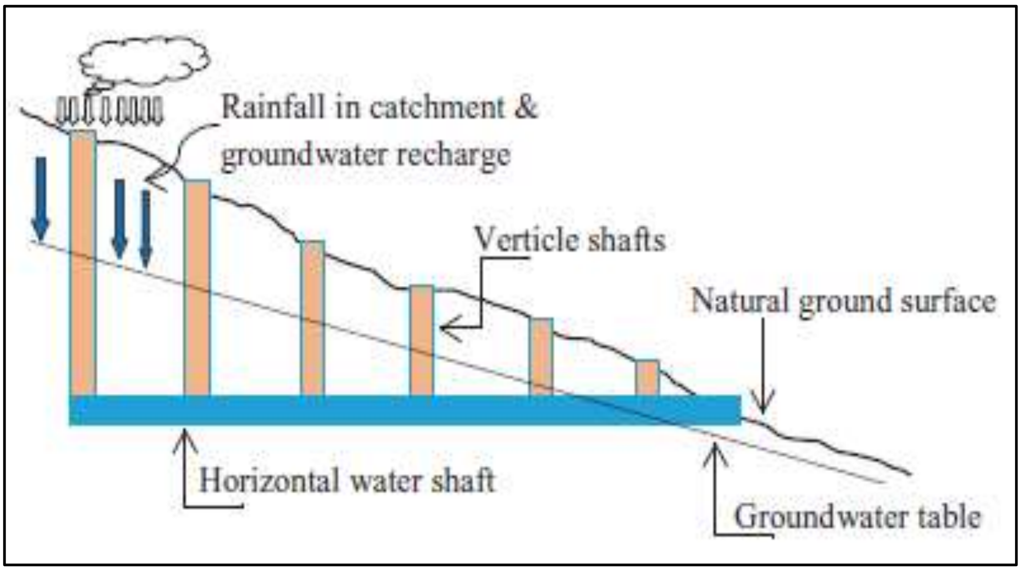


Figure 2. 5 Groundwater Harvesting Qanat. (Source: Cech 2009)

2.3.3 Rainwater harvesting

Rainwater harvesting (RWH) encompasses a range of techniques that collect and store a locally generated runoff during a rainfall event from a catchment that has been modified (Movie et al. 2006). Rainwater is the term often used interchangeably with runoff which refers to the water that runs over a land surface on which rain has directly fallen. After the collection of runoff, the stored water may be used for irrigation, human and animal consumption. There are commonly two (2) types of rainwater harvesting which is distinguished by the size of the harvested catchment: Micro and macro rainwater harvesting (Boustani 2009).

2.3.3.1 Rooftop water harvesting

Rooftop water harvesting (rooftop WH) is a system that collects and store water from the roof of houses or large buildings, greenhouses, courtyards, impermeable surfaces including roads (Mekdaschi and Liniger 2013). The local rainfall and the effective area of the roof will determine the quantity of water that will be captured(Rahman et al. 2014). Usually, 80-85 percent of rainwater is collected from roof surfaces with a runoff coefficient that varies from 0.5 to 0.9. Rooftop WH is useful in areas with local rainfall between 20-1000 mm and it consists of roof, gutters, first flush device and above or below the ground storage tank. Rooftop WH is suitable in areas with two separate rainy seasons (bimodal) where tap water is unavailable. Rooftop water is mainly used for domestic purposes, if consider for drinking, its quality should be checked. Depending on the uses, rooftop water may be used for irrigation (Thomas and Martinson, 2007).

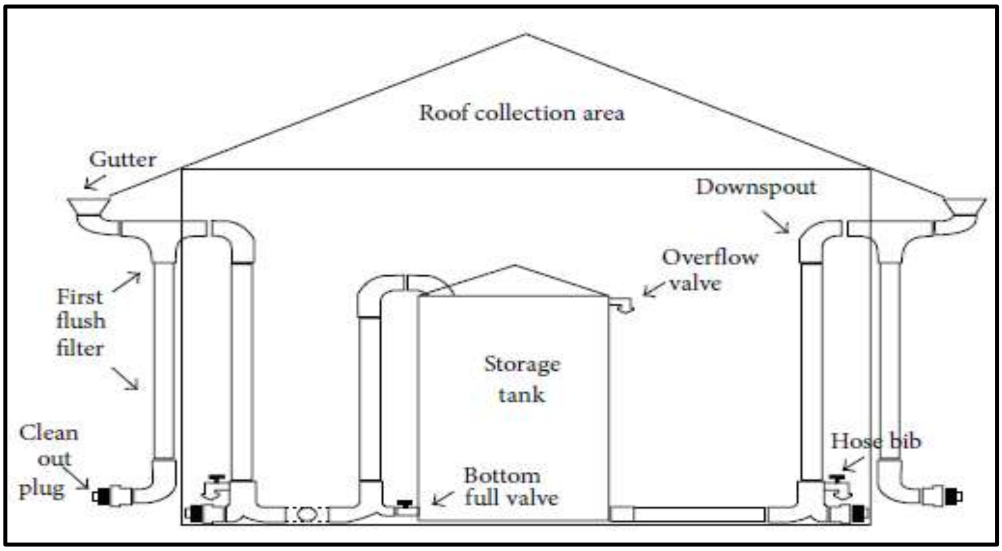


Figure 2. 6 Schematic of a rooftop water harvesting. (Source: Rahman et al. 2014)

2.3.3.2 Microcatchment Water Harvesting

Microcatchment water harvesting (Micro WH) is a method that collects surface runoff from a small catchment area with main rill or sheet flow over a short distance(Yosef and Asmamaw 2015). The runoff flows to adjacent agricultural land and is stored in the root zone and used directly by plants. Micro WH is simple in design and may be constructed at low cost. The range of the annual rainfall for a micro WH is between 200 to 800 mm (Yazar et al. 2014). The catchment length is usually between 1 and 30 meters with the size of individual catchment between 10 to 1000 m^2. The catchment area ratio is between 1:1 and 10:1with high runoff coefficient than macro-catchment water harvesting. It is easily replicable and adaptable (Ali et al. 2010). The land user often has control within his farm over the catchment and the application area. It is suitable for crops planted in pits or strips within the cropland. Micro WH prevents or reduces soil erosion and can be adapted in sloppy and plane lands (Oweis and Hachum 2009). There are little variations in the methods and techniques employed in different regions of the world. Some of the micro WH practices may include pitting, contour ridges, semi-circular bunds, again terraces or hill slope Microcatchment.

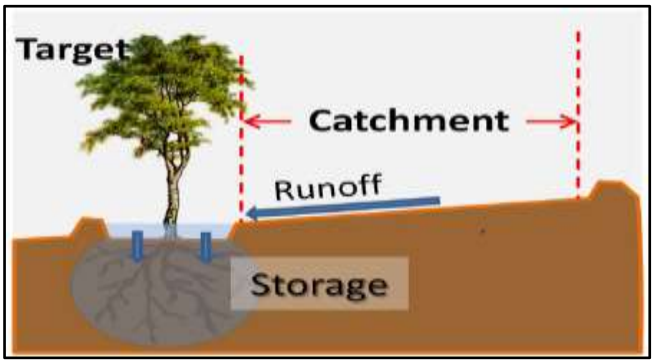


Figure 2. 7 Microcatchment WH. (source: Oweis et al. 2012)

2.3.3.3 Macrocatchment water harvesting

Macrocatchment water harvesting (Macro WH) is a method that involves the collection of runoff water from a large natural catchment such as a hill or a long slope of a mountain (Oweis et al. 2012). The catchment area is located outside the cropland boundary and the farmer has no control over it. It is characterized by turbulent runoff and channel flow. The runoff water may be directly stored in the soil or collected and stored in a pond or reservoir for later use for agricultural production, human and livestock consumption during periods of high demands. The annual range of the rainfall is between 200-1500 mm. The catchment length is between 30 to 200 meters with size which varies from 0.1 to 200 ha. The catchment area ratio is 10:1 to 100: 1 with runoff coefficient that varies from 0.1 to 0.5(10-50% of annual rainfall) (RAIN, 2009). It is suitable for annual and perennial under temporal waterlogging areas. Crops are usually planted on terraced areas or flat terrain which rapidly mature on residual moisture. Examples of Macrocatchment include hillside conduit systems, cultivated areas, stone dams, large semi-circular hoops and trapezoidal bunds (Näser 2010).

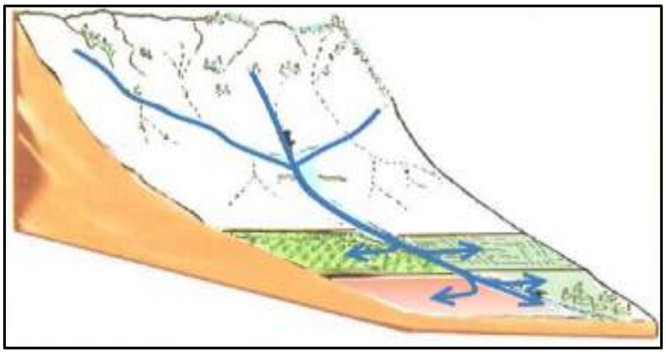


Figure 2. 8 Diagram of a Macro WH (Hillside conduit system).The farmland is levelled and surrounded by levees with a spillway to evacuate excess water from the farmland. When the water fills the farmlands, the water is allowed to join the wadi. (Source: Oweis et al. 2012)

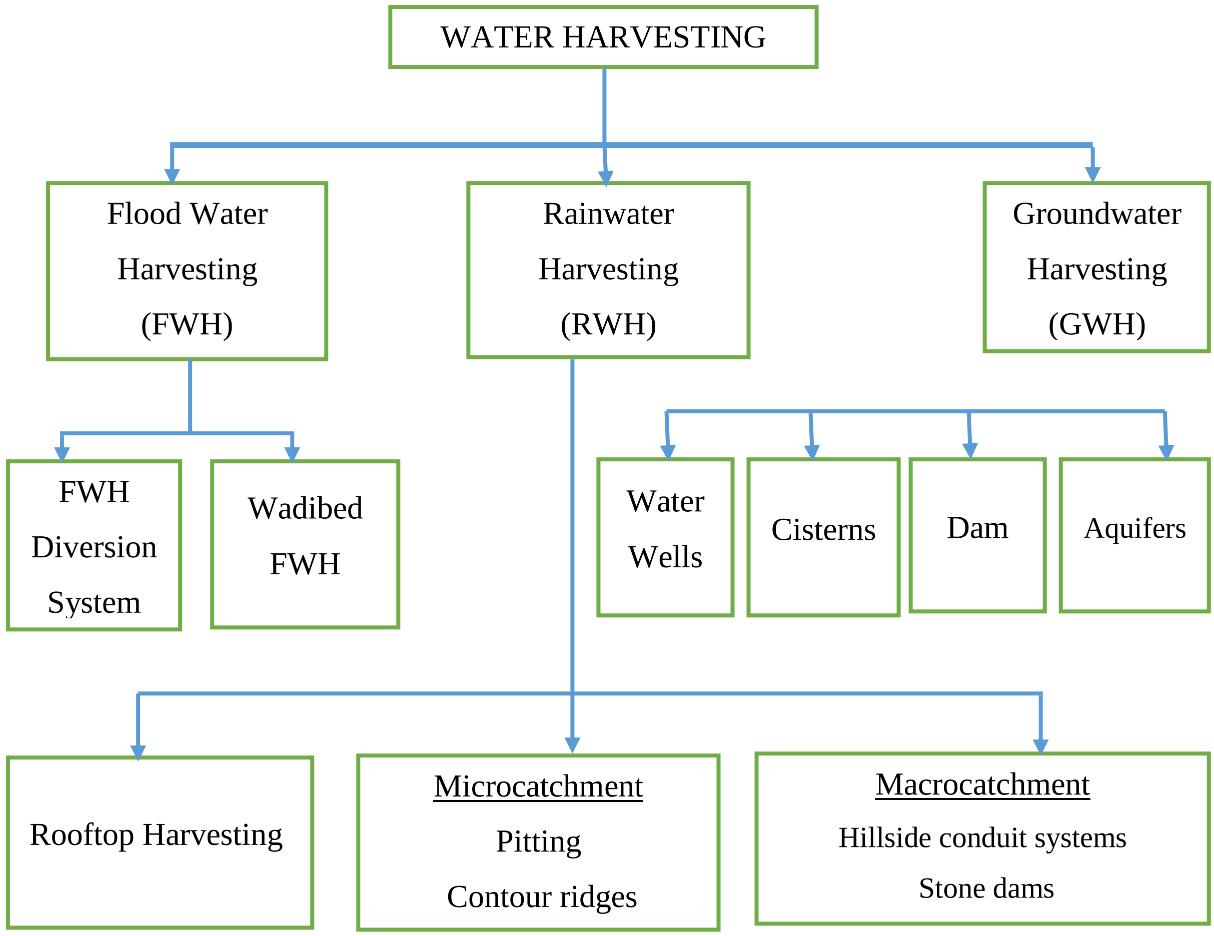


Figure 2. 9 Classification of water harvesting systems. (Sources: Gowing and Bunclark 2013; Bunclark et al. 2018)

2.4 Water Harvesting Structures in Arid Regions

2.4.1 Haffir

Haffir is a Sudanese Arabic word which refers to a type of an earth dam that is used to provide water for human and livestock consumption(UNICEF 2009). Haffirs are hand or machinery ponds dug into natural depressions of the Sudan savannah, or lacs collinaires in Algeria, made in Morocco, deep in Senegal, charco ponds in the drylands of Tanzania, khaks in Turkmenistan or mahafurs in north-west Arabia (Saudi-Arabia) which are commonly used for livestock consumption. Haffirs may be rectangular or semi-circular in shape and the soil at the construction site is clay in nature. The size of a haffir varies from 10000 to 100000 m^3. In recent years, the size has been standardized to 30000 m^3. Am improved haffir is one with a water treatment plant that is used primarily to supply water for human consumption(Ahmed 2012).

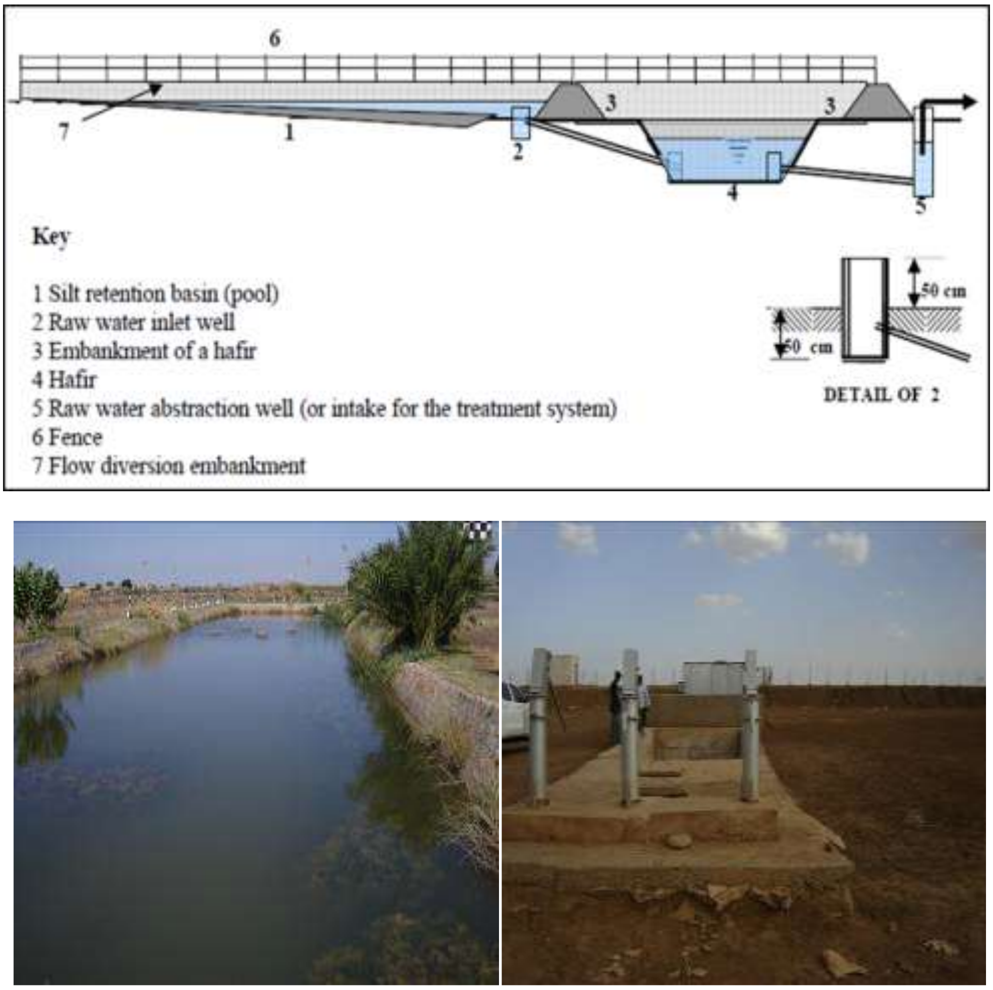


Figure 2. 10 Components of standard Hafir system in Sudan (source: Ahmed 2012)

2.4.2 Sand Dams

Sand Dams are the cheapest structures of WH compared to earth dams, hafirs, rock dams and rainwater harvesting tanks (Steenbergen 2009). A typical sand dam is between 1 to 5 meters high and 10 to 50 meters long. A successful sand dam is the one that can store millions of liters of water and is able to provide continuous supply throughout the year to 1,000 people. In 2012, a sand dam was constructed in eastern Kenya with the capacity of 140 m3 using 500 bags of stone masonry of which 40% are made of sand and cement and 60% is rock(Nissen-petersen 2000). It is appropriate for a river which is 30 meters wide with a spillway of 30 meters above the bedrock in the river bed level. In Kenya with long traditional experience in the construction of sand dams, it only takes 6 to 12 weeks to plan and prepare for constructing a dam and 2 days to 2 weeks to build a dam. They provide water for agriculture and potable water for humans through wells. Sand dams are suitable for arid and semi-arid regions(Rain 2009).

Figure 2. 11 A Sand dam in eastern Kenya. (Source: Rain 2009)

2.4.3 Permeable rock dam

Permeable rock dams are long, low but broad rock dams across valleys to slow spread floodwater and repair gullies. However, the central portion of the dam if a spillway is required may reach 2 meters high above the gully floor (Sawadogo 2011). The dam has a length between 50- to 300 meters (Critchley and Siegert, 1991). The dam wall is 1or more than 1 meter high within a gully and varies from 80 to 150 cm elsewhere. The downslope side of the dam is 2:1 or 3:1 while the upslope side is 1:1 or 1:2, to give better stability to the structure when it is full. A trench with shallow depth at the foundation improves the stability and reduces the risk of undermining (Barry 2008). Small stones are used on the inside and the large stones are used on the outer wall. The permeable rock dams are usually sited specific and considerable volume of loose stones are required as well as the means of transport. Permeable dams are found in Burkina Faso, Niger, and India.

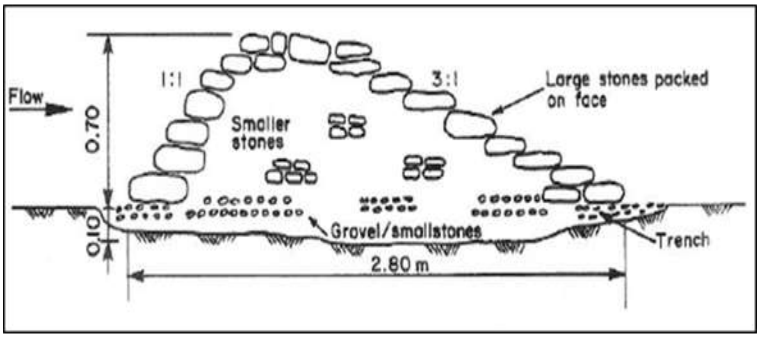


Figure 2. 12 Dimensions of permeable rock dam. (Source: Sawadogo 2011)

2.4.4 Planting pits

Planting pits are small basins planted with a few seeds of annual or perennial crops. The pits have different sizes, shapes and densities (pits/ha) (Critchley and Mutunga 2001). They are usually 20-30 cm wide and 20-30 cm deep and spaced 60 cm – 1 m apart. The catchment area ratio is 3:1. Pits are dug by hand. Manure or fertilizer are often added to the pit. The dug earth is placed downslope of the pit and may be formed into a small ridge to capture rainfall and runoff effectively (Mati 2005). Pits are often combined with stones lines to regenerate cultivated areas that have been degraded. Planting pits are applied on slope land of 0 to 5% that receives rainfall of 350 to 600 mm/yr. They are called tassa in Niger, Zai pits in Burkina Faso, Chololo pits in Tanzania, gun pits in Sudan, kofyar in Nigeria, Yamka in Kyrgyzstan (Ouédraogo and Sawadogo 2001).

Figure 2. 13 Planting pit (tassa) in Burkina Faso. (Source: Critchley and Mutunga 2001)

2.4.5 Water spreading weirs

Water spreading weirs (WSWs) are built across the dry valley and span the entire width of the valley which is usually between 100 and 1000 wide (GIZ 2011). They are constructed of stone masonry or concrete up to 50 cm above the surface of the surrounding sand. They are usually built in a series to stabilize the entire valley(Schöning et al. 2012). Construction work is done by trained members of local communities. The weirs permit spate flows to overflow and flood the inland valleys. Initially, the water flows over the low wing walls of the structure to the outer limits of the valley. Subsequently, it covers large areas in front of and behind the weir (Bender 2005). The alluvial deposit can be used for agriculture and the infiltrated water recharges the groundwater which is accessed through wells for human and livestock consumption. WSWs are mostly used in Chad, Niger, Burkina Faso, Yemen and Brazil(GIZ-KFW 2012).

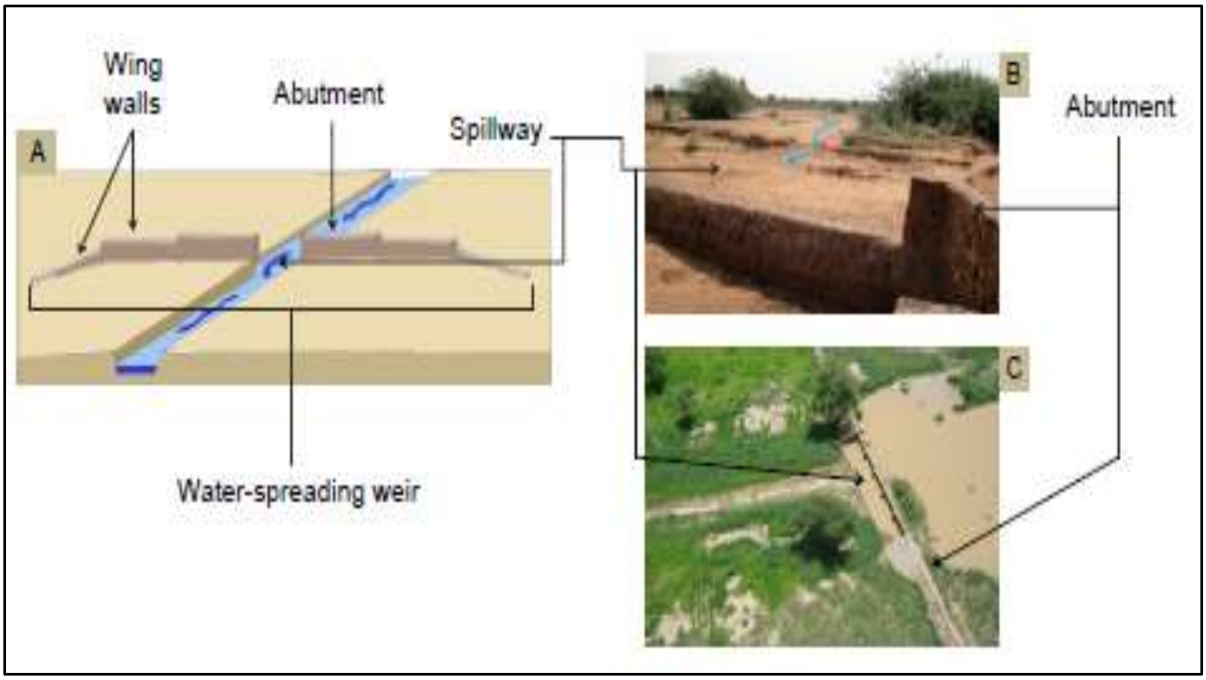


Figure 2. 14 Water spreading weir. (Source: GIZ-KFW 2012)

2.4.6 Tabia

Tabia is considered as a new technique developed by mountain dwellers who migrated to the plains (Alaya et al. 1993). Tabias consists of an earth dyke of length between 50 to 150 meters and height between 1 to 2 meters, a spillway which located in the central or lateral position and an associated WH area (Ben Mechlia and Ouessar 2004). The cultivation area ratio is 1:6 to 1:20. Tabias are mostly used to grow trees and annual crops. They can also be used to control soil erosion and groundwater recharge. They are commonly used in Tunisia.

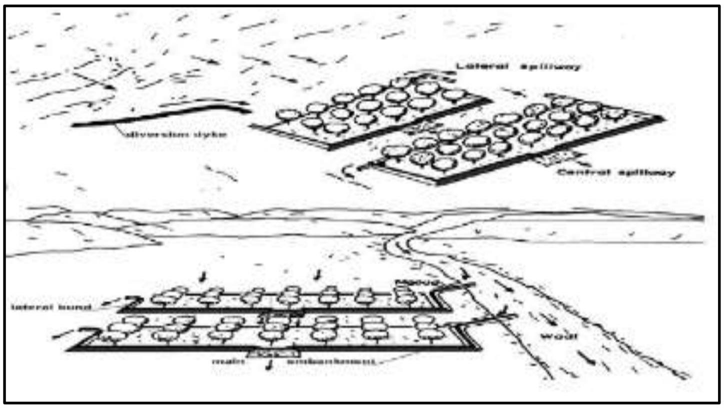


Figure 2. 15 Tabia with natural water collection (upper) and tabia on an expanded system with additional floodwater diversions (lower). (Source: Alaya et al. 1993)

2.4.7 Hillside runoff/Conduit system

This system is suitable in hilly or mountainous regions with an annual rainfall of 100 to 600 mm/year. The catchment to application ratios(C:A) is 10:1 to 100: 1,it can reach 175:1 (Prinz 2011).Concentrated runoff water on a slope greater than 10% is guided through small conduits and deliver to flatlands at the foot of the between 0 to 10%. Farmlands are levelled and surrounded by impounding walls with a spillway to drain excess water downstream farmlands. This type of structure is called sylaba in Pakistan, caag in Somalia and takyr cultivation in Turkmenistan. The system is also practiced in Israel (Liniger 2007).

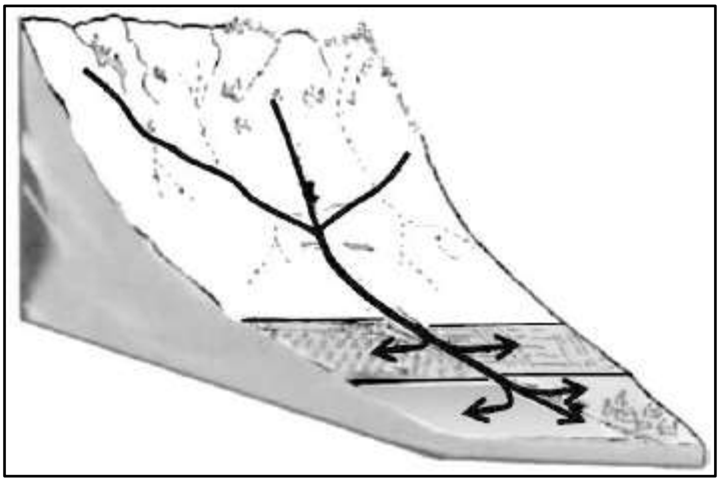


Figure 2. 16 Hillside runoff system. (Source: Prinz, 2011)

2.4.8 Trapezoidal bunds

They consist of earthen bunds with base bunds, connected to two side bunds at an angle of about 135° and a distance between the tips of 10 to 100 meters on a slope of land between 0 to 10%. The excess water is discharged around the tips of the side bunds (Taamallah 2010). They are often constructed using machinery and the wings of the side bunds are usually reinforced with stone. They are suitable in areas with an annual rainfall of 200 to 400 mm with a catchment area ratio of 15:1 to 100:1. The structures collect runoff water from outside catchments upslope and are used for annual and perennial crops as well as pastures (Oweis et al., 2012).

Figure 2. 17 Sketch of a trapezoidal bund. (Source: Taamallah 2010)

2.4.9 Check dam

A raised wall is built using stone, concrete, and gabion across a gully to pond the water flow behind for irrigation purpose using either gravity or lifting mechanism and slowing down the flow velocity and improving gully rehabilitation (Oweis, Prinz, and Hachum 2013). The height of the dam varies between 2 to 4 m depending on the gully depth and the width ranges between 1 to 2 m. The length of the check dam depends on the gully width while the spacing between adjacent check dam is determined based on the availability of water and a potential land that can be irrigated (Liniger 2007).

Figure 2. 18 Small check dam, Rajasthan India. (Source: Liniger 2007)

2.4.10 Rock catchment masonry dams

More than hundreds of rock catchment dams have been built by the Agricultural Services and a number of NGOs in Kitui, within Eastern Kenya since the 1950s (Clements et al. 2011). The rock catchment dams in the region have a wide range of storage capacities (20 – 4,000 m3) and are primarily used for domestic purposes (Liniger 2007). However, they can also be used for small-scale irrigation in vegetable gardens. It has been observed that the local communities prefer rock catchments over any other form of water supply (except rooftop water harvesting), because maintenance is simple and cheap, and rock catchments do not occupy farmland (Nissen-Petersen 2006b).

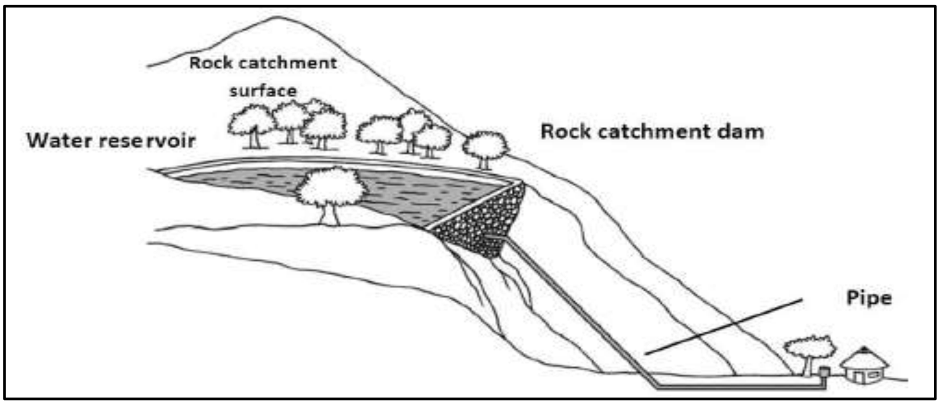


Figure 2. 19 Rock catchment dam. (Source: Clements et al. 2011)

2.4.11 Recharge well

In Tunisia, recharge wells are used in combination with gabion check dams to enhance the infiltration of floodwater into aquifers in areas where surface water cannot reach the aquifer because of an impermeable (or slowly permeable) layer (Schwilch et al. 2012). Recharge wells are installed in wadi (Ephemeral River) beds. A recharge well consists of a long inner tube surrounded by an outer tube, the circumference of which ranges between 1 and 2 m. The area between the tubes is filled with river bed gravel which acts as a sediment filter. Water enters the outer tube through small openings (20 cm long, a few mm width) and flows through the gravel and the perforated inner tube. From there it reaches the aquifer (Temmerman 2004). The above-ground height of the well is around 2 to 3 m while the depth is linked to the depth of the water table (normally up to 40 m) (M. Ouessar and H. Yehyaoui in Schwilch et al, 2012). Recharge well is found in Tunisia, East Africa, India (Oweis, Prinz, and Hachum 2013).

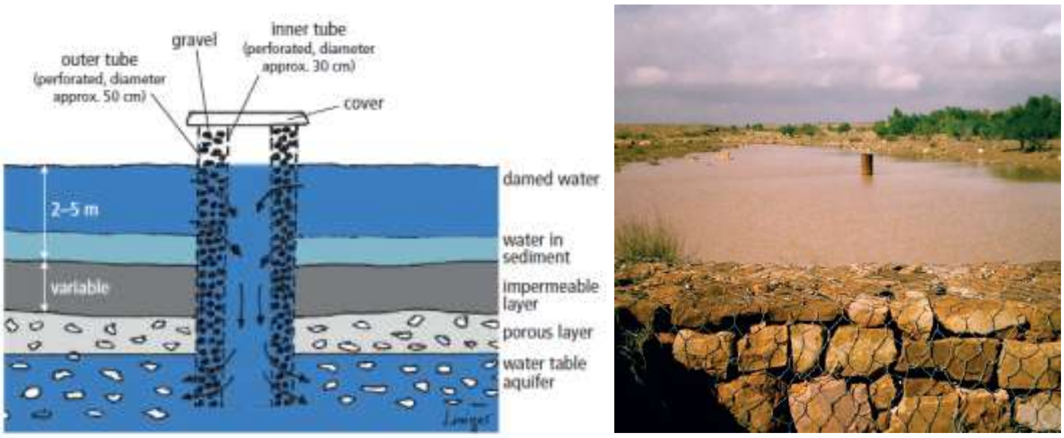


Figure 2. 20 Component of the recharge well (left), a recharge well-constructed behind a gabion check dam after rain (right). (Source: Oweis, Prinz, and Hachum 2013)

2.4.12 Stones lines/bunds

Stones lines can be used as a water conservation measure on slopes greater than 5% of for water harvesting on gently sloping plains in semi-arid regions. A stone line is 25 cm high and has a base width of 35 to 40 cm. It is constructed of a combination of small and large stones along with the contour and across the field. Stones with smaller size are placed upslope and the large ones beneath to slow down runoff, trap fertile soil sediment and increase infiltration (Critchley 2010). The distance between lines is 20 m for slopes less than 1%, 15 m for slopes of 1 to 2%. Stones lines are easy and cheap to build, provided the stones are locally available. They are commonly used in Africa. Especially in Burkina Faso and Niger, they are of small size, at most three stones wide, and one or two high (Reij, et al. 2009).

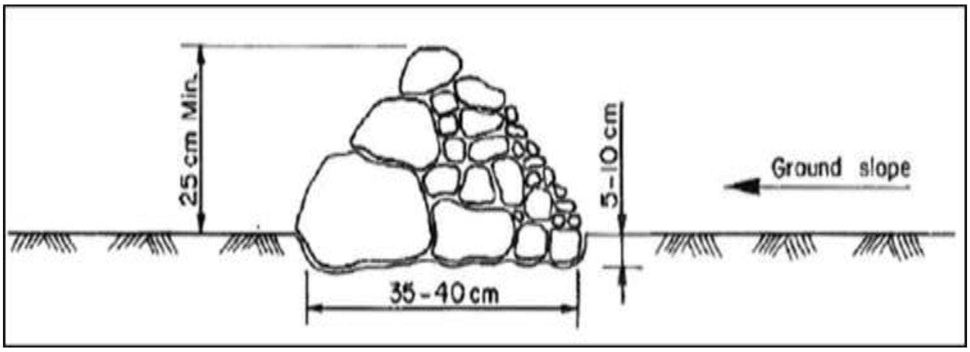


Figure 2. 21 The dimension of Stones lines. (Sources: Critchley 2010)

2.4.13 Eyebrow terraces:

Eyebrow terraces are used to re-establish vegetative cover on almost totally bare pasture land. The catchment size is 5 to 50 m^2 and the cultivated area is 1 to 5 m^2. They are suitable in areas with an annual rainfall of 200 to 600 mm on a slope of up to 50%. The steeper the slope, the more the bunds have to be reinforced by stone (Schauwecker, 2010).

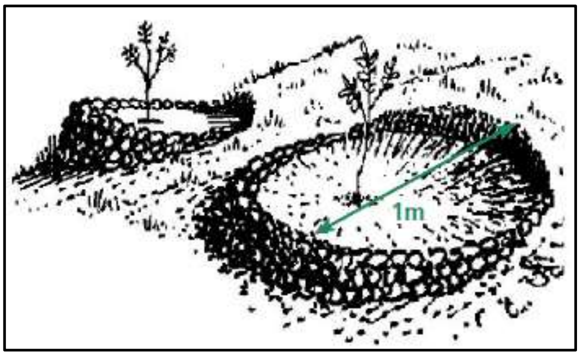


Figure 2. 22 Eyebrow terrace from the side and above. (Source: Schauwecker, 2010)

2.4.14 Mechanised demi-lunes (Vallerani-type basins)

They are constructed by two types of modified tractor plow: the train and the dolphin. The dolphin plow creates crescent-formed micro-basins at the rate of up to 5000 to 7000 per day, 400 micro-basins /ha (Prinz, 1996). The micro-basin is 4 to 5 m long, 40 cm wide and 40 cm deep. The catchment has a water capacity of about 600 liters. The plow has been used for afforestation and pasture improvement in the Mediterranean, African, and Asia countries. It is suitable in areas with an annual rainfall of 100 to 600 mm and a slope of 2 to 10% (Akhtar 2006).

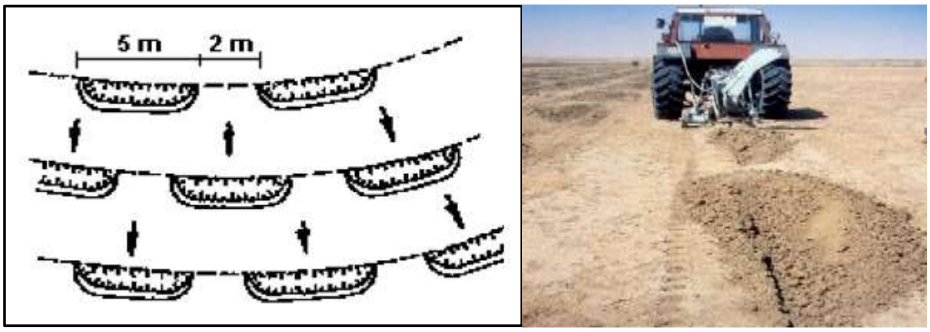


Figure 2. 23 Fully mechanised Vallerani micro-basins. (Source: Prinz, 1996)

2.4.15 Semi-circular bunds

Semi-circular bunds have a diameter of 2 to 8 m (up to 12 m) and are made of earth or stone. They are 30 to 50 m high and the tips of the bund are set on the contour line, facing upslope (MoALD 1984). They are built in a staggered sequence over a plot; that is the second line harnesses runoff that flows between the structures in the line above; and so on. The C: A ratio ranges between 1:1 and 3: 1. The bund is usually big during the dry season (Oweis et al. 2012). They are suitable on lands with an annual rainfall of 300 mm and slope up to 15%. They are used for grazing land rehabilitation of fodder production. Half-moon with close-spaced is used to grow trees and shrubs. They are used in the Sahel to grow pearl millet (Mati 2005).

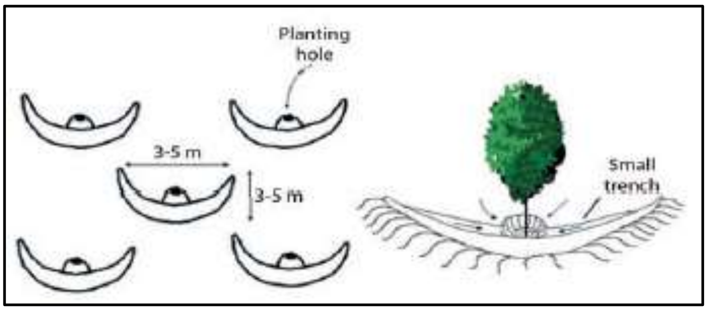


Figure 2. 24 The layout of a semi-circular bund system (Source: Mati 2005)

2.4.16 Negarim

Negarim is small diamond-shaped runoff basins, surrounded by low earth bunds. Runoff infiltrates at the lowest apex, where the trees are planted. Reported sizes of negarim are 100-250 m² in Israel and up to 400 m² in India (Ben-Asher1988). As 15-90% of rainfall may be harvested as runoff and used for the tree crop, the catchment to cropping area ratio ranges between 3:1 and 10:1; in flatter catchments and drier areas, this may be up to 25:1. They are applied on sloping land (1-20%), however, are commonly found on slopes of 1-5% in areas of 150-500 mm/year of rainfall. In the Middle East, negarim are used for fruit trees, especially apricots, olives, almonds, grapevines, pomegranates, and pistachios; but they are also used for the establishment of fodder bushes and indigenous trees (Schauwecker 2010).

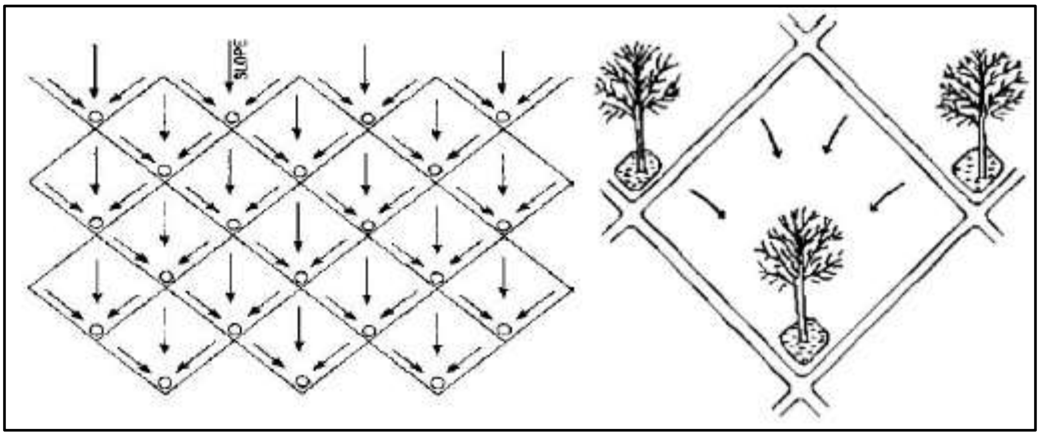


Figure 2. 25 Arrangement of several negarim (left); Close-up of a single negarim (right) (Sources: Schauwecker 2010)

2.4.17 Meskat

Meskat is rectangular shaped runoff basin. It consists of a catchment area called meskat of about 500 m² in size, and a cropping area called mankaa of about 250 m² (C: A ratio of 2:1). The entire system is surrounded by an approximately 20 cm high bund and provided with spillways to allow runoff to flow into the mankaa (Prinz 1996). The meskat system is a traditional MicroWH which is only used for tree cropping. In Tunisia, it covers around 300,000 ha where olive trees, mainly, are cultivated in the integrated manual plots. They are applied in areas with 200 – 400 mm annual rainfall and slopes from 2 – 15% (Taamallah, 2010).

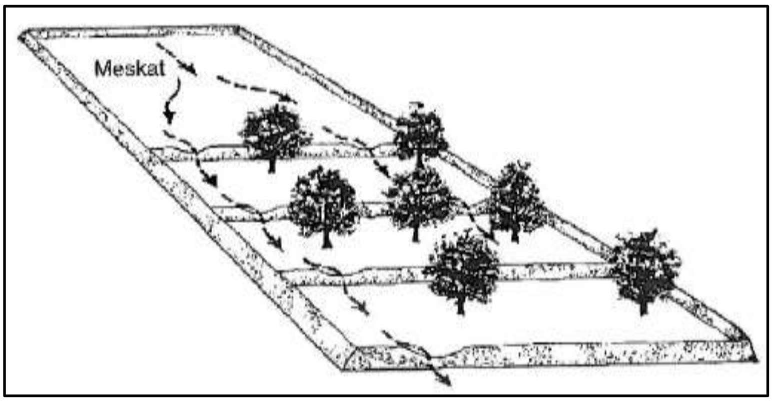


Figure 2. 26 Meskat Microcatchment in Tunisia (Source: Prinz 1996)

2.4.18 Rooftop systems

Rainwater harvesting (RWH) system was constructed in a very remote and rural village in Khulna, Bangladesh, for a 4-membered household (Shittu 2012). RWH consisted of a concrete catchment of 40m^2 area, a supporting and collection system made of PVC pipes, and two locally available plastic storage tanks having a capacity of 2000 L. The quantity of water that runs off a roof into the gutter system was calculated using the following equation (Thomas and Martinson 2007):

$Q = \mathrm{RC} \times R \times A$, (1)

where Q is the quantity of runoff water, RC is the runoff coefficient, R is the total rainfall (mm/y), and A is the roof area or the catchment area (m^2). The table below gives the runoff coefficients of traditional roofing materials:

Table 2. 1 Runoff coefficients of traditional roofing materials

Types	Runoff coefficients
Galvanized iron sheet	>0.9
Corrugated metal sheet	0.7–0.9
Tiles	0.8-0.9
Concrete	0.6–0.8
Brick pavement	0.5-0.6
Rocky natural catchment	0.2–0.5
Soil with slope	0.0–0.3
Green area	0.05–0.1

For the study, RC was taken as 0.8, R was 1800 mm/y (for Khulna region), and A was 40m^2, the quantity of water (Q) was found to be 57.6m^3/y (≈57600 L/y). Thus the amount of water to be harvested was 157 L/day. Four months as rainy season was assumed, the amount of water that could be harvested was 157 × 30 × 4 = 18840L, which was more than enough for storing the required amount of water (3600 L) for drinking, cooking, and food preparation purposes for the studied household(Biswas and Mandal 2014).

In Thailand, jars of 100 to 3000 liters are used to store water from the rooftop for drinking purposes. A 2000 liters jar store a sufficient quantity of water to be used by the six-person household during the dry season and it is the most commonly used (UNEP 2002).

Brick tanks of 25,000 liters are the most used water storage facility in Sri Lanka, Uganda, and Nepal. The tanks are made of backed bricks, cut stones, compressed soil, bricks and concrete quarry (Worm and Hattum 2006).

Ferro-cement tanks are made using a solid mold of either corrugated or flat galvanised steel sheet made in curve section that bolt together forming a cylinder (Worm and Hattum 2006). Mesh is wrapped around the mold and galvanised wire wound in a spiral around the tank with spacing at the bottom and a larger space at the top. The mesh is then plastered over with mortar, which is left to cure overnight. The form is then dismantled and the inside plastered with mortar the straight cylinder design using sheet metal for the mold is the most used Ferro-cement tank. They are used in South Africa, Sri Lanka and Thailand and Burkina Faso (Thomas and Martinson 2007). Most of the rooftop tanks adopted in arid regions are mostly concrete tanks, PVC tanks, impluvium tanks, fero cement tanks and CPVC tanks respectively(Salman 2017).

2.5 Economic Viability of Water Harvesting Structures

The use of planting pits in Burkina Faso increase the yield to 0.3 – 0.4 t/ha in a year of low rainfall, and up to 1.5 t/ha in a year of good rainfall compare to zero yields without the pits. Half-moons were used to grow sorghum grain, the yields were higher compared to normally plowed fields on completely degraded soils. The same studies on ngoro pits in Tanzania revealed that 2 m wide pits had the highest maize grain yield (1.85 t/ha) compared to 1 m wide (1.44 t/ha) and 1.5 m wide pits(1.66 t/ha) (Malley et al., 2004). An earth dam constructed to increase agricultural production of sorghum and tomato was modelled for study sites in Burkina Faso and Kenya. Earth dam establishment resulted in a net profit of 626 US$/y/ ha for Burkina Faso and 477 US$/y/ha for Kenya depending on the opportunity cost of labour, compared to

83 US$/y/ha and 130 US$/y/ha of the current farming practices. A study conducted in Kenya revealed that a sand dam used by 25 families had a net income of US$ 3,000/year (Tuinhof et al., 2012). Another study conducted in Tanzania showed that earth dams are the cheapest per cubic meter compared to above or underground tanks(Lunduka 2016). They are used by a large number of beneficiaries. Improving Resilience in Dry using Water spreading weirs showed the area under cultivation increased from 2,847 to 8,132 ha, the yields increased from 333 to 675 kg/ha and the production augmented from 948 to 5,489 tonnes(Schöning et al. 2012). Negarims are techniques developed in Israel for fruit trees production but are not always viable. The benefit in arid and semi-arid regions after many years will be the soil conservation effect and grass for fodder until the trees become productive. A study in Senegal showed that with a US$ 600 investment and a water tank with an average lifespan of 15 to 20 years, the annual costs of the structure would be around US$ 40. This is a low-cost, effective and sustainable water supply option for areas which suffer water quality or quantity problems (Van Steenbergen and Tuinhof, 2009).

2.6 Operation and Maintenances of Water Harvesting Structures

Food and Agricultural Organization of the United States (FAO) technical guideline on Planning, Construction and Operation of Water Harvesting Structures was carried out in South Sudan (FAO 2012). Based on analysis by FAO, the management committee should be established with clear roles and responsibilities and received appropriate training for sustainable water harvesting structures. However, the management committee should establish a water user fee from the beginning with the agreement of the community, with low cost and then, the cost can be increased gradually with time when the community feels a sense of ownership (Eshetu 2014). The fees can be used for the operation and maintenance of the systems. According to FAO, the role and responsibilities of stakeholders should be clear from the planning stage to avoid misunderstanding. Government commitment and low-cost technology are key factors in the choice of the system(FAO 2015). A regular maintenance schedule and budget allocation for the maintenance is very important. A delay in the maintenance of the WH facility will lead to greater costs or to complete failure of WH facilities.

Operation and Maintenance (O&M) of WHTs should exclusively be done by communities. This is highly relevant for any kind of WH structures includes dams (surface catchment systems and small scale dams) (AFDB 1999). The obligation of users to ensure low soil erosion from the catchment area and annual desilting must be included in the workshops or interactions with the beneficiary groups (Nissen-Petersen et. al. 2005). For earth dams and water ponds, erosion at the catchment should be assured, silt traps should be emptied annually, cracks in the embankments should be repaired instantly, and fence preventing livestock from entering the structures should be maintained. It is crucial that the beneficiaries should work themselves. Rooftop water harvesting using jars as a storage facility, the jar should be clean Once or Twice a year and fishing contaminated water. The maintenance cost is US$ 15 per year and 100 percent of the money is met by the beneficiaries (Harma 2001).

2.7 Benefits of water harvesting

The excess water collected during heavy rainstorms in large storage facilities helps reduce floods in some low lying areas(FAO, 2001).WH also contributes to the reduction of soil erosion and contamination of surface water with pesticides and fertilizers from runoff water which results in cleaner lakes and ponds. WHSs rehabilitate degraded lands in arid regions to combat desertification. WH can be used to replenish groundwater and restore the ecosystems.WH increases infiltration and water retention in the soil profile (World Bank, 2006). WH is used to re-establish vegetation cover to improve crop growth in order to alleviate poverty and increase food security in drylands. It can improve the availability of clean and safe water for human and livestock consumption. WH has improved the livelihoods of poor farmers in Somalia and Ethiopia. Through WH adoption, the workload of women is reduced significantly (Liniger and Critchley 2007).

2.8 Policy on Water Harvesting Structures

Policies were recommended by Cleveland in arid-located regions of America that intend to pursue their own implementation of water harvesting techniques by reviewing the Policies of existing water harvesting techniques in the southwest semi-humid region of the united states of America. Water Harvesting structures should be made mandatory for all new commercial building(Cleveland 2013). Kloss concluded by saying that little policies are developed in arid regions and encourage more research on policies for water harvesting techniques in arid regions in general (Kloss, C. 2008). A study on the Effectiveness of National Rainwater Policy and Strategy in Sri Lanka showed that the Policy has not given an effective framework for the area of RWH, and also the law is very silent and not in practice(Dissanayake and Ranasinghe 2016). Studies on WH policies by FAO and AgWA showed that communities that plan to implement WHSs should collect necessary data, engage the communities, including nongovernmental organizations (NGOs), in planning WHSs(FAO and AgWA 2014). Specific institution or department within an existing institution should be encouraged to participate in the planning and implementation stage of the water harvesting project so that it can supervise the project after its implementation. A study by Maher on WH policies in Jordan also stated that priority should be given to WH within the government agenda with a specific accent on ensuring the sustainability of WHSs(Maher et al. 2018). A comprehensive database should be developed for water harvesting to include biophysical studies, socioeconomic studies, hydrologic and technical studies as well as increase funding for WH should be integrated into the national budget**.**

This study will incorporate the technical feasibility, economic and social acceptability of water harvesting techniques to ensure the sustainability of WHSs that will be adopted in Chad and other arid regions of Africa.

CHAPTER THREE

3.0 RESEARCH APPROACH

3.1 General presentation of the study area

Chad is a landlocked country in the heart of Africa and is ranked as the fifth (5) largest country in the continent. It is located in the north-central part of the continent and covers a surface area of 1,284,000 square kilometers with 1, 259,200 km² of land and 24,800 km² Water(Louis 1984)(AGH 2010). The country has a population of 15,162,044 with a population density of 12.0 per km^2 and a total annual growth of 3.4% (NISEDS 2019). The rural population accounts for 75 percent of the total population(The Global Fund 2018). The country has two (2) official languages which are French and Arabic with CFA Franc as Currency. It is bordered by Libya to the north, Sudan to the east, the Central African Republic to the south, Cameroon and Nigeria to the southwest, and Niger to the west(Moustapha 2018). From 1960 to 1999, it was divided into 14 prefectures. They were replaced in 1999 by 28 departments. Currently, the country has 23 regions. N'Djamena is a national capital city and Abéché is the economic capital. Chad forms an immense plain whose edges are raised towards the north and the east(Angel et al. 2011). The highest peak is the Tibesti Mountain at 3145 m. In the south-west of the country are located vertisols, while the north is colonized by sand dunes sands unsuitable for agricultural activities, except in the oases. Polder soils from the isolation of the arms of Lake Chad, are particularly rich and allow many crop growth. The average annual rainfall is estimated at 322 mm/year and it is unevenly distributed due to high geographical variability of rainfall, which is accompanied by high interannual variability. Droughts are common.

As a continental country, Chad has three major agro-climatic zones, from north to south, where the distribution of natural resources in water, land and biomass is very varied: the Saharan zone with a rainfall of less than 300 mm at the edge of the desert to the north, while the rains are episodic throughout the rest of the area. It covers about 47 percent of the country's total area but contains only 2 percent of the population; the Sahelian zone where rainfall is between 300 and 600 mm/year in the center of the country(World Bank 2015). It covers about 28 percent of the total area and its population represents 51 percent of the total population; the Sudanian zone, characterized by a rainfall greater than 600 mm /year (sometimes reaching 1200 mm to the southern tip), occupying 25 percent of the total area. The maximum rainfall during the year is in July / August. There are two seasons for the Sahelian and Sudanian zones: a rainy season from June to September and a dry season from October to May(FIDA 2017).

Evapotranspiration sometimes reaches 3000 mm in some areas. Average monthly temperatures are 28 ° C to 42 ° C during the day, depending on the month, but can drop overnight at 14 ° C. In the north temperatures range from 13 ° C to 29 ° C in January and from 25 ° C to 44 ° C in May. In the south temperatures are between 15 ° C and 34 ° C in January and between 23 ° C and 35 ° C in May(Mcsweeney 1960). The drinking water supply rate for the entire urban area is only 61 percent, while in rural areas only 33.5 percent of the population has access to improved sources of drinking water. Agriculture and livestock occupy about 73 percent of the labor force (MEWAF 2019).

Figure 3. 1 Map of CHAD**.** (Source: Google map)

3.1.1 Location and description of the case study

The Ouaddaï Region is made up of three Departments: Ouara, Assoungha and Abdi. It covers an area of 29 940 square kilometers and is bounded on the north by the Wadi Fira region, on the east by Sudan, on the south by Dar Sila and on the west by the Batha. The Ouaddaï has 997257 inhabitants (NISEDS 2019) distributed among the main ethnic groups which are: Ouaddaïens, Goranes, Zaghawas, Massalites, Peuls, Haoussas, Tamas, for and Arabs.
The region has a domestic livestock population of 2,119,020 heads of cattle; 5,361,870 heads of goats /ovines, 100,067 head, of camels, 131,247 head of equine, 413,589 heads of asins(OCHA 2012). The district of Abougoudam is located about 20 km south-west of Abéché city, Ouara Department, Ouaddaï region. It is between 13 ° and 14 ° North latitude and 20 ° and 21 ° East longitude. The district is bordered on the north by the Khachim Al Wadi and Mandjobok Township, on the south by the Massalat Township(Adey et al. 2017), on the west by the Guéri Township and the Batha East County and on the east by the Ouadi Hamra and Marfa Township. Its area is estimated at 2320 Km². Currently, Abougoudam has 27 townships in which live 62 161 inhabitants (National Institute of Statistics, Economic and Demographic Studies (NISEDS 2019) and is mainly composed of farmers and/or cattle breeders. The area has an estimated domestic livestock population of cattle 75006, goats 102420, camel 6599, horses 13300, donkeys 31157, and sheep 77944. Cattle and sheep farming is professionally practiced by nomadic, semi-nomadic and sedentary Arabs. The population lives mainly on agriculture and livestock products. Livestock is frequently confronted with the difficulties of water, pasture, epizootic and also conflicts in case of stray animals in the fields(LDP 2014).
The relief of Abougoudam is characterized by important mountain ranges and hills. There are important mountains such as Hadjer Abougoudam, located 5 km north of Abougoudam town nationally recognized. Other less important mountains are those of Atim located at 20 km south of Abougoudam and are located precisely in the village of Atim and others are: Damire Al Hadjer, Kakara, Andinga, Hadjer Tarfana, Djemile, Kamack, Hireine, Kadama, all located in the south of the district, bear the names of the villages bordering them.

The area was also marked by painful events in the past, the most important of which are: the famines of the years 1914 and 1985 that had caused thousands of deaths and displaced.

3.1.2 Vegetation and Flora

The district presents in its generality little vegetation consisting of species of trees and shrubs distributed according to the topography of the ground. The grass cover is medium(H. GILLET

1963). According to the regional plan, the Ouaddaï / Biltine around the year 2005, 40% of the total surface of Abougoudam are denuded. The lack of vegetation is due to human pressure on the ecosystem due to the clearing of new crop fields and cutting of trees for fencing of farmlands and houses(Miré and Quézel 1961).

3.1.3 Fauna

The fauna consists of a few small wild animals (hare, jackal, hedgehog, red-fronted gazelle, monkeys, turtles, hyenas, squirrels, lizards ...)(Miré and Quézel 2018). Large wild animals such as elephants, antelope, buffalo, Austria that once existed in the district have completely disappeared because of hunting, charcoal cutting and especially because of drought. The famine of 1985 caused the departure of antelopes, ostriches and elephants to the south. Lions and panthers fled the gun sounds of the events of 1979(Brundu and Camarda 2013).

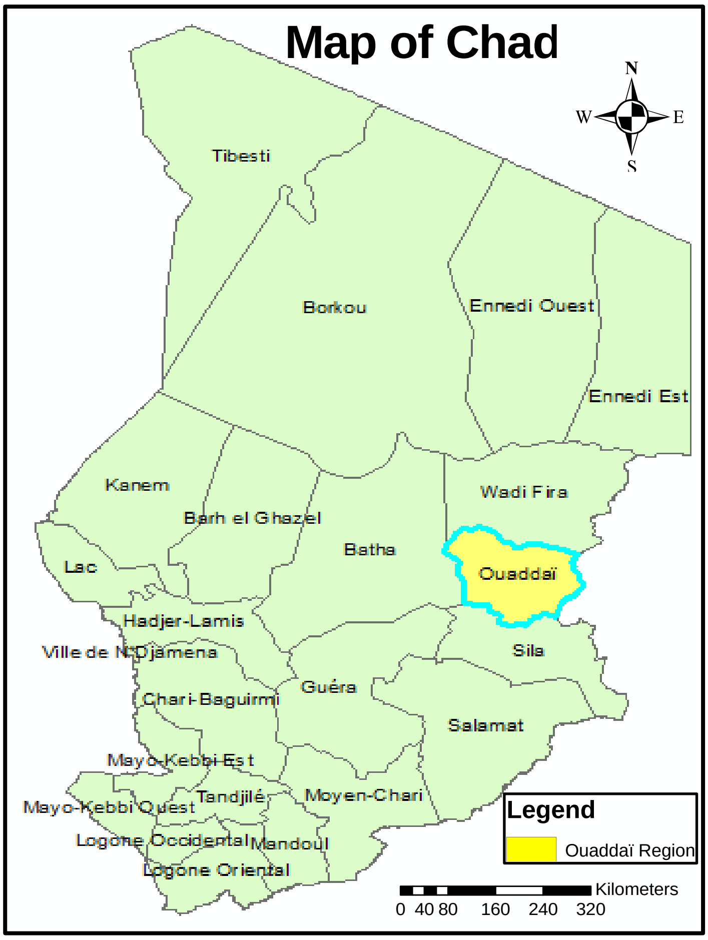


Figure 3. 2 Map of Chad showing the 23 Regions and the location of the Ouaddaï region shaded in yellow colour. (Source: Author 2019)

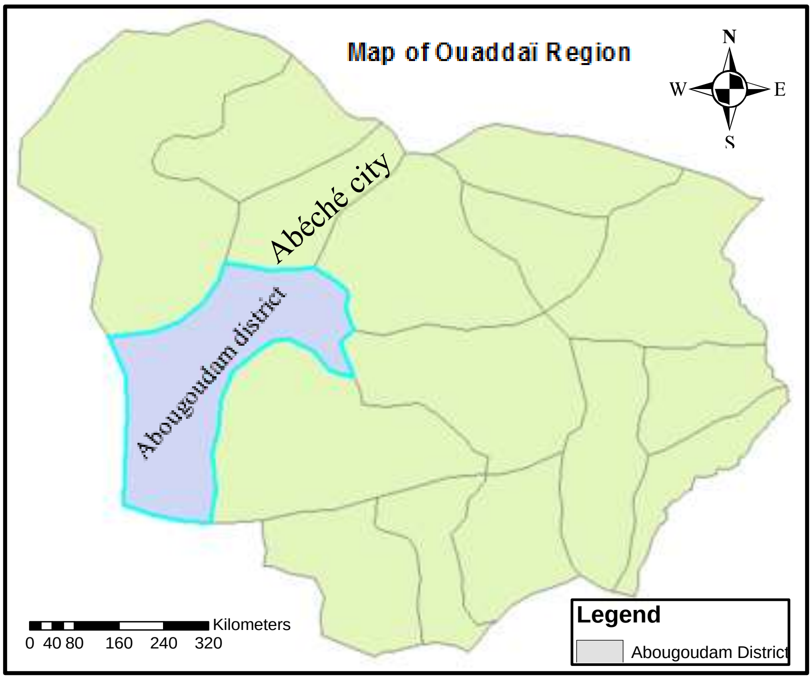


Figure 3. 3 Map of the Ouaddaï region showing Abougoudam district shaded in grey colour. (Source: Author 2019)ï

3.1.4 Climate

The climate of Abougoudam is of the Sahelian type characterized by a long dry season from October to June and a rainy season from July to September. The district of Abougoudam is under the influence of two prevailing winds: From October to June, blows almost permanently the harmattan, dry wind from the North-East sector to the South-West and raises dust and sand(Adey et al. 2017). From May to September, the monsoon blows, westerly wind from the Southwest sector to Northeast, and it brings the clouds humidity. Their succession is fairly regular during the year. The first rains usually fall at the end of June (DWR 2018). The rainy season runs from May to September, but most of the rainfall falls mainly between the months of July and August. Annual rainfall is between 200 - 400 mm of rainfall per year. As in all Sahelian countries, the rains are often torrential over a very short period resulting in strong soil erosion and the banks of Wadis. The District is also characterized by annual rainfall irregularity(Mahe and Hote 2001).

3.1.5 Hydrography

The hydrographic network consists of watersheds, ponds and wadis that cross the sub-prefecture. The main wadis that cross the Abougoudam are the Wadi Bithea, recognised nationally because of its breadth and reputation in onion farming. Irrigation is practiced in the dry season (November to March). Other secondary wadis of minor importance also cross Abougoudam which are(LDP 2018): Wadi Chaou and Ouadi Guelia. In all these wadis, the water table is almost superficial generally between (1.5- 4 meters) depending on the period. However, the years of abundant rainfall, some wadis overflow their natural bed, forming flood zones favourable to off-season small-scale irrigation and livestock. The district is also concerned by the watersheds of Bas-Chock and Toumbang / Marchoud. The insufficiency of groundwater resources, as well as the technical difficulties of their accessibility, depending on the geological formations of the district (MEWAF 2018). In some villages of the prefecture, the development of boreholes are negative and yet there are suitable areas: it is the case of the villages of Marchoud, Hadjar, Harazé, Afoul, Argoudi, Tardjam Hidjer, Ouled Moussa, Atourda, Kourdoufan, Batouma, and Matar. There is also the problem of chemical content in groundwater (very high conductivity) in the villages of Argoudi, Afoul, Banatil and Marchoud. Crystalline rock residues may contain groundwater in aquifers but erosion, steep slopes and low rainfall in some areas of the area limit the potential of the groundwater (DWR 2018). The ponds of the study area also play an important role in the water supply and especially in the watering of livestock, although they are natural. Often a drying problem results in a decrease in their importance and permanence(Guibert and Kakiang 2011).

At the level of the glacis, the infiltration of rainwater and the rooting of vegetation are limited to shallow depths. In some localities such as Abougoudam and northern Abkhuta, the soils (goz soils) are permeable, deep, poorly fertile and easy to work. They are not very erosive, but sensitive to the undermining of the banks, in particular in the sandy wadis where the torrential regime causes flow of the vertical banks(Abderamane 2012). Differential erosion is frequent to such an extent that the width of the bed of several wadis increases and a few hundred meters in some places. Soils are often bare after harvest and are exposed to wind erosion. The arable soils have decreased in thickness around some villages because of the lack of adequate protective measures. The sub-basement geology is almost entirely granite Precambrian basement, a metamorphic folded complex, granite crystalline type dominates the southwestern part of the prefecture (Abkhouta and along Bithea)(Louis 1984).

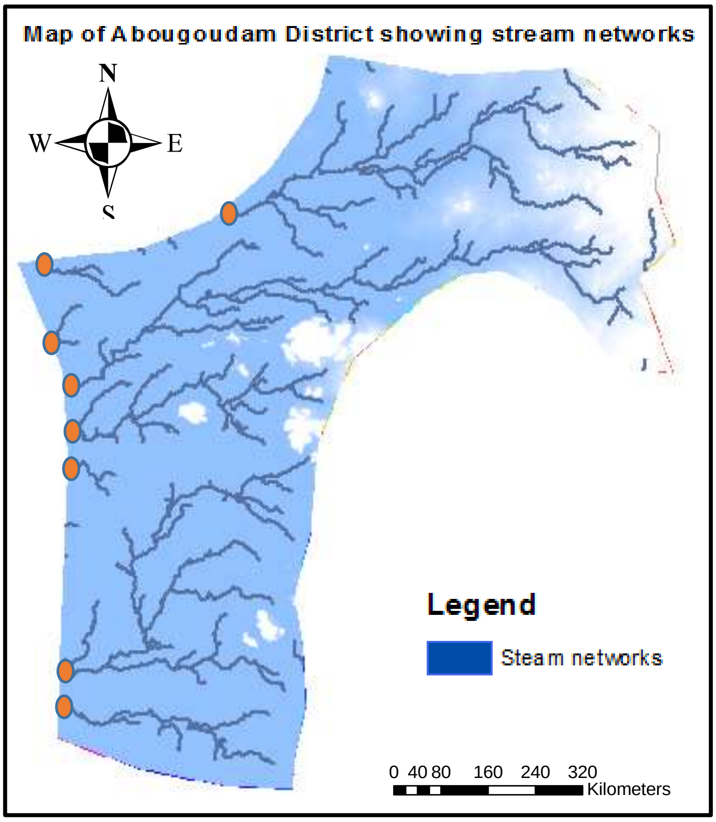


Figure 3. 4 Map of the study area showing the stream networks of the Wadis. (Source: ArcGIS)

3.2. Legal Framework of Chadian's Water Regime

Access to the freshwater of sufficient quantity and quality is essential for all aspects of life and for sustainable development. The fundamental right to water and sanitation is widely recognized by the Member States of the United Nations(SDG6 2018). Water resources are intrinsically associated with all dimensions of development such as food security, health promotion and poverty reduction, for contributing to the growth of agriculture, industry and energy production, as well as the preservation of ecosystem health. However, the right to water is most effective when nations incorporate it in their domestic water policies and legal framework. The state of the nation has the obligation to enforce the right to water into their judiciary law if it is being compromised(FAO 2018).

In Chad, The Ministry of Environment, Water and Fisheries (MEWAF) is responsible for implementing and monitoring the policy adopted by the Government in the field of environment, urban, village, pastoral water supply and sanitation. It is also in charge of the design and the implementation of the water points and hydraulic installations. Other stakeholders include Ministry of production, Irrigation and Agricultural Equipment and the

Ministry of Livestock and Animal production; Ministry of Urbanism and Habitat and the Ministry of Public Health.

The Water Law (No. 016 / PR / 99 of 18/08/1999) is the only recent official document defining a regulatory framework for the water sector in Chad. A document to enforce this law was only published in 2002. It is a general document that focused on aspects of public service in urban areas, while aspects relating to village water supply and pastoral (wells, boreholes, various equipment, etc.) are not mentioned in the official document(MEWAF 2018).

Unfortunately, the Sustainable Development Goals (SDGs6: Ensure access for all to water and sanitation and ensure sustainable management of water resources) is recognized under the Chadian law but the rights to water are not explicitly included in the Chadian Constitution. It stated that all everyone has the right to a healthy environment. The right to water and sanitation is embodied in the right to a healthy environment. It very unfortunate that the right to water is not recognized as a basic right but as a sovereign right of the government.

The Master plan of Water and Sanitation (SDEA), a living document of water policy in Chad which has been validated by the nation and approved in 2003. The SDEA is not robust as it should be because the water in general and pastoral hydraulics, in particular, suffers from a lack of a regulatory framework, which often leads to overlapping institutional stakeholders, particularly between the Ministry of Environment, Water, and Fisheries(MEWAF);Ministry of production, Irrigation and Agricultural Equipment and the Ministry of Livestock and Animal Production.

Chad does not have an agency that is in charge of basin management, however, there is the Directorate General of Water Resources of the MEWAF that plays this role. Similarly, there is the National Water Fund whose prerogatives are limit in seeking funding in the framework of drinking water supply.

Some of the Articles state:

- ❖ Article 1: The management of fluvial or underground water and that of the exploitation and hydraulic works are subject to the respect of the international agreements. All water resources, located within the limits of the national territory are a collective good. As such, they are an integral part of the public domain of the state which is unchangeable and imprescriptible.

- ❖ Article 2: The Water User Association (WUA) of drinking water has the sole responsibility for the operation and management of public drinking water supply.

- ❖ Article 45: The water price of potable water is defined by a regulatory body.

- ❖ Article 74: Artificial use or accumulation of rainwater falling on private property is permitted provided that such water remains on the land.

- ❖ Article 75: In the case of artificial accumulation on private funds, the holding is required to declare the capacity, the final destination and the water use regime, in accordance with Article 79 below.

- ❖ Article 79: Anyone harvesting groundwater or existing surface water for profit-making is required to declare his operation within six months to the Administration concerned(Vullien 2012).

According to laws governing water in chad, WH is free and has no restriction from the state. This favours the peaceful adoption of WH in Abougoudam district.

3.3 Data collection and Methods

3.3.1 Introduction

This research focused mainly to analyse successful water harvesting techniques in arid regions with the intention of attracting investments in Chad. This research proposed proven techniques that would be implemented in Chad to stabilize water demands for humans, livestock and agriculture. It also developed a knowledge product to ensure the sustainability of the structures. In order to achieve the objectives of this research, physical, economic and socio-cultural data had to be obtained and analysed. As such, the field survey and desk study was conducted.

3.3.2 Rainfall data

It is not possible to pursue WH technologies without considering one of its major components which is precipitation. Rainfall must be available for WH uptakes. It is of considerable importance to obtain and assess rainfall data for a minimum of 10 years to have a solid impression of the rainfall pattern in a particular study area before choosing WH as an option to supplement water for agriculture, humans and livestock. Long term data help to identify and understand the sharp increase of rainfall over a wide range of data. Rainfall data (Weather Station of Abéché) of Abougoudam district and the current monthly temperature were obtained from the Meteorological Department of the ministry of Meteorology and Aviation. The sample size of the data was 20 years (1999-2018). Below are annual monthly rainfall totals and monthly temperature of 2018 for Abougoudam district, Ouaddaï Region. The data were analyzed using Excel.

Table 1. Annual monthly rainfall totals for Abougoudam District

Years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Totals
1999	0	0	0	0	0	4.5	216.2	224.3	94.7	0	0	0	539.7
2000	0	0	0	0	0	5.6	141.9	79.2	52	9.4	0	0	288.1
2001	0	0	0	0	0	44.1	89.6	138	40.8	0	0	0	312.5
2002	0	0	0	0	0	0	150.5	167.8	51.3	0	0	0	369.6
2003	0	0	0	0	3.8	42.6	162.1	120.3	39.8	2.5	0	0	371.1
2004	0	0	0	0	20.8	45.4	147.3	136	18.6	0	0	0	368.1
2005	0	0	0	0	10.2	22.1	100.6	147.8	65.9	0	0	0	346.6
2006	0	0	0	0	0.2	44.4	100.8	67	61.1	1.8	0	0	275.3
2007	0	0	0	0	3.7	10	181.9	82.7	49.4	0	0	0	327.7
2008	0	0	0	0	0	52.8	21.8	37.2	51.4	0	0	0	163.2
2009	0	0	0	0	0	0	45.3	61.9	16.7	0	0	0	123.9
2010	0	0	0	0	0	20.7	123.5	39	32.9	8	0	0	224.1
2011	0	0	0	0	14.8	16.8	11.9	71.1	86.6	0	0	0	201.2
2012	0	0	0	0	12.4	36.9	127.7	146	72.8	0	0	0	395.8
2013	0	0	0	0	0.6	4	28.5	186.6	19.4	0	0	0	239.1
2014	0	0	0	0	3.9	0	127.2	124.7	41.4	0	0	0	297.2
2015	0	0	0	0	0	0	175.8	136.2	63.2	0	0	0	375.2
2016	0	0	0	0	4	16.4	82.7	100.3	48.1	0	0	0	251.5
2017	0	0	0	0	7	52.5	103.4	173	54.2	0	0	0	390.1
2018	0	0	0	21.5	93.5	129.3	197.4	317.7	239.4	0	0	0	998.8

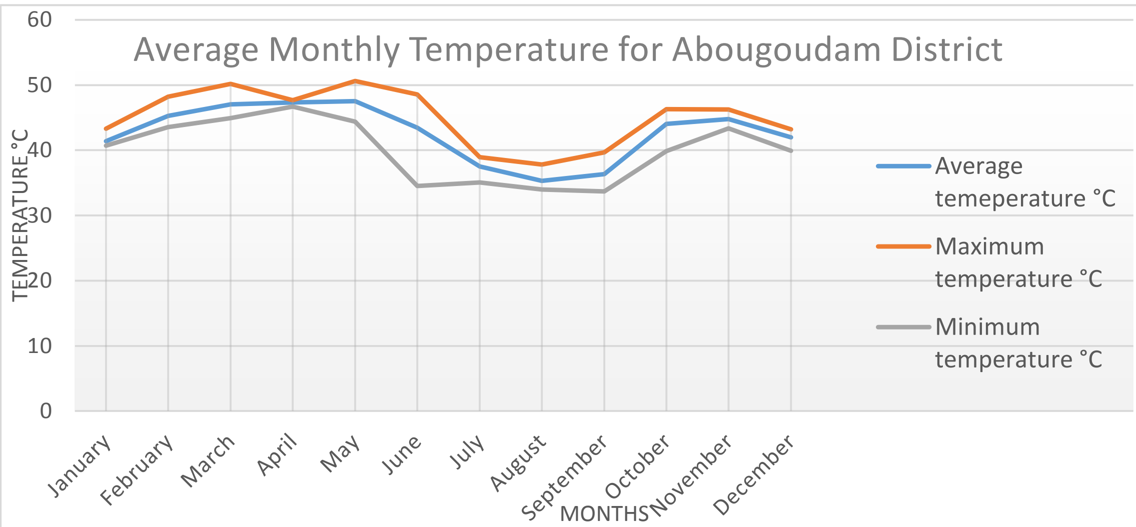


Figure 3. 5 Average Monthly temperatures for Abougoudam. (Source: DWR, 2018)

3.3.3 Soil data

Soil data is needed before sitting water harvesting structures in a specific location. Soil characteristics are to be considered for the stability of the structure. The soil data for the study area was obtained from the Ministry of Production, Irrigation and Agricultural Equipment. The Digital Soil Map of the World (DSMW) was downloaded from the Fao Soil Map (http://www.fao.org/geonetwork/srv/en/metadata.show?id=14116) and the administrative areas of Chad were also downloaded from diva-gis.org/data down. The clip analysis tool in ArcGIS 10.5 was used to clip the soil map of the study area and then the feature to raster tool was used to divide the soil hydrological groups (HSHs) of the study area. The soil map of the study area with its characteristics was shown and discussed in chapter 4.

3.3.3 Water consumption data

Water consumption data is required to show the water consumption pattern in the study area. This will give knowledge on water demand for humans, livestock and agriculture. The consumption patterns also vary from continent to continent, with about 5 liters per day or less in most African countries. The minimum water consumption of 20 liters per day per person is required in rural communities in third world countries. The amount of rainfall in Abougoudam is sufficient to surpass such values and rescue inhabitants facing water scarcity.

The equation used in order to obtain the water consumption per capita in the study area takes a series of factors into consideration. Normally, the simple estimation will be: the water use (in liters) multiplied by the number of persons in the house and then multiplied by the number of days in a year (WHO and UN standard figure). Camels consumption per day= 144 liters/week (camels drink weekly not daily; hence camels consumption is about144liter/week. Cows and donkeys consumption per day= 72 liters/day; Sheep's and goats consumption per day= 18liter/day. The data on water consumption pattern was obtained from the Nation non-Government Organization (NGO) HELP. It was then analysed and presented in chapter 4.

3.3.4 Sampling approach

There are two important sampling approaches when scientific research is considered. Probability and non-probability sampling methods are the two major approaches which are further divided into many subcategories. Probability sampling implies the random selection while non-probability sampling does not. Non-probability is divided into accidental sampling and purposive sampling.

The purposive sampling method is considered for this study. This method is suitable in a situation where there is a target group for sampling. It is also characterized by focusing on a particular target group of the population. In this method, the information needed is obtained from the target population but care should be taken so that a set of groups in the target population that are more readily accessible should not be given much weight or consideration. There are two (2) types of this method which are: snowball sampling and expert sampling methods.

3.3.5 Expert sampling

This method is applicable in a situation where the information needed is obtained from individuals that have extensive knowledge on the research topic. Such individuals provide resourceful information that is relevant and might have been very difficult for the researcher to obtain within the stipulated time. In this study, a set of meeting was carried out with water experts in Chad to have in-depth knowledge of the existing WHSs and potential areas for WH.

A consultative approach was adopted with key stakeholders, which involved discussions with the extension officers. The first discussion was carried out with the experts of the Ministry of Environment, Water and Fisheries (Department of hydraulic pastorals) and the Ministry of Water and Sanitation (Department of domestic water supply). Through the discussion, valuable information on regions with existing WHSs, the type of systems, O&M of the systems, cost of WHSs, areas with potential for WH and the financial capacity of the government to adopt WH was obtained.

The second discussion was carried out with the experts of the Ministry of Production, Irrigation and Agricultural Equipment (department of rural agriculture). The information on areas with existing WHSs to improve irrigation during dry season and areas in need of irrigation practices was obtained. A focus group discussion was conducted with the management community and farmers of one of the WHSs in AKA village, northeast of Chad to provide information on O&M and the benefit of the WHSs. An interview was also conducted with a farmer and villagers that make use of the water stored in the micro rock dam located in tologone, northeast of Chad. The information was presented and discussed in chapter 4.

3.3.6 Questionnaire

In this study, the questionnaire was adapted to collect relevant information with regards to the adoption of WH in Chad. It is a standard form of questionnaires that provide quantitative information on WH uptake. The data obtained by this questionnaire was then analysed with the help of the Statistical Package for the Social Sciences (SPSS). The questionnaire is composed of semi-structured closed-ended and open-ended questions which were administered by a researcher and an assistant. The closed-ended questions allowed the respondents to make an answer choice from the list of answers. Open-ended questions allowed the respondents to express their opinion independent of any influence from the part of the researcher.

One hundred and fifty(150) questionnaires in total were administered in five(5) villages in Abougoudam municipality with their geographical coordinates, which include Djawami with coordinates of 13°62,559’ N and 20°67,920’ Matar with coordinates of 13°37,556’N and 20°40,748’E,Attim with coordinates of 13°63,211’ N and 20°68,423’ Abougoudam town with coordinates of 13°84,361’ N and 20°83,675’ E and chikalfagara West with coordinates of 13°65,626’N and 20°74,351’E. The questionnaires were administered and collected at the residences of the respondents. Most of the respondents were not literate enough to understand the questions. In such cases, the questions were communicated to the respondents in local Arabic.

The questionnaires were divided into three (3) sections. Section A gave general information on the respondents. It was set to assess their demographics and level of education. Section B targeted Households, Farmers and livestock header. This part of the questionnaire was to collect information on existing water sources, need for an alternative source of water, willingness to pay for water fee, the income of the respondents and their perception to the different sources of water available. Section C of the questionnaire was to assess the respondents’ knowledge of WH, its practices during the dry season and possible adoption.

3.3.7 Selection considerations of Best Practices of Water Harvesting Structures

To effectively select a Water Harvesting technique that is suitable for a local community, the characteristics of the different techniques need to be assessed. They include those that are typically physical (hydrologic, terrain and technical), culturally acceptable and socioeconomic (institutional and economic) in nature (Tumbo et al. 2011).

WH should be technically physical depending on the local condition of the field. However, it is important to take into account the socio-cultural acceptable of the technique by the community and the need for sustainable management after implementation. Sustainability of WH techniques is very important in the success of the technique and it is also necessary if the available water is to be used by many people in one village or between several villages. Many examples of water harvesting projects have failed to meet the expected targets as a result of improper design, lack of financial capacity to O&M the techniques, or simply the techniques were not accepted by the beneficiaries because of cultural, environmental or economic reasons.

The technical feasibility, availability of labour, know-how, the cost and most especially, the quantity and quality of water need to be considered. Water quality is very important when the structure is to provide water for domestic use. When the water is considered for irrigation purposes, the quality is less important (Lasage and Verburg 2015). Every year, there is freshwater water available to provide water for the intended use for the population on earth. However, Arid and Semi-Arid Regions are faced with climate change, rainfall variability, high evaporation, and increase in runoff and population growth which affect the current water supply to meet the demand of its current population (Qadir et al. 2007).

WH is an alternative source to bridge the gap between the supply and the demand but its feasibility should be investigated. WH is becoming an important strategy to deal with water scarcity or water stress, it is important to consider the factors involved in selecting the appropriate WH technique to maximize hydrological returns. It is tempting to assume that a technique which works in one area will also work in another, apparently similar zone. However, there may be technical difference such as the availability of stone or intensity of rainfall, and obvious socio-economic differences (Critchley and Siegert 1991).

The selection criteria of best practices for this research to be adopted in Chad and other Arid Regions of Africa are the design, technical specification cost-benefit, sustainable O&M, Adaptability, Challenges and the socio-cultural acceptability of the structures. The data was obtained from the field survey in Chad and online papers.

3.3.8 Development of a policy brief

Investment in the water sector for food security, health promotion and poverty reduction by both the public and private sectors require an enabling environment with supporting, socially integrated water institutions most especially in Sub-Saharian Africa. From the integrated management outlook, long-lasting policies will make the uptake of technology easier especially where they are several uses of systems combined together. There is a need for conducive policies to encourage private sectors to invest in innovative water technologies in a cost-effective manner (Molden, 2007). In the past, the major driven force behind investment in water for agriculture was the fear of famine the poor farmer in the rural areas (de Fracture et al., 2010). The current investment in the water sector is driven by the need to change the type of food, and the sources of energy which increase the need for water to produce meat, high-quality food and biofuel crops as a result of population growth (de Fracture and Wichelns, 2010).

Increase in water supply and agricultural production still a key option to reduce poverty and hunger. The future of water supply and agricultural production in Africa largely depends on government policy and decision makings (Jayne et al., 2010). Small scale water technologies for humans, livestock and agricultural growth have often been unsuitable or contrary to the investment.

When donors make money available to invest in the water sector, government prefer to large scale water technologies for water management forgetting the fact small scale technologies, like water harvesting that provide a more cost-effective way of increase the benefit of local farmers thereby increasing the socio-economic activities of the local communities in order to achieve the Sustainable Development Goals.

The institutions in charge of water management may need to change their policies in order to attract more investment in the water sector. Usually, the poorest stakeholders almost have little voice and political power to understand clearly the access to water, cost involved and the water allocation. Capacity-building should be integrated into local policies.

Review of FAO, IsDB report on water harvesting policies, a book by William Critchley on Water Harvesting in Sub-Saharian Africa and the legal framework on water management in Chad were used to generate information for the checklist policy brief on sustainable management of WHSs.

Table 3. 1 Summary of data collection and techniques

Sources	Techniques	Nature	Interpretation
Primary	Non-probability (purposive, expert sampling) Semi-structured open-ended and closed-ended questionnaires Interviews	1. Questionnaire 2. Interview 3. Telephone 4. Focus group discussion	EXCEL, Statistical Package for Social Science (SPSS)
Secondary	Internet(google search, Elsevier, Researchgate Institutions www.rainwater harvesting.org	1. Literature review 2. Reports(FAO, World Bank, UNICEF, IsDB) 3. Manual for water harvesting systems 4. Meteorological data 5. Soil data 6. Scientific paper, books, online thesis and Dissertation	1. Statistical 2.Simulation(Google earth, ArcGIS 10.5)

3.3.9 Research design

The process of collecting data for the study will be carried out in two stages:

The first stage involved a desk study of the online review of best practices of WHSs in Arid Regions and the second stage was a field survey in Chad that provided detailed information on the feasibility adoption of WHSs.

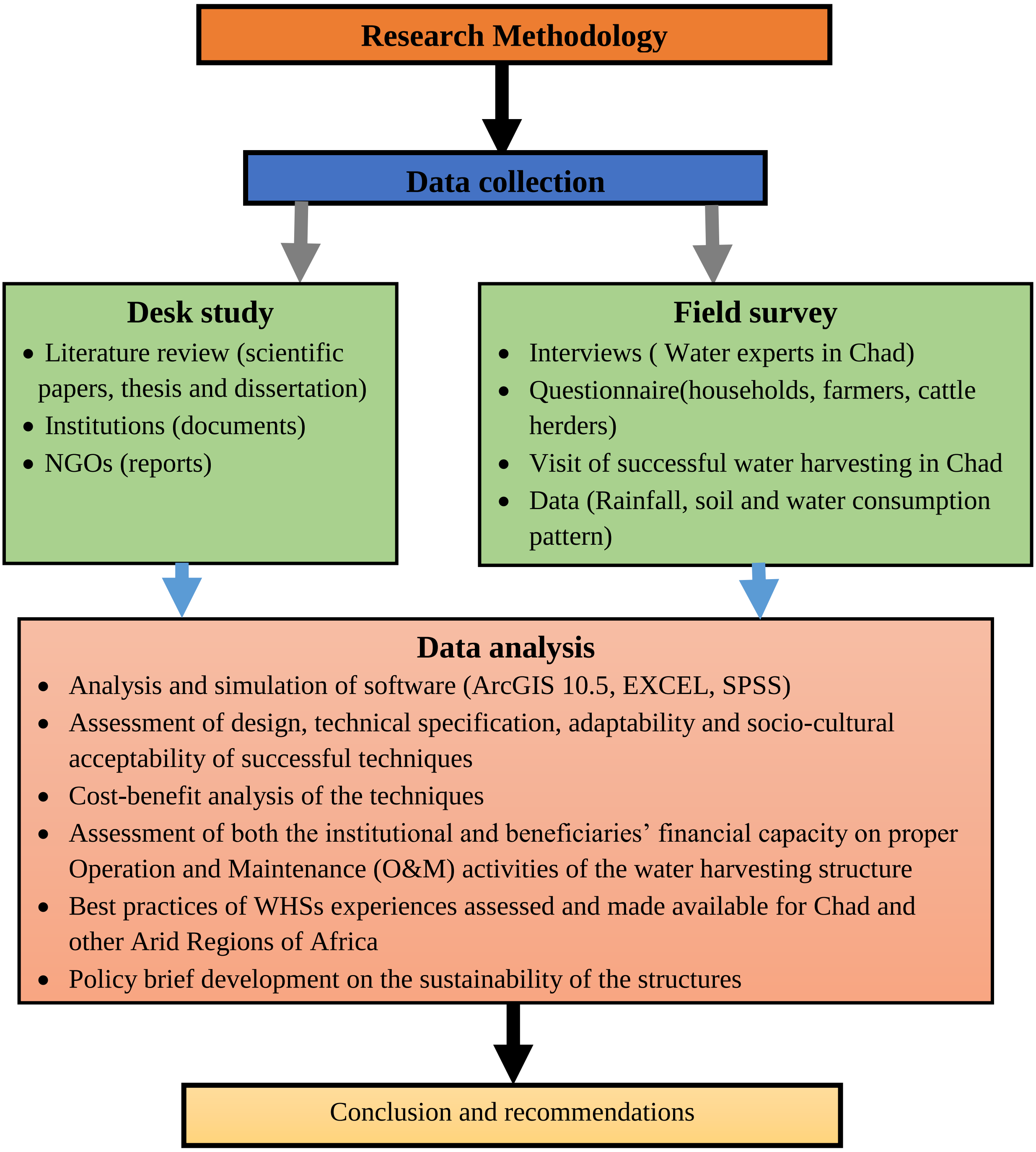


Figure 3. 6 Flow chart of the research methodology

3.4 Data Analysis

This study made use of both primary and secondary data. The researcher analysed meticulously the primary data that were obtained from the field survey. The soil map of Abougoudam district was constructed using GIS(ArcGIS 10.5) which is a software designed to collect, store, process, analyze, manage and present all types of spatial and geographic.GIS is used by government agencies, scientists, people, individuals and research institutions. The rainfall and water consumption data were assessed using Microsoft excel while the questionnaire was analyzed using SPSS. The case study of WHSs best practices was assessed. However, the secondary data obtained from the literature review were also used for the study.

The data were represented in the form of bar chart, table, graph, figures and text.
The results of data were presented in an orderly manner followed by the discussion to simply coherency and understanding. The results and discussion are the focus of chapter 4 below.

CHAPTER FOUR

4.0 RESULT AND DISCUSSION

4.1 Assessment of Annual rainfall data series for Abougoudam District

4.1.1 Variability of Annual Rainfall

Arid and Semi-Arid Regions are faced with difficulties in the limited amount of rainfall which is associated with the degree of its variability. The Annual rainfall in Abougoudam District is between 200 - 400 mm per year. As in all Sahelian countries, the rains are often torrential over a very short period resulting in strong soil erosion of the banks of Wadis. Figure (4.1) shows the average monthly rainfall from 1999 to 2018. There are seven months without rainfall and only four (4) months with rainfall. The rainfall starts increasing from the month of May and reaches its maximum in the month of August and suddenly decreases in the month of September. This shows the irregularities in the rainfall intensities with short duration. According to FAO (2003b), areas receiving more than 100 mm/year to 1000 mm/year should be considered for WH technologies. The fact is that areas with less than 100 mm/year have no productive water-based activity while there is no motivation to implement WH technologies in areas with more than 1000 mm/year. However, the seasonal rainfall of Abougoudam District can be harvested to increase water supply during months of the dry period.

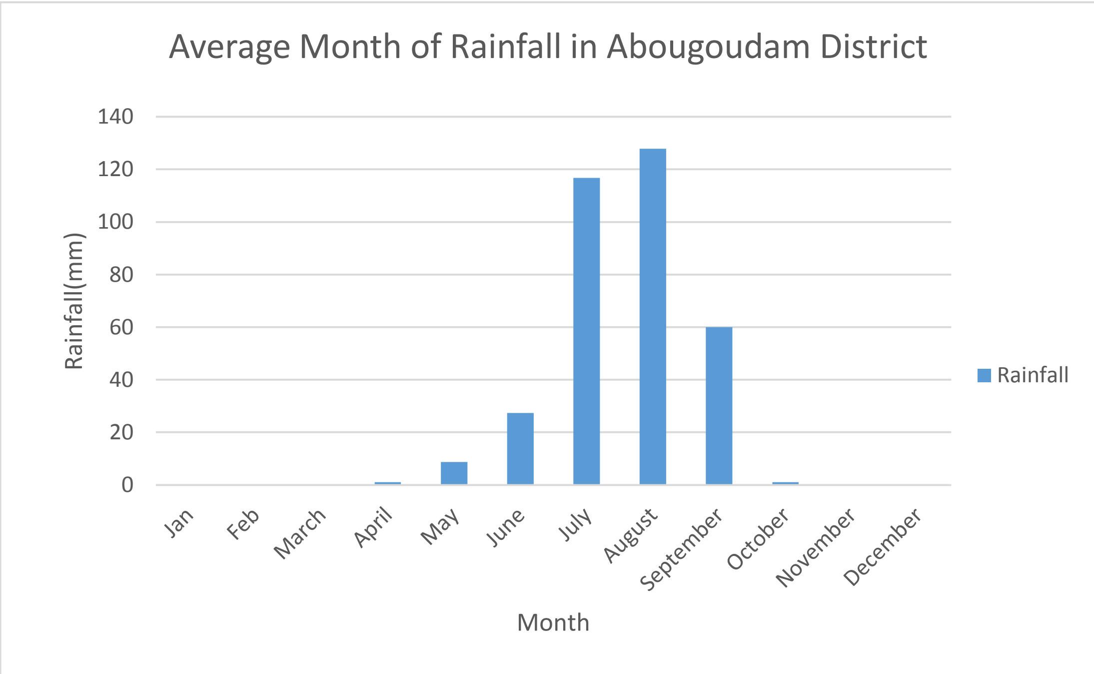


Figure 4. 1 Average Month of Rainfall in Abougoudam District. (Source: Author)

4.1.2 Design of Rainfall

Rainfall design is the total amount of rain to meet the demand of water supply over the year, not only in a wet and normal year but also in the dry period. For this study, a simple probability analysis method was employed for the design of rainfall. Figure (4.2) shows a continuous annual rainfall data series over 20 years with an estimated average annual rainfall of 342.94 mm. The annual rainfall totals were ranked from the highest to the lowest in the table 4.1.2 with m= 1 for the highest value and m=20 for the lowest value. The empirical frequency of the annual rainfall was used to calculate the probability of occurrence P (%) for each of the ranked observations with Eq. 4.1

$$P = \frac{m}{n+1} \qquad \text{Equation 4. 1}$$

where P is the probability in % of the annual yearly rainfall of the observation of the ranked m, m= the rank observation and N is the total number of annual yearly rainfall data used. For this study, the value of N is 20 years. The equation 4.1 is used for N=10 to 100. In the table 4.1.2, we can find for example a probability of occurrence or exceedance of 71.4 %(column **VI**) with a rainfall of 251.5 mm (column **IV**) in the year 2016(column **III**). The frequency of 71.4% signifies that in the 20 years, there are 15 years of annual rainfall no less than 251.5 mm. We can also say that we have 71.4% of chances to have an annual rainfall equal to or greater than 251.5 mm. If the design rainfall for Abougoudam district is taken as 71.4% then the size of the WHSs can ensure a water supply reliability of 71.4%. For example, if the reliability is 75% but table 4.1 only contains the frequency of 71.4 and 76.2 correspondings to 2016 and 2013 and rainfall of 251.5 and 239.1. To find the rainfall at 75%, an interpolation calculation is necessary as shown below:

$$R_{75} = R_{76.2} + (R_{71.4} - R_{76.2}) * (76.2 - 75) \div (76.2 - 71.4) = 242.2\,mm$$

Where R_{75}, $R_{76.2}$ and $R_{71.4}$ is the rainfall at a frequency of 75, 76.2 and 71.4% respectively.

The rainfall design provides an aid for the selection of an appropriate WHSs in Abougoudam District. A rainfall with the reliability of more than 50% can be considered to obtain optimum water to cater to the demand for the off-season, livestock and Humans.

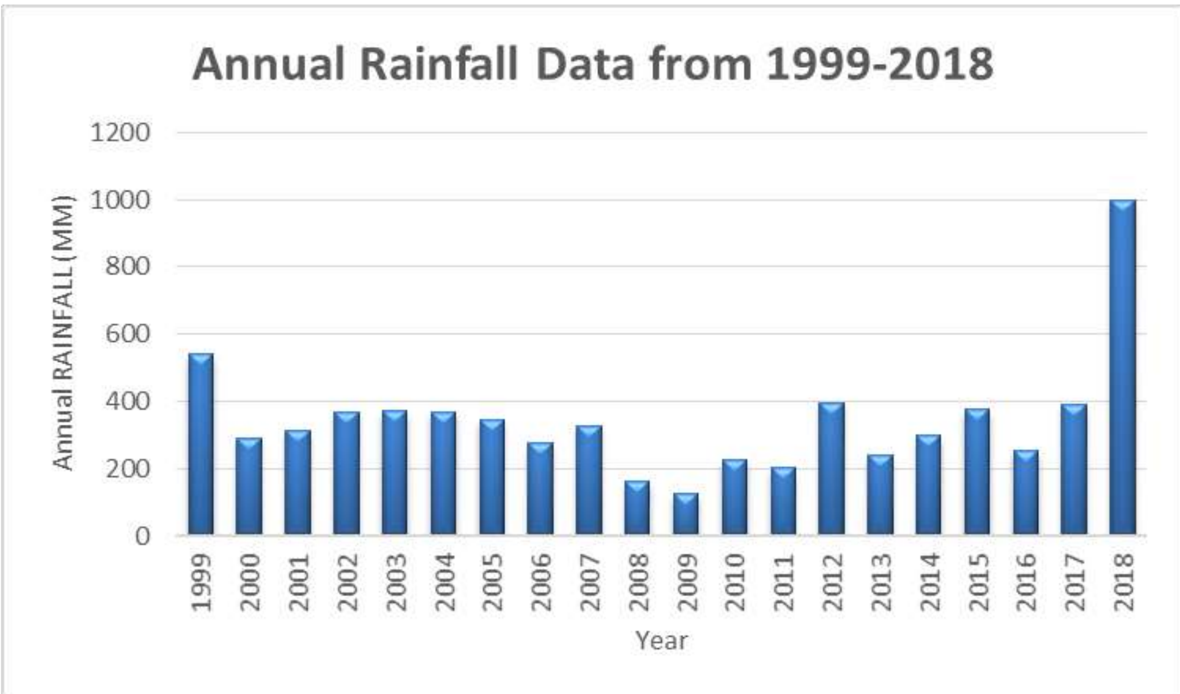


Figure 4. 2 Annual Rainfall Data from 1999 to 2018. (Source: Author 2019)

Table 4. 1 Ranked Annual Rainfall Data Abougoudam District

Year	Rainfall(mm)	Sort of Rainfall (mm)		Rank(m)	Probability(P%)
1999	539.7	2018	998.8	1	4.8
2000	288.1	1999	539.7	2	9.5
2001	312.5	2012	395.8	3	14.3
2002	369.6	2017	390.1	4	19
2003	371.1	2015	375.2	5	23.8
2004	368.1	2003	371.1	6	28.6
2005	346.6	2002	369.6	7	33.3
2006	275.3	2004	368.1	8	38.1
2007	327.7	2005	346.6	9	42.9
2008	163.2	2007	327.7	10	47.6
2009	123.9	2001	312.5	11	52.4
2010	224.1	2014	297.2	12	57.1
2011	201.2	2000	288.1	13	61.9
2012	395.8	2006	275.3	14	66.7
2013	239.1	2016	251.5	15	71.4
2014	297.2	2013	239.1	16	76.2
2015	375.2	2010	224.1	17	81
2016	251.5	2011	201.2	18	85.7
2017	390.1	2008	163.2	19	90.5
2018	998.8	2009	123.9	20	95.2
I	**II**	**III**	**IV**	**V**	**VI**

(Source: Author 2019)

4.2 Soil Mapping of Abougoudam District

WH is highly dependable on its soil characteristics such as the structure, infiltration capacity, texture and depth. Soil structure influences the amount of runoff that is generated; the infiltration rate determines the movement of water into the soil; the texture and depth affect the amount of water stored in the soil (Prinz and Singh 2000). In the study area, soils range from sandy clay loam and pure sandy, clay soils with a depth ranging from 0.05 m to more than 0.8 m (Ministry of Production, Irrigation and Agricultural Equipment). Soils with high holding capacity are mostly suitable for WH. Sandy soils are not suitable therefore loamy soils are the most suitable for WH. Vertisols with a high proportion of clay generally between 40 to 60 percent should be avoided because of their cracks on drying which affect both the storage of water and the stability of the structures (FAO 2003b). The soil types in the study area are grouped into three(3) as follows: Group A: Sandy clay rock, silt clay, stone and rocks; Group B: vertisols(black and brown clay with the proportion varying from 40 to 60 percent, silt clay and sandy soils; Group C: Sand, Sandy-clay, gravel, loamy sand and loamy-clay as shown in figure 4.3 below.

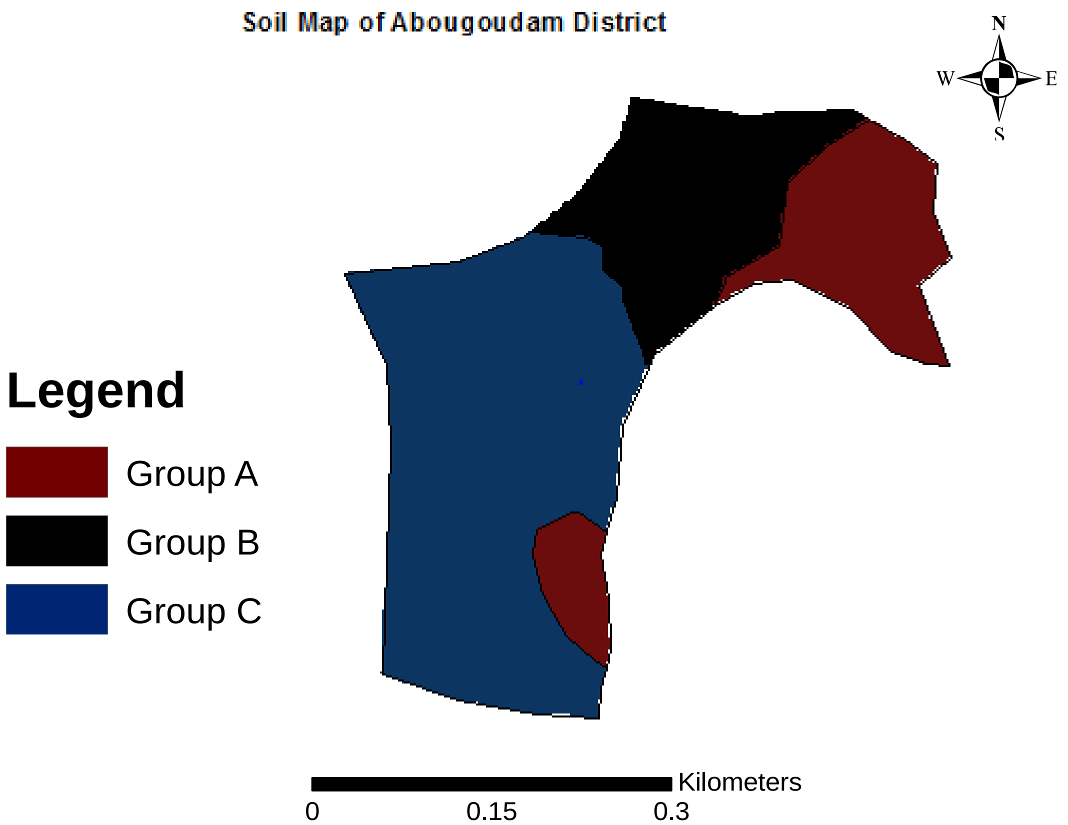


Figure 4. 3 Hydrological Soil Groups (HSGs). (Source: Author 2019)

4.3 Analysis of Water Consumption Pattern in Abougoudam District

The population of Abougoudam district is 62161 and depend on hand pump boreholes and open wells from wadis as sources of water supply during the dry season. There are 22 hand pump boreholes and 25 open wells in total with the yield of 8 m^3/day which provide drinking water supply for the population. Six (6) of the boreholes are not functioning currently. Therefore, we have 16 hand pump boreholes and 25 open wells with a yield of 8 m^3/day for 62 161 people. The basic drinking water supply is 20 l/day according to WHO and it is set at 30 l/day by the Chadian Water Company. From table 4.3 below, we can see that the basic water supply is 5.16 l/day which is far below the standard given by the Chadian water Company. For 62161 people, we will need 1,864,830(62161×30) liters to meet the water demand in the district. The current domestic water supply for humans is 328000 liters and the deficit is 1,536,830 ($1{,}864{,}830 - 328000$) liters.

The livestock population is estimated at about 293126 with a water demand of 2,321,063,327 liters (table 4.3) but the existing water supply cannot meet the water demand. That is why the livestock header used to migrate to the south in search of fodder and water during the dry season which is usually a source of conflict between farmer and livestock header.

With this current situation, an alternative source can be exploited to reduce the water demand and WH is a perfect case for Abougoudam District.

Table 4. 2 Domestic water supply consumption

No	**Description**		**Remark**
1	Number of functional hand pump	16	
2	Number of non-functional hand pump	6	
3	Quantity of water pumped by borehole per day(m^3)	128	$8\text{m}^3 \times 16 = 128\text{m}^3 = 128000$ liters
4	Number of functional open wells	25	
5	Quantity of water pumped by open well per day(m^3)	200	$8\text{m}^3 \times 25 = 200\text{m}^3 = 20{,}000$ liters
6	The total quantity of water pumped by both hand pump borehole and open well per day(m^3)	328	$(200 \times 128 = 328\text{m}^3 = 328000$ liters
7	The average quantity of water available per day	**5.17**	$\frac{328000}{62161} = 5.17$ l/p/d
8	Number of people per water point	1517	1 water point(borehole/open well) for 1517 people

(Source: Author 2019)

Table 4. 3 Livestock water demand

No	Livestock	population	Quantity of water per day in a liter	Total water required for 7 months
1	Camels	6599	6599×144 46,193 l/week	1,431,983 liters
2	Cows	75006	$75006 \times 72 = 5{,}400{,}432$ l/day	1,150,292,016 liters
3	Sheep	102420	$102420 \times 18 = 1{,}843{,}560$ l/day	392,678,280 liters
4	goats	77944	$77944 \times 18 = 1{,}402{,}992$ l /day	298,837,296 liters
5	Donkey	31157	$31157 \times 72 = 2{,}243{,}304$ l/day	477,823,752
Total		**293126**		**2,321,063,327 liters**

(Source: Author 2019)

4.4 Key informant interviews

Pastoral wells, water spreading weirs, micro rock dams, sand dams and earth dams were the existing WHSs in the regions of Ennedi Ouest, Ennedi Est, Wadi Fira and part of Ouaddaï. According to the director of pastoral hydraulic of the MEWAF, most of the systems failed to perform well because of lack of financial capacity from both the government and the beneficiaries. However, the beneficiaries were not having a sense of ownership and they believed that it was the responsibility of the government to maintain the structures after the implementation. Another factor to consider was the fact that the beneficiaries still believed that water was free and they did not have to pay for the water service. Many WHSs in Chad did not have management committees to ensure the O&M of the systems. That was why the systems were abandoned in the hands of the beneficiaries. Some of the pastorals wells were now having Water User Associations to collect water from the livestock header to ensure the O&M of the systems but they failed to account for the money collected from the water service. Currently, the government wants to adopt a new policy by given the contract of water management to a private WUS. The director also said that they had always engaged the beneficiaries in the implementation of the structures and training were also given to them in terms of operation and maintenance. Water harvesting weirs happened to be one of the structures that are currently performing well in the country. They were financed by the Swiss Agency for Development and Cooperation and implemented by German development agency (GIZ) under the project called Management of Runoff Water in Sahelian Chad. Before water spreading could be implemented in the targeted areas, the beneficiaries have to contribute 10% of the investment cost. Apart from that, they have a management committee that ensures the O&M of the systems and the beneficiaries are involved in the project right from the planning stage. Although the regions of

Ennedi Ouest, Ennedi Est and Wadi Fira had existing WHSs, still investment was needed to supplement the water need for the local community that still had a high demand for water supply in the regions. Moreover, the region of Guera, Ouaddaï, Salamat and Mayo-kebbi Est were given great attention as regions that need the implementation of WHSs to increase water supply for livestock, humans and off-season irrigation but the government did not have the financial capacity to engage in the implementation of the WHSs and were in need of financial assistance from the financial institutions. According to the water experts, the cost of a pastoral well was 30,000,000 million FCFA ($53,000 depending on the regions. The cost of sand dams and earth dams varied from 60,000,000 to 90,000,000 million FCFA($103000 to 1540000) and the cost of water spreading weirs ranged between 60,000,000 to 100,000,000 FCFA($103000 to 1710000 depending on the regions.

According to the management committee of water spreading weir located in AKA village (N14°32’36, 4 and 22°01’41, 0 E), Wadi Fira where the field visit was undertaken, and they were organized in 9 groups. Each group pays 1000 FCFA ($1.8) every day as a contribution to the maintenance of the system. Apart from that, any beneficiary that was practicing off-season irrigation around the wadi where the structure was located, had to pay 2500 FCFA($5) with farmland of 2h in size after harvest and 1200 FCFA ($3) if the farmland was just 1h. Onions, garlic, groundnuts were the crops grown during the dry season. The money was used for the operation and maintenance of the system. The management committee also said that they could handle minor repair but they could not handle the major repair of the structure.

In terms of benefits from the water spreading weirs, there was water available for off-season irrigation throughout the dry season. Most of the degraded lands were regenerated as the result of water spreading weirs. The beneficiaries were also able to send their children to school from the income generated from the post-rainy season irrigation and they also engaged in bricklaying for sale. There was water available for livestock which limited their migration to the southern part of the country in search of fodder and water.

The micro rock dam located in tologone(N15°01’42,42 and 21°57’47,1 E) at 30 kilometers from Iriba town in the region of Wadi firm was also another successful WHSs in Chad in terms of water availability throughout the drying season. There was a huge quantity of water in the reservoir of the dam but a little amount of it was used for off-season irrigation. Thousands of livestock got their drinking water from the dam. The dam had no management committee therefore, water was used free of charge. One of the challenges with the dam was that when livestock drank from the dam, they were also defecating around the reservoir leaving their wastes. Their wastes were washed into the reservoir during rainy season given room for water contamination. The local people were fetching water directly from the reservoir for drinking purposes and this could affect their health.

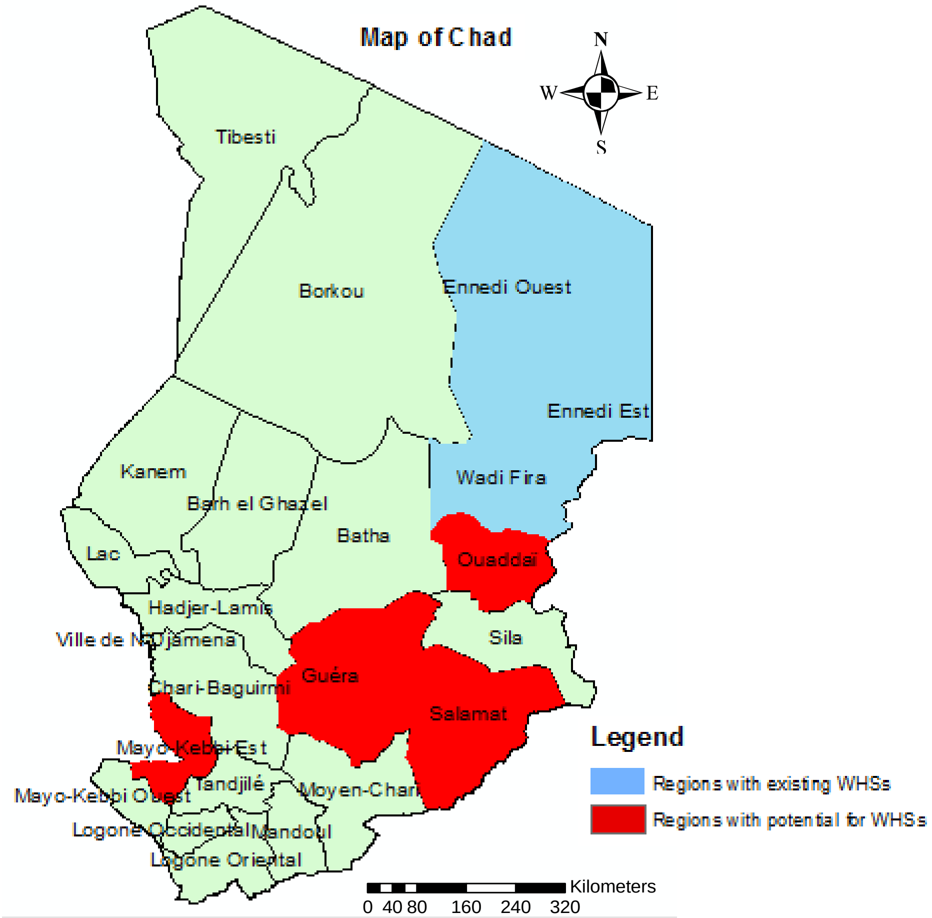


Figure 4. 4 Regions with existing WHSs shaded in blue and regions with potential for WHSs shaded in red. (Source: Author 2019)

4.5 Assessment of the questionnaire

The sampled size of the households revealed 85% of males while 13% were females. The average size of the family households was 10 with a maximum of 40 people in a house and 3 as the minimum. The average age of the respondents was 46 years old with a maximum of 80 years and a minimum of 21 years old. The farmland size of the sample households ranges from 0 to 60 ha with an average size of 4 ha. All the respondents (100) were not practicing post-rainy season irrigation because of water scarcity. The study also showed that 96% of the respondents were illiterate and only 2.7% of them attended primary school and 1.3% attended secondary school. Amount the respondents, 64 % of them were relying on traditional well as a source of drinking water in which water was free of charge while 36% were also using water from the hand pump boreholes and were paying for the water as a contribution for O&M. 100% were willing to adopt WH and contribute to O&M of the structures but all of them were not ready to finance 50% of the investment cost of WHSs. Agriculture and animal rearing were their main sources of income with only 2% of them which were into small scale businesses.

Table 4. 4 Results of sample household questionnaire

General information					
	N	Minimum	Maximum	Mean	
Age	150	21	80	46.2267	
Family size	150	3	40	9.74	
Farmland size	150	0	64	3.6633	
Valid N (listwise)	150				
Gender					
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Male	127	84.7	84.7	84.7
	Female	23	15.3	15.3	100
	Total	150	100	100	
Level of Education					
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Primary School	4	2.7	2.7	2.7
	Secondary School	2	1.3	1.3	4
	Other	144	96	96	100
	Total	150	100	100	
Water Scarcity					
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	YES	150	100	100	100
Off-season irrigation practices					
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	NO	150	100	100	100
Existing Water Sources					
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Traditionnal Well	96	64	64	64
	Hand pump borehole	54	36	36	100
	Total	150	100	100	
Need for alternative water source					
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	YES	150	100	100	100
Source of income					
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Agriculture and animal rearing	147	98	98	98
	Small business	3	2	2	100
	Total	150	100	100	

Water charge					
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Borehole	55	36.7	36.7	36.7
	Open well	95	63.3	63.3	100
	Total	150	100	100	
Willingness to contribute to O&M of WHSs					
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	YES	150	100	100	100
Willingness to pay fifty percent of the investment					
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	NO	150	100	100	100
Willingness to adopt WH					
		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	YES	150	100	100	100

(Source: Author 2019)

4.6 Best practices of WHSs to be proposed in Chad and other arid regions of Africa

4.6.1 Water spreading weir in dry valleys

- **Technical specification**

Water spreading weirs (WSWs) are built across the dry valley and span the entire width of the valley which is usually between 100 and 1000 wide. They are constructed of stone masonry or concrete up to 50 cm above the surface of the surrounding sand. They are usually built in a series to stabilize the entire valley. Construction work is done by trained members of local communities. The weirs permit spate flows to overflow and flood the inland valleys. Initially, the water flows over the low wing walls of the structure to the outer limits of the valley. Subsequently, it covers large areas in front of and behind the weir. The alluvial deposit can be used for agriculture and the infiltrated water recharges the groundwater which is accessed through wells for human and livestock consumption. WSWs are mostly used in Chad, Niger, Burkina Faso, Yemen and Brazil.

- **Design**

The design specification below is derived from a project in Chad and Burkina Faso. Although each project varies in details, the majority conform to the basic pattern below. The first parameter to be determined is the catchment area(S) and the perimeter where the water spreading weir is to be implemented. Below are the parameters to be calculated when designing a water-spreading weir. A case of the Amdabouka Valley (N 19°30’08, 44’’ and 13°0518, 23’’ in Chad was considered.

The catchment area of the valley was delineated using the geographical information system (GIS). From the GIS software, the area and the perimeter of the catchment were found to be 2280 Km^2 and 226.50 Km respectively.

The length of the main drainage channel was estimated using Google Earth interactive satellite images. It was found to be 4686 m.

The average slope of the drainage channel was calculated from the longitudinal profile of the main drainage channel. It was given as the difference between the extreme points of the profile divided by the length of the main drainage channel.

$$\boldsymbol{S_l = \frac{\Delta S_{max}}{L}} \qquad 4.\ 2$$

Where

S_l is the average slope of the channel (m / km); ΔS_{max} is the maximum slope of the channel (m) (difference in altitude between the furthest point and the outlet) and L is the length of the main drainage channel (km). The average slope was found to be 0.17 m/km.

The values of decennial annual rainfall (Pan) and decennial daily rainfall (P_{10}) could be directly obtained if meteorological data are available. Pan and P_{10} have a return period of 10 years. Their values could also be obtained from the isohyet maps by linear interpolation, knowing the longitude and latitude of the watershed (FAO 1996). The values of Pan and P_{10} were found to be 640 mm and 83 mm respectively.

The method of CIEH(FAO 1996) was used for the calculation of decennial flood flow(Q_{10}). The study area belongs to the Sahelian zone (isohyets 300 and 750 mm) and a catchment area of 2280, the quarter (1/4) downstream of the catchment with an area between 350 and 1500 km^2 was considered.

Longitudinal slope (S_L) of the catchment was determined using the simplified formular of GRESILLON:

$$S_L = \frac{0{,}026}{\sqrt{S}} \qquad 4.\ 3$$

S_L= 0.9

Overall slope index (S_O) was taken as the longitudinal slope, therefore

$S_L = S_O$ 0.9

Average decennial daily precipitation over the watershed (Pm_{10}) was obtained by multiplying the decennial daily rainfall (P_{10}) by the rainfall coefficient of reduction (P_C), the simplified equation of Vuillaume (1974):

$$P_{m10} = P_C \times P_{10} \qquad 4.4$$

where

$$P_C = 1 - \left[\frac{(161 - 0{,}042 \times P_{an})}{1000} \times logS\right] \qquad 4.5$$

S= catchment area in Km^2 and decennial annual rainfall (Pan) in mm

P_C = 0, 63 therefore, Pm_{10} = 0.63*83= 52.29 mm
Decennial flood flow is given as:

$$Q_{10} = a \times S^s \times P_{an}^p \times S_O^i \times K_{r10}^k \times D_d^d \ldots \ldots \ldots \qquad 4.6$$

where

a, s, p, i, k, d ... are coefficients to be determined

S is the catchment area (Km^2)

S_O is the overall slope index (m / Km)

Kr_{10} is the decennial runoff coefficient (%)

D_d is the drainage density (Km^{-1})

For the study area, this equation can be written in the following forms (FAO Bulletin 54 1996)

$$Q_{10} = 2{,}03 \times S^{0{,}590} \times S_O^{0{,}588}$$

$$Q_{10} = 0{,}00372 \times S^{0{,}605} \times P_{m10}^{1{,}778}$$

$$Q_{10} = 2{,}72 \times S^{0{,}626} \times S_O^{0{,}360}$$

Q_{10} = (Eq 4.7+Eq 4.8+ Eq 4.9)/3= 145.23 m^3/s

Therefore, Q_{10}= 145.23 m^3/s

The spilling lengths and heights of water over the different components of the spreading weir were calculated using the law of flow for unsubmerged weirs given by Jean Maurice DURAND) as:

$$\boldsymbol{Q} = mL\sqrt{2 \times g \times h^{3/2}} \qquad 4.7$$

where

Q is the flow on the weir / low or high wings (m3 / s);L is the corresponding spilling length (m); h is the height of water over the crest/wings (m) ;m is the weir coefficient flow taken as 0.39 and g is the acceleration due to gravity (g = 10 m / s^2)

The calculations are done iteratively as a function of the water heights on the different parts of the weir (the water levels on the wings depends on the water level on the weir) until the approximation of the flow of the calculated decennial flood flow, that is, the sum of the flows calculated on the different parts of the weir must be greater than or equal to the decennial flood flow based on Jean Maurice DURAND law of 1998.

Table 4. 5 Components of water spreading weir and their characteristics

characteristics	weir	Abutment	High wing	Low wing	
Spilling length(m)	32.5	173.5	0	196.05	
Height of water(m)	1.10	0.10	0	0.4	
Flow	65.4	9.6	0	86.5	161.5
Specific flow rate(qi=Qi/Li) in m^3/s/ml	2.012	0.055	0	0.441	

Thus, with a flow qi = 2.012 m^3 / s / ml and assuming H=1.2 m, $qi^2 g \times H^3$= 0.23

From the graph provided in the appendix, Y_2/H= 0.8, therefore Y_2= 1.5*0.8= 1.2

L'/H= 7.5,L'= 7.5*1.2= 9 m for the weir across the channel width. Therefore, the length of the energy dissipator is 9 m.

The depth D with respect to the downstream width of the channel is given as:

$$D = \frac{L}{6} - y_n \qquad 4.8$$

Where

Y_n is the normal depth of flow downstream of the weir. But, considering the lack of data for the calculation of this depth by the formula of Manning-strickler, the depth (D) of the energy dissipator was taken as 0, 50 m.

For the downstream riprap protection of the bed, we take a length identical to that of the respective basin with a layer of a thickness of 50 cm. the protection basin of the wings and abutment are designed on the basis of the wing discharging the highest specific flow. From table 4.5, the low wing has the highest specific flow equal to 0.441 m^3/s/ml.

H_0 = 0.4 m; q = 0.441 m3 / s / ml

The height of fall H = H_0 + D where D is the depth of the energy dissipator.

D = 0,8y_c. Yc is the critical depth. $Y_c = \sqrt[3]{}$ (q ^ 2 / g) = 0.271 m

Therefore, D= 0.22 m ≈ 0.25 m corresponding the energy dissipator of Type 190 based on Heinz BENDER classification.

Depending on the height of the walls, height of water and soil type, foundation, depths and thicknesses were estimated using the LANE rule. This rule is specifically designed for concrete foundations but it could be used here as a check for weir foundations, given the rigidity of the structure and assuming the waterproof foundation as cyclopean concrete.

It is therefore given as:

$$L_v + \frac{1}{3} L_h \geq CH \qquad 4.9$$

where

L_v is the vertical flow of water; L_h is the horizontal flow of water; C is the Coefficient that depends on the nature of the soil and H is water level upstream of the weir.

- **Benefits**

i. More than 20,000 ha of cultivation area was improved in Chad, Niger and Burkina Faso
ii. Deposited fertile soil available for high-value crops and staple foods.
iii. Regeneration of degraded lands
iv. Market crop production improved
v. The reduced distance of fetching water by women and children
vi. Less migration
vii. Year-round employment
viii. Improved access to services(education, school and transportation)

ix. Availability of forage, food security assured through crops and livestock farming.
x. Reduction of poverty
xi. Bricks made for sale

- **Cost**

The construction cost is between EUR 600 to 1500 per ha. It varies from $ 20,000 to 70,000 in the Sahel regions. The availability of local materials and labour may decrease the construction cost.

- **Socio-cultural acceptability**

Water spreading weirs have been implemented by 100% of land user families with external support. The construction of WSWs has directly benefited between 4000 and 8000 households in Eastern Chad. More than 370 WSWs have been implemented in the Sahel regions (Chad, Niger and Burkina Faso) benefitting 40,000 households in total.

- **Challenges**

i. Lack of know-how and experience of WSWs, only a few countries, engineering firms and construction companies that have contributed to the improvement of the technology.
ii. No documents on the know-how technology, therefore, limit the spread of WSWs to other countries
iii. The investment cost depends solely on institution or external funding
iv. Market price drop and lack of sale as a result of excess production
v. Lack of necessary means and experience by the local communities to fund activities in the valleys
vi. Lack of sufficient capacity by the local communities to maintain the systems

- **Sustainable operation and maintenance**

i. Involving all stakeholders at the beginning in the planning and implementation, training local helpers and craftsmen during the construction process and setting up a management committee for the task of supporting construction, organising the use of the weirs and maintaining them
ii. Encouraging each farmer and livestock header to pay for the water use depending on the tariff set by the management committee and the users

iii. A participatory approach involving all stakeholders to create a sense of ownership and lay a foundation for successful future use
iv. Removal of excess soil at the back of the weir to prevent overtopping
v. 10% contribution to the investment cost from the beneficiaries
vi. Continuous training after the implementation in order to help the stakeholders to have the necessary skills and experience on the O&M of the system
vii. 10% allocation of the investment after implementation for O&M
viii. Engaging in contract farming with wholesalers

- **Adaptability**

WSWs are mostly used in arid and semi regions. Currently, they are used in areas receiving annual rainfall ranging from 50 to 1,200 mm/year. They are suitable for the rehabilitation of shallow and wide dry valleys in which severe gully erosion prevents regular flooding. They are also used for improving agricultural productivity in more or less intact valley floors.

4.6.2 Hafir system

- **Technical specification**

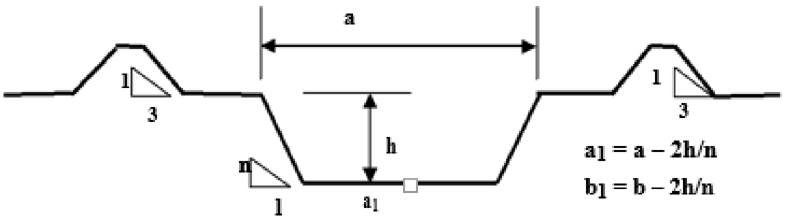
Hafirs are manmade ground reservoirs dug in the earth at suitable locations to store water for drinking purposes for both human and livestock use during the dry season. The concept is that water running in natural streams during the rainy season is diverted into natural depression. Haffirs are rectangular or semi-circular in shape. Hafir size in Sudan in the past varied by State, from 15,000m^3 to 100,000m^3. The current practice is 30,000m^3 in North Sudan and 10,000 to 30, 000 m^3 in Southern Sudan. Hafirs are usually fenced and protected to decrease pollution and hygiene hazards. An excavated hafir or improved haffir is the one with a water treatment system to supply safe drinking water-primarily for human consumption. The bottom of the hafir is compacted or line with Masonry, concrete or durable plastic sheets to reduce seepage. Hafirs are selected in a place where there are clay soil and available materials.

- **Design**

Hafir systems are simple hydraulic structures that deal with the impoundment of water. The components of a hafir system consist of feeding facilities, drainage facilities, and seepage control structures. The design and peak flows have to be estimated by hydrological studies. Table 4.5 shows the dimension of improved hafir system of 30,000 m^3 and equation 4.6 gives the formular for calculating any dimension of a haffir system developed by UNICEF.

Table 4. 6 Dimensions of an improved haffir system with a size of 30000 m^3

Top width	70 m
Depth	4 m
Bottom length	114 m
Top length	130 m
Bottom width	54 m
The slope for the length	2:1
The slope for the width	4:1



The equation for determination of dimensions of a hafir for any given volume:

$V = (A + A_1) \times (½) \times (h) = ((a \times b) + (a_1 \times b_1)) \times (½) \times (h) = (abh) – (a+b) \times (h^2/n) + (2h^3/n^2)$
4.13

Where V is the volume of a hafir, A is the area of a hafir at the top, A_1 is the area of a hafir at the bottom, h is the depth of a hafir, a is top width of a hafir, a_1 is width of a hafir at depth of h, b is top length of a hafir, b_1 is a length at depth h, n is vertical height of the slope of the sides of a hafir for horizontal distance of 1 unit. Depth of a hafir is very important as it is determined per the thickness of clay soil.

- **Benefits**

i. Increased availability of water for livestock and domestic water supply during the dry season.
ii. Limitation of pastoralists' seasonal movement in search of water and grazing land during the dry season. Reduction of incidences of clashing with other communities while competing for the use of limited water sources.
iii. Improved income levels for pastoralist households from their production of livestock.
iv. The reduced distance of fetching water by women and children.
v. Promotion of peace and stability.

vi. Availability of more time for grazing and resting favours improved productivity.
vii. Provision of safe drinking improves the health conditions of the local population.
viii. Improved income farmers.

- **Cost**

Hafir systems required significant capital investment cost for construction. The construction cost ranges from $ 17 to 22.5 per m^3.

- **Socio-cultural acceptability**

Hafirs systems are popular in Soudan indicating the level of acceptability by the local communities. It is the most used WH technique in Sudan.

- **Challenges**

i. Lack of repair and maintenance services and inability to purchase the spare parts by the local communities.
ii. The inability of local authorities to provide support because of limited capacity, including technical, human resource, budgetary and practical skills.
iii. Often, the pumps break down for lack of a minor spare part or a technician with ordinary-level skills to repair.
iv. There is no money to procure unavailable parts or no one would accept the responsibility for procuring them. As a result, the pump could no longer be used and the community members are forced to collect water from the haffir directly.
v. The inability of Haffir systems to serve the local communities long enough because of limited storage size and excess of users In Kapoeta Eastern Sudan. Subsequently, cattle could still be driven to other places to obtain water and pasture during the critical period of the dry season.
vi. Increased incidences of Water-related diseases among local communities drinking water from the hafir.
vii. The large surface of the hafir system is subject to evaporation.

- **Sustainable Operation and Maintenance**

i. Allocation of 25% of the investment cost for O&M.
ii. Monitoring of water quality from the hafir.
iii. Appropriate design of the hafir system with adequate storage capacity based on demand and population growth.

iv. Effective use of water from the hafir.
v. Encouraging the users to pay a water fee based on the tariff set by the management committee and the users.
vi. Training of all stakeholders with the appropriate skills on the O&M of the haffir systems.
vii. Engaging women in water decision making.

➢ **Adaptability**

Hafir systems are most used in Arid and Semi-Arid Regions with limited existing water resources. Areas with pastoral headers, remote and difficult to access where there are clay soil and available local materials. Hafir systems are used in Sudan or lacs collinaires in Algeria, made in Morocco, deep in Senegal, charco ponds in the drylands of Tanzania, khaks in Turkmenistan or mahafurs in north-west Arabia (Saudi-Arabia).

4.6.3 Sand Dam

➢ **Technical specification**

Sand dam (or sand storage dam) is a small dam build on and into the riverbed of the seasonal sand river to provide water for humans, livestock and off-season irrigation. Typical sand has between 1 to 5 meters high and 10 to 50 meters across the river bed. During the rainy seasons, it captures water and coarse sand upstream of the sand dam wall. The water trickles through the trapped sand and provides a reservoir from which water can be taken through pipes and pumps. A sand dam can store up to 40 million liters of water, protecting it from evaporation and contamination by holding it safely within the sand. There are three types of sand dams: Stone-masonry dam which is built with concrete blocks or rubble stones and it is durable and cheap where construction materials are available; Reinforced concrete dam consists of thin wall made of reinforced concrete, it is durable, relatively expensive but suitable for any type of dam and an earth dam consisting of impermeable soil materials (clay soil or black soils) but it can be easily damaged or destroyed by underground flow they are not popular. Site selection, community involvement and water use assessment are very important in choosing sand dams for implementation.

➢ **Design**

They are four (4) components of a sand dam which are: the dam spillway, the wing walls and the stilling basin. One fundamental design principle is that the dam yields as much water as possible without increasing the construction cost. For doing so, the dam is built on an underground dyke with a gentler slope to produce higher throwbacks. It is required that the water level and the maximum flood level remain below the riverbank after construction. This prevents spilling over the bank and creating a new river. The maximum height of the spillway is the difference between the height of the lowest riverbank (m) and the height of the maximum flood level (m). The design of the sand storage dam is based on the African Land Development Board (ALDEV) in which the total final maximum spillway height allows a safe discharge of overflowing water. It is recommended to have a fixed stage heights from 20cm to 60 cm on a case by case basis. Table 4.1 below gives the design for cost-efficient sand storage dam with h, the height of the spillway. The foundation of the dam is built on murram clay or bedrock to prevent seepage.

Table 4. 7 ALDEV design recommendations for cost-efficient sand storage dams

ALDEV variables	(m)
Base of dam	$h \times 0.75$
The slope of the front wall	$h \times 0.125$
Base of trench	$h \times 0.55$
Vertical back wall	$h \times 0.2$
With of apron	$h \times 0.75$
With of crest	$h \times 0.2$
Depth of trench	1-2

➢ **Benefits**

i. Less evaporation (water storage in sand).
ii. Less contamination with sand (not direct contact of water with livestock and other animals).
iii. Increased fodder production.
iv. Increased drinking water availability of better quality.
v. Increased farm income.
vi. Reduced water-related diseases.
vii. Increased animal production.
viii. Increased school attendance.
ix. Reduction of distance covered for fetching water women and children.

- **Cost**

Sand dams are the world's lowest-cost method of capturing rainwater in dry rural areas by a factor of 3 to 30 times compared to rainwater harvesting tanks, earth dams, haffirs and rock catchments There even less expensive where local materials are available with labour. In 2012, in Machakos County, Kenya, the cost of materials and technical support for a dam using 250 bags of cement is $7, 000 and $11, 700 for a 500 bag dam. In general, the unit cost is 10 – 25 pe rm^3, 1.82 per m^3.

- **Socio-cultural acceptability**

Over 500 sand have been constructed in Kituï District of Kenya and 100% of land user families have implemented the technology with external material support. Sand dams have a high degree of acceptability.

- **Challenges**

i. No control over the use of water.
ii. Risk of water contamination by livestock if proper care is not taken.
iii. Risk of the high rate of erosion downstream.
iv. 2 to 7 years required for the sand dam to fill in with sand.
v. The technology is labour intensive and external aid is needed for implementation.

- **Sustainable operation and maintenance**

i. Awareness of the contamination risk of water from the sand dam.
ii. Effective management and water use from the reservoir
iii. Encouraging users to pay a water fee based on the tariff set by the management committee and the users.
iv. Regular monitoring and utilization of the dam
v. Involving all stakeholders to ensure operation, management and maintenance after implementation.
vi. The proper linkage between the local community, local administration and government sector to ensure technical and advisory assistance for the community.
vii. Training the stakeholders with the appropriate skills to maintain the system.
viii. Allocating 10% of the investment cost for operation and maintenance.
ix. Involving women in water decision- making.
x. Engaging in contract farming with wholesalers.

- **Adaptability**

Sand dams are used in Arid and Semi-arid regions where suitable sandy river beds are usually seasonally dry. Sand dams are technically replicable. They are mostly used in Kenya and are also found in Ethiopia, Chad and Burkina Faso.

4.6.4 Permeable rock dam

- **Technical specification**

Permeable rock dams are forms of floodwater harvesting where runoff waters are spread in the bottom of valleys to improve agricultural production and at the same time to control gully erosion. The structures are usually long, low dam walls made from loose stone. The central part of the dam is perpendicular to the valley, while the wall extensions to either side curve back down the valleys almost following the contour. The concept is that the runoff water that accumulates in the middle of the valley to create a gully is spread across the valley floor to give favourable condition for crop growth. During peak flows, the excess water infiltrates through the dam or overtops it. As water continues to infiltrate, the dam is silted up with fertile soils. Normally series of dams are built along the same valley bed to stabilize the valley system entirely. The technique is labour intensive and needs a group approach, as well as some assistance to transport the stones.

- **Design**

The dam wall is about 7 cm high and it may be as low as 50 in some areas. The middle section of the dam including the spillway (if needed) may have a maximum height of 2 m above the gully bed. The dam spreader (wall) can be as long as 1000 meters across the widest valley beds. The lengths normally range between 50 to 300 meters. The number of stones used can be 2000 tonnes in the largest structures.

The dam wall is made of loose stone, positioned with care, the larger boulder form the framework and the smaller stones are packed in the middle like a sandwich. The side slope ranges from 3:1 or 2:1(horizontal: Vertical) on the downstream side and 1:1 or 1:2 on the upstream side. The structure is more stable with shallower side slopes but very expensive. It is recommended to set the dam wall in a trench of about 10 cm depth to prevent undermining by runoff waters. It is strongly advisable to place the layer of gravel, or at least smaller stones in the trench when they are erodible soils.

- **Benefits**

i. Erosion control and increased crop yield.
ii. Fertile deposits finning in gullies, therefore land management improved.
iii. Boost the groundwater level.
iv. The yield of sorghum increased from 1 to 1.9 ha as a result of rock permeable dam.
v. Used for growing rice, millet and peanuts.

- **Cost**

Permeable rock dam providing water supplies and erosion control to plots of 2 to 2.5 ha costs about $500 to 650 for transportation of material about 300 to 600 person-days of labour.

- **Socio-cultural acceptability**

The technology is accepted by local communities in Burkina Faso.

- **Challenges**

i. High Stone transportation cost;
ii. Huge quantity of stone needed
iii. Specific to a site

- **Sustainable operation and maintenance**

i. Replacing washed off stones.
ii. Repair of small damage to prevent deterioration.
iii. Careful observation of the construction method.
iv. Allocation of 5% of investment cost for repair.

- **Adaptability**

Permeable rocks are used in Arid and semi-arid regions where the annual rainfall is between 200 to 750 mm/year. They are suitable for all agricultural soil with the best slope of 2%for the effective spread of water across the valleys. They are mostly used in Burkina Faso.

4.6.5 Rooftop water harvesting

- **Technical specification**

Rooftop and courtyard WH provide water very close to the household. Rainwater is collected as it runs off the catchment area of house roofs or paved/compacted surface in and around the courtyard. The collected water is transported through a conveyance system of gutters and downpipes to underground above ground storage facilities or a combination of both. The storage facilities are called tank of various types, jar or cistern. Rooftop materials used for water harvesting are galvanized iron aluminum or cement sheets. Gutters, downpipes, filtration and storage facilities could b made of local materials or manufactured the bigger the roof, the higher the runoff yield. In tropics, only 85% of water runoffs and15% is lost to evaporation.

- **Design**

The quantity of water that runs off a roof into the gutter system could be calculated using the following equation:

$$Q = \mathrm{R_C} \times R \times A, \tag{4.15}$$

where Q is the quantity of runoff water, $\mathrm{R_C}$ is the runoff coefficient, R is the total rainfall (mm/y), and A is the roof area or the catchment area (m^2). The method of estimating water demand is as follows: the water use (in liters) multiplied by the number of persons in the house and then multiplied by the number of days without the rain. The size of the storage facility is estimated when water demand is known.

For Abougoudam District with an average household of 10 people based on the questionnaire, annual rainfall of 312.5 mm/year(0.3125 m/year) with a probability of 52.4%, a roof catchment of 281 m^2 and runoff coefficient of 0.9 (corrugated sheet metal mostly used in Chad).

The total amount of water harvested in a year =$0.3125 \times 0.9 \times 281 = 79.03125\ \mathrm{m3/year} = 79031.25\ \mathrm{l/year}$ = 216.52 l/day which is enough to supply a household of 10 people with a water demand of 200 l/day (20 l/p/d). The size of the storage facility is the difference between the total amount of water harvested and the total water demand in a year. The total water demand in a year=$20 \times 10 \times 365 = 73000\ \mathrm{l/year}$. The size of the storage facility= 79031.25 l/year-73000 l/year= 6031.25 l/year= 6.031 m^3/year.

- **Benefits**
  1. Increased reliability of clean and affordable drinking water for domestic use, hygiene, livestock consumption, irrigation of kitchen gardens.
  2. Reduced distance covered by women and children to fetch water, therefore enhancing their health condition.
  3. Enabling water storage for off-season use.

iv. Water management at the household level, therefore avoiding conflict on water management at the community level.

- **Cost**

The cost of rooftop water harvesting depends on the tank, gutter, downpipe and filtration system, the volume of materials, design, where and how the system is constructed. It may require a high capital cost from the beginning but the running cost is very cheap. $600 was used to adopt rooftop in Senegal with a tank of up 20 years life span. Galvanized iron roof with 22m^3 in Botswana cost $2,000 with $13 labour cost. Ferro-cement jar of 90 m^3 cost $2,555.

- **Socio-cultural acceptability**

Rooftop water harvesting is used in Botswana, Burkina Faso, Ghana, Kenya, Nigeria, Senegal, South Africa, Uganda in Africa; China, Kyrgyzstan, India, Indonesia, Japan, Nepal, Sri Lanka, Tajikistan, Thailand in Asia and Brazil, Australia, Germany, Spain.

- **Challenges**

i. Reliance on rainfall and adequate storage capacity.
ii. Risk of contamination of water from a high level of phosphate bird drops and accumulation of dust on the roof which are washed into the storage facility.

- **Sustainable operation and maintenance**

i. Removal of contaminants using the first-flush diversion.
ii. Regular cleaning of tanks.
iii. Disinfection of water when considered for domestic drinking.
iv. Need for information, education and training on the technology.

- **Adaptability**

The technology is suitable in arid and semi-arid areas where rainwater is the most suitable accessible source of water.

4.6.6 Zai pit (Tassa)

- **Technical specification**

Zai pit (planting pit) is Microcatchment technique that is practiced on land which is not very permeable so that runoff can be captured. Zai is hand-dug technology to improve infiltration of runoff. Manure and fertilizer are added to the pit resulting in improved crop yields. The dug earth is placed downslope of the pit and may be formed into a ridge to capture rainfall and runoff effectively. Zai pits are often combined with stones lines to regenerate cultivated areas that have been degraded. They normally used to grow sorghum, maize, millet, cowpeas, sweet potatoes, groundnuts and bananas.

- **Design**

Zai pits are usually 20 to 30 cm wide and 20 to 30 cm deep and spaced 60 cm to 1 m apart. The catchment ratio is 3:1. They are applied on a slope of 0 to 5%.

- **Benefits**

i. Rehabilitation of degraded lands.
ii. Increased sorghum yield. From 0.7 to 1.0 t/ha/
iii. Increased yield millet in Tanzania from 124 kg/ha to 360 kg/ha.
iv. Increased farm income.
v. Increased fodder production.

- **Cost**

The cost of zaï pit estimated in terms of the time it takes a farmer to dig the holes and fill them with organic matter. It requires between 30 to 70 people per hectare as input for digging the holes depending on the hardness of the ground. For the fertilization with manure and compositing, 20 person-days per hectare. If the wear and tear cost of materials by the farmers are taken into account, the cost may be estimated at about 8$ha.In Niger, it is $ 65/ha.

- **Socio-culture acceptability**

The technique has no negative use in the countries where it has been practiced. Therefore, there is no contradiction in social-cultural practices. They are called tassa in Niger, Zai pits in Burkina Faso, Chololo pits in Tanzania, gun pits in Sudan, kofyar in Nigeria, Yamka in Kyrgyzstan.

- **Challenges**

i. Efforts needed to watch the state of the holes by the farmers.
ii. Subject to waterlogging in a very wet season.
iii. Labour requirement for repair and maintenance.

- **Sustainable operation and maintenance**

i. Checking of holes before planting.
ii. Checking of holes after every storm.

iii. Filling of holes with the required amount of organic manure.
iv. Adequate digging of holes with debris evenly placed in the holes.

- **Adaptability**

Zai pit can be used in all Sahelian countries.

4.6.7 Stones line bunds

- **Technical specification**

Stones lines (stones bunds) are laid along the contour to rehabilitate barren or crusted soils. They are often used in combination with zaï pits by farmers to regenerate their degraded lands and increase crop yields. The stones lined along contour do not collect runoff but keep it spread thereby slowing the speed of runoff in order to allow it infiltrate, which is further improve through the use of zaï pits. The farmers usually start by lining the stones at the lower points of the field and work upslope. Since the stones are not easily damaged by runoff they start at lower points to collect enough runoff for crop production in a year with less than average or irregular rainfall. Stone lines are constructed by mixing both small and large stones. Small stones are placed upslope and the larger ones below to slow down runoff catch fertile soil sediment. Stone lines are easy and cheap to construct provided stones are locally available.

- **Design**

The height of line/bund is 25 cm with a base with of 35 to 40 cm. The bund is usually laid in a shallow trench with a depth ranging from 5 to 10 cm, which helps in being not undermined by runoff. The mixture of both small and large stones allow effective harvesting of runoff. Bunds spacing of 20 m is laid on a slope of less than 1% while the spacing of 15 m is laid on a slope of 1 to 2%.

- **Benefits**

i. Improved water availability for plants.
ii. Increased farmers' income.
iii. Improved erosion knowledge.
iv. Regeneration of degraded land.
v. Increased soil organic matter.

- **Cost**

The cost of stones linked to the availability of stones and transportation. It is cheap wherever stones are available. In Niger, the cost is $31/ha.In Kenya, it ranges from $32 to 62/ha with a maintenance cost of $30/year.

- **Socio-cultural acceptability**

Stones line have been traditionally used by farmers in Katanga, Burkina Faso. They are also used in Niger and Kenya. The concept of stone lines has been readily accepted. Farmer to farmer extension is effective to spread the technology.

- **Challenges**

i. Shortage of stones.
ii. Increased in establishment cost.

- **Sustainablee operation and maintenance**

i. Relaying of stones from time to time as a result of siltation.
ii. Preventing bund overtopping to reduce risk of gully formation and bund undercutting on the downstream face.

- **Adaptability**

Stone lines are common throughout Africa, both in dry and humid regions. They are suitable in areas receiving between 200 mm to 750 mm per year.

4.7 Policy brief on the sustainability of water harvesting structures in Chad

Water harvesting is a traditional practice that has been employed over the years to supplement water for humans, livestock and off-season irrigation. Most of the structures failed to perform well in the past because of improper design; the beneficiaries were not involved in the planning and implementation of the structures; there was lack of proper operation and maintenance of the structures and there was also lack of knowledge on the impact of WHSs. The existing water resources may not be able to meet the growing demand for humans, livestock and agricultural production for sustainable development. As a result of climate change, rainfall variability and increase in temperature, there is a growing interest level to invest in WH to supplement water for the intended use. Below are some of the issues related to the sustainability of WHSs and possibly incorporating them into policies may attract investment in order to improve the livelihoods of the local communities with chronic water shortages.

Overlapping of Institutional stakeholders: WH projects are implemented to provide water for humans, livestock and off-season irrigation. The Ministry of Environment, Water and Fisheries is the only one handling water projects. Since the beneficiaries are expected to be responsible for the O&M, involving the Ministry of Agriculture at the planning stage helps to provide advice to the farmers on how to grow high-value crops to increase their income, thereby willing to contribute for the management of the structures.

Farmer-livestock conflict: During the dry season, water demand for off-season and livestock is high. Introducing water harvesting techniques in pasture lands helps to limit movement of livestock to the nearby farmlands. This could prevent the destruction of the crops grown. Therefore, the farmers will be able to contribute after selling their products.

Land tenure and WH projects**:** WH projects are mostly managed at the community level. WH project may be implemented between two administrative areas and this may bring conflict over the use of the water**.** Defining the responsibility of each administrative area over the use of the water will help in the management of the system**.**

WH projects and socio-cultural acceptability: WH harvesting is mostly implemented without consulting the beneficiaries on the choice of the structure and what they really need. Developing a small, medium and strategic water harvesting structures in an economically efficient, socially acceptable and environmentally responsive manner, promote beneficiary's awareness for contributing and improving their water harvesting infrastructures.

The socio-economic and political context of WH projects: A sound understanding of the socio-economic and political context selected areas, where WH structures are constructed, help in designing appropriate strategies for sustainable use and management of WH structures, particularly if the WH structures are intended to address livelihoods.

WH projects and issues of water demand: As a result of irregularities in rainfall, increase in the population of humans and livestock and extension of farmlands during the dry season may affect the reliability of the structures to provide adequate water supply to the intended users. Therefore, designing the adequate storage capacity through carefully estimated demand levels, water losses consideration of unforeseen variations with the seasonal rainfall will help to ensure the management of the system.

Non-participation of all stakeholder in WH projects: Beneficiaries are always omitted in the planning and selection of WHSs. The participation of all key stakeholders in the entire process from the choice to site selection through implementation and management will ensure the sustainability of the system.

Supervision and monitoring of WH projects: WH is implemented by considering just a water scarcity problem in a particular area without given attention to the supervision and monitoring of system after implementation affects the sustainability of the structure. Therefore, establishing proper supervision and monitoring mechanisms before starting any construction with defined and clear responsibilities at national, regions and local levels will ensure the sustainability of the structure.

Water tariff in WH projects: Water is free in Chad, therefore, most water users feel that it is the responsibility of the government to provide water and ensure the operation and maintenance which is not mostly the case. Setting up WH management committees, engaging farmers in growing high-value crops, encouraging water use service fee in cash or in-kind where possible, this could help in using water more efficiently and generate revenue to maintain existing water infrastructure and build new facilities where needed

Knowledge on proposed WHSs: Implementation of WH technologies could be an existing or new facility to the beneficiaries, therefore promoting technologies that the users are able to maintain will surely ensure the sustainability of the structure.

Public-private partnership: Most WH projects is only discussed between the government and the financial institution without involving the direct users to understand their needs and the government always decide on the behalf. The financial institution does not have any idea on what the beneficiaries need at the local level. Increasing private sector participation in WH harvesting related projects and discussing directly with the beneficiaries to understand their needs will help in sustaining the structures.

Management of WHSs: Beneficiaries may not be conversant with the WH technologies put in place. Strengthening trained and equipped management committees and beneficiaries even after implementation of the structures will ensure sustainability.

Participation of Beneficiaries in WH projects: Enable communal WH projects beneficiaries, citizens, to fully participate effectively in the formulation and implementation. Protection zones for all drinking water sources shall be delineated and monitored

Climate change and erosion: The effect of climate change and erosion may not be clear to the beneficiaries and with the variation of rainfall and increase in temperature affect the reliability of WHSs to provide the water needed during the dry season. This could reduce the trust of the beneficiaries. There is a need to educate the beneficiaries on the effect of climate change and erosion possibly provide a mitigating measure, for example, encouraging beneficiaries to plant trees that uptake less water around the catchment to minimize evaporation.

Based on the above-mentioned issues, the sustainability of WHSs may be achieved if they could be incorporated into the policies governing water resources.

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

Chad as part of Arid and Semi-Arid Regions is faced with difficulties in the limited amount of rainfall which is associated with the degree of its variability. Abougoudam District which is located at 17 km from Abéché City in the region of Ouaddaï has seven (7) months without rainfall with a high increase in temperature and only four months with rain. From figure 4.1, the rain starts increasing from May and reaches its peak in the month of August and suddenly decreases in the month of September. This shows the irregularities in the rainfall intensities with short duration. The District has 16 hand pump boreholes and 25 open wells with a yield of 8 m^3/day for 62161. From table 4.3, the basic water supply is 5.16 l/p/day which is far below the basic drinking water supply standard set by the Chadian Water Company (30 l/p/d). The current domestic water supply for humans is 328000 liters with a deficit of 1,536,830 liters. As for livestock, the water demand is 2,312,063,327 liters. The results of the designed rainfall totals from 1999 to 2018 showed that an annual rainfall with the probability of more than 50% might be able to supplement the water demand in the Abougoudam District with the adoption of WHSs.

The soil map of the case study was generated using ArcGIS 10.5. The result showed three (3) group of soil: Group A: Sandy clay rock, silt clay, stone and rocks; Group B: vertisols (black and brown clay with the proportion varying from 40 to 60 percent, silt clay and sandy soils; Group C: Sand, Sandy-clay, gravel, loamy sand and loamy-clay. Vertisols should be avoided because of their cracks on drying which affect both the storage of water and the stability of WHSs.

From the result of the questionnaire, the population of Abougoudam District is willing (100%) to adopt water harvesting but government and beneficiaries have shown the weak financial capacity to adopt and maintain WHSs. Increasing public-private partnership and integrating WH into socio-economic development programs make it attractive enough for sponsorship by donor organization especially the United Nations and IsDB in their attempt to eradicate poverty and foster environmental sustainability in order to achieve the SDGs(goal number 2and 6).

With regard to best practices of WHSs to supplement water for human, livestock and off-season irrigation, Water spreading weirs, Hafir system, Sand dam, permeable rock dam, rooftop, Zai pit and Stone lines have been highlighted in this study. The analysis focused on technical specification, design, socio-cultural acceptability, cost-benefit, challenges, sustainable O&M and adaptability. These factors have to be addressed properly to ensure that any WH system is able to perform cost-efficiently and improve the livelihoods of the local community.

Based on adaptability, the technologies mentioned above could be adopted in Chad and most specifically in Abougoudam District but water spreading weir, Sand dam and combination of the zaï pit and stones lines are more preferable. This is because of their capacity to regenerate degraded lands in valley regions, reduce evaporation, recharge groundwater and have the potential to improve water supply for humans, livestock and off-season irrigation through wells. They have also proven to increase crop yields in order to fight food insecurity, this is very important since Chad has been pointed out as a country that suffers from very high food insecurity in WFP 2018 report. Another factor that needs to be considered is that most off-irrigation are practiced around the wadi bed and the local communities got most of their drinking water from the wells in the wadis which has become part of their culture. In addition to that, there are also available local materials which could be used to reduce the construction cost. Hafir system could also be considered because of its potential to provide water both for human and livestock.

The sustainability of these structures could be addressed by incorporating overlapping of Institutional stakeholders; Farmer-livestock conflict; Land tenure and WH projects;WH projects and socio-cultural acceptability; The socio-economic and political context of WH projects; WH projects and issues of water demand; Non-participation of all stakeholder in WH projects; Supervision and monitoring of WH projects; Water tariff in WH projects; Knowledge on proposed WHSs; Public-private partnership and Management of WHSs into the national policy.

The government has the responsibility to provide water for her population and the population also have the responsibility to provide water for themselves. Therefore, both parties have to work hand in hand to ensure the sustainability of WHSs. WH sustainability has worked in Sudan, Kenya, India, Burkina Faso, Jordan and other Arid and Semi-Arid Regions of the world, it can also work in Abougoudam District. "Change is the law of life and those who look only

to the past or present are probably to miss the future," said John F. Kennedy. It is always better to look into the future. Could WH be the future of Abougoudam District population suffering from chronic water shortage?

5.2 RECOMMENDATIONS

In view of the above discussion and conclusion, this study recommends the following that would be beneficial to the adoption and sustainability of WHSs in Chad and other Arid Regions of Africa:

- Improving the financial capacity of the Chadian government and beneficiaries with the support of the international financing organizations to unlock the potential investment in water harvesting. Improving the capacity of the Chadian government and local community on the issue of O&M of water harvesting through training and provide the institution and local communities with the right training on water harvesting technologies.
- Encouraging the beneficiaries to pay for water fee by improving their livelihoods because water is used free of charge in areas with water harvesting projects apart from water spreading weirs. This could affect the maintenance of the structures.
- Setting up WUA for community water harvesting projects because the study revealed that only water spreading weirs have management committees amount all WHSs in Chad.
- Sensitizing the local community on water harvesting and its impacts because the beneficiary may not be aware of the technology.
- Reducing tax on construction materials such as cement and steel bar by the government because the study has revealed that water harvesting projects in Chad are more expensive compared to other regions in Africa.
- Creating the spirit of ownership right from the planning stage of the projects since the O&M is solely the responsibility of the local community. It could give input in the sustainability of the structures.
- Building a comprehensive database for water harvesting to include biophysical studies, socioeconomic studies, hydrologic and technical studies. This could provide necessary information on the areas considered for WH adoption.

- Minimizing sediment caused by soil erosion by delineating bare soil areas on sloping terrains and planting them.
- Delineating and monitoring all drinking water sources to enhance water quality.
- The inclusion of policy brief into the national policy to ensure the sustainability of WHSs in Chad and other Arid Regions of Africa.

5.3 FUTURE PROSPECTS

The future of WH in Chad will depend on the public and private partnership between the Chadian government and the financial institutions to unlock the potential investment to improve the socio-economic activities of the local community. Abougoudam has the potential for animal production and off-season irrigation for high-value crops to contribute to the national economy and create employment for the local population. WH is an ancient practice that has been employed to supplement water for humans, livestock and off-season irrigation. The future lies in the adoption of WHSs that have performed well to provide water for the intended use. The renewal interest in WH adoption is on the increase in areas that the existing water resources could not meet their water demand. The use of green water and its impacts will definitely enhance the livelihoods of the local communities but the sustainability of the structures should be addressed properly in order to mitigate against the impacts of climate on water supply, food security and physical condition of livestock. Chronic water shortages will surely be felt in the future but WH will reduce the degree of the severity in Abougoudam district, Chad and other Arid Regions of Africa.

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APPENDICES

Appendix A: Questionnaire

SECTION A: General Information

Name of City/Village……………………………………………………………………......

Gender……Male……… ……………….... Female …… ……………………………….

Age…………………………………………………………………………………………...

Family members…………………………………………………………………………...

Level of Education

Primary School ☐ Secondary School ☐ University ☐ Others ☐

SECTION B

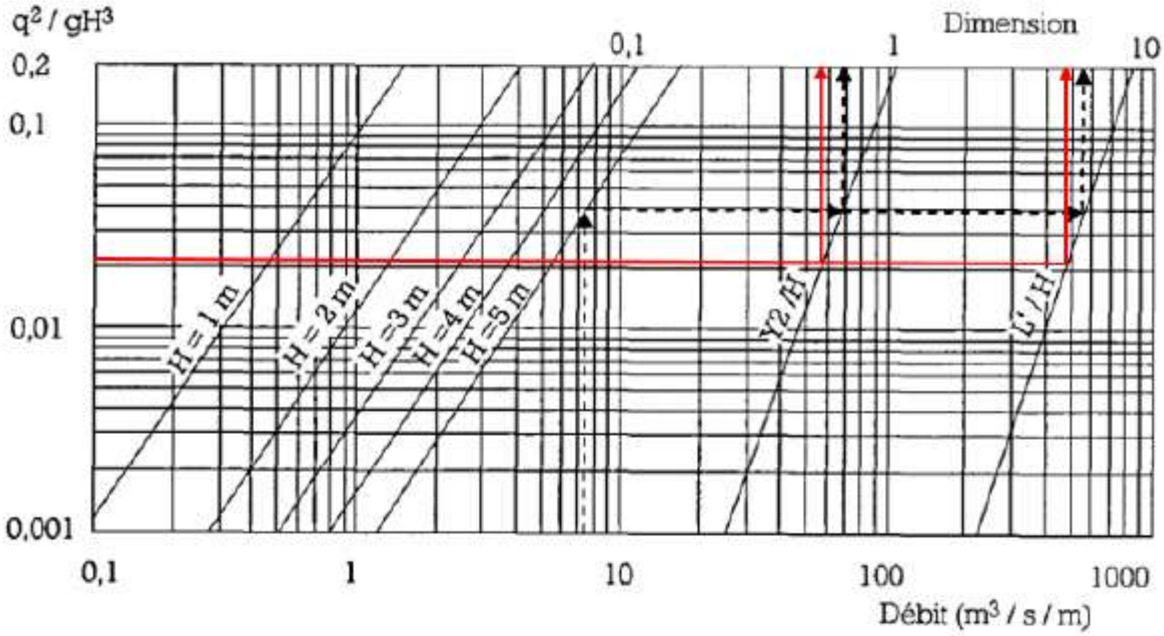
1. Do you face water scarcity? Yes ☐ No ☐
2. What is your existing water source? ______________________________
3. Do you pay for water fee? borehole ☐ Open well ☐
4. What is the source of your income? ______________________________
5. Do you practice off-season irrigation? Yes ☐ No ☐
6. What is the problem with the actual water source? Quantity ☐ Quality ☐ both ☐
7. Do you need another source of water than the current one? Y☐ N☐
8. Do you own farmland? Yes ☐ ☐
9. What is the size of your farmland? ______________________________

SECTION C

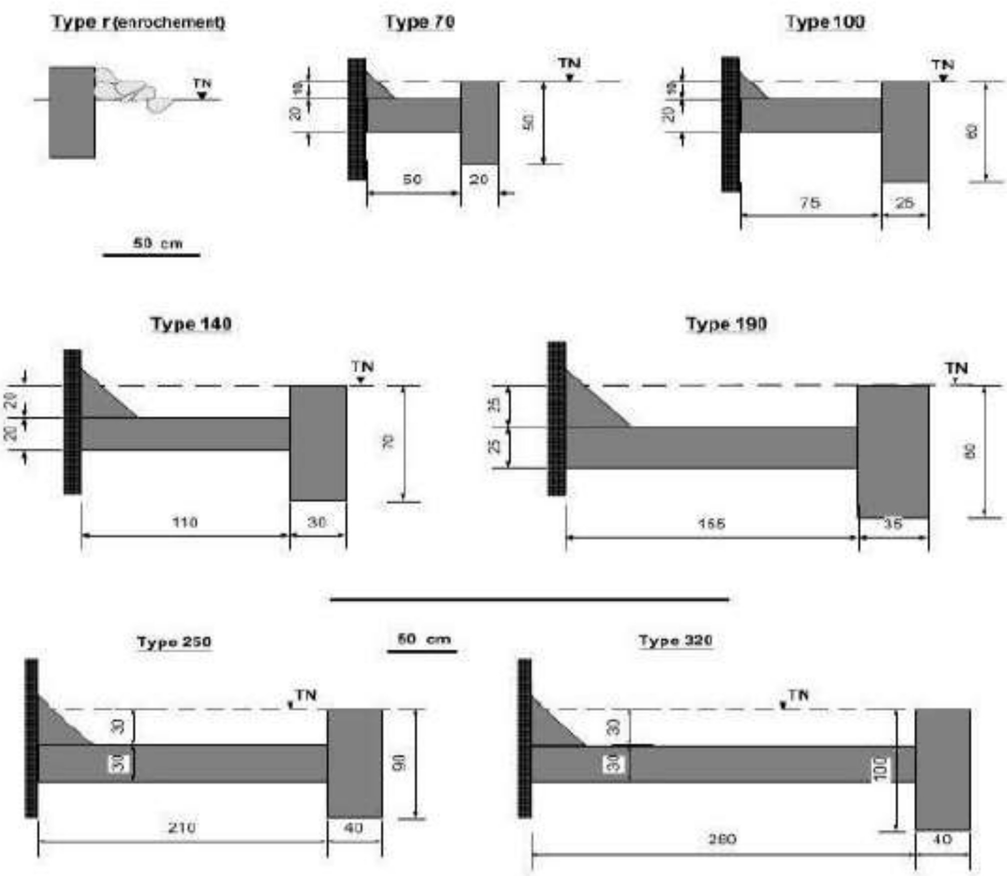
10. Are you aware of water harvesting? Yes ☐ No ☐
11. Do you practice any kind of water harvesting? Yes ☐ ☐
12. Are you willing to participate in water harvesting to improve your water needs if the government provides 50% of the installation costs? Yes ☐ No ☐
13. Are you willing to contribute to the operation and maintenance cost after installation of the system? Yes ☐ No ☐

14. Are you willing to adopt water harvesting? Yes ☐ No ☐

Appendix B: Graphical calculation of specific flow

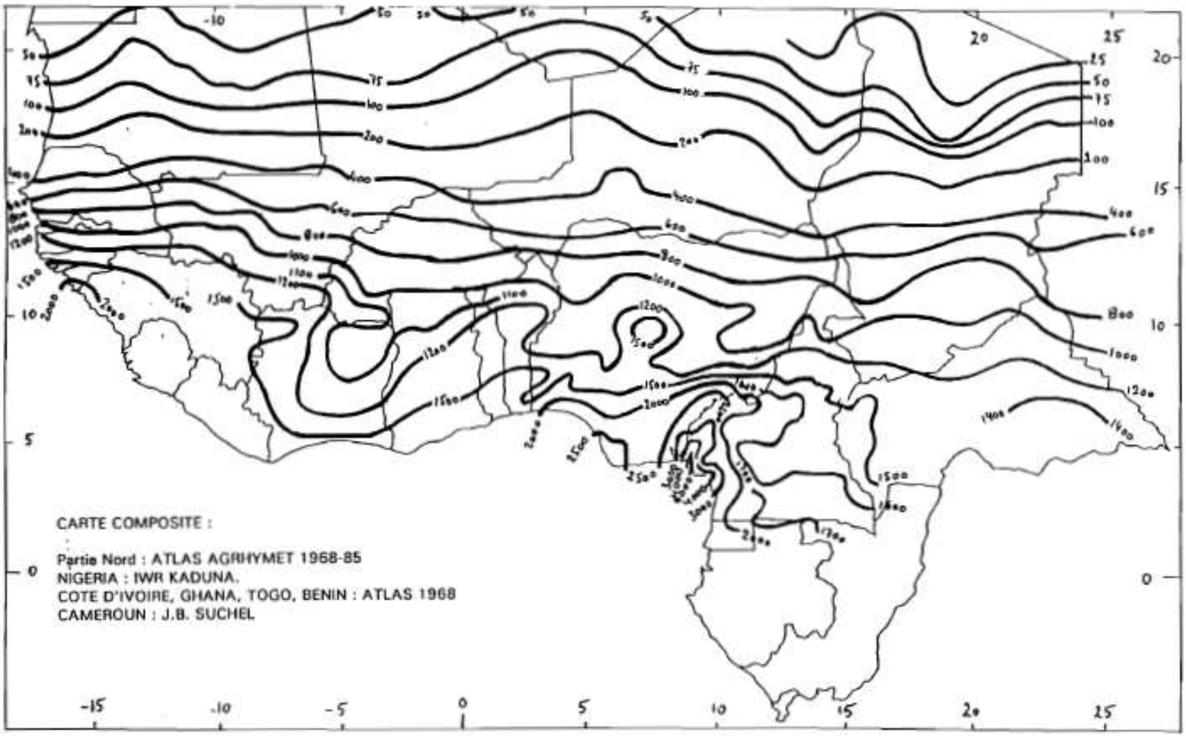


Appendix C: Heinz BENDER classification

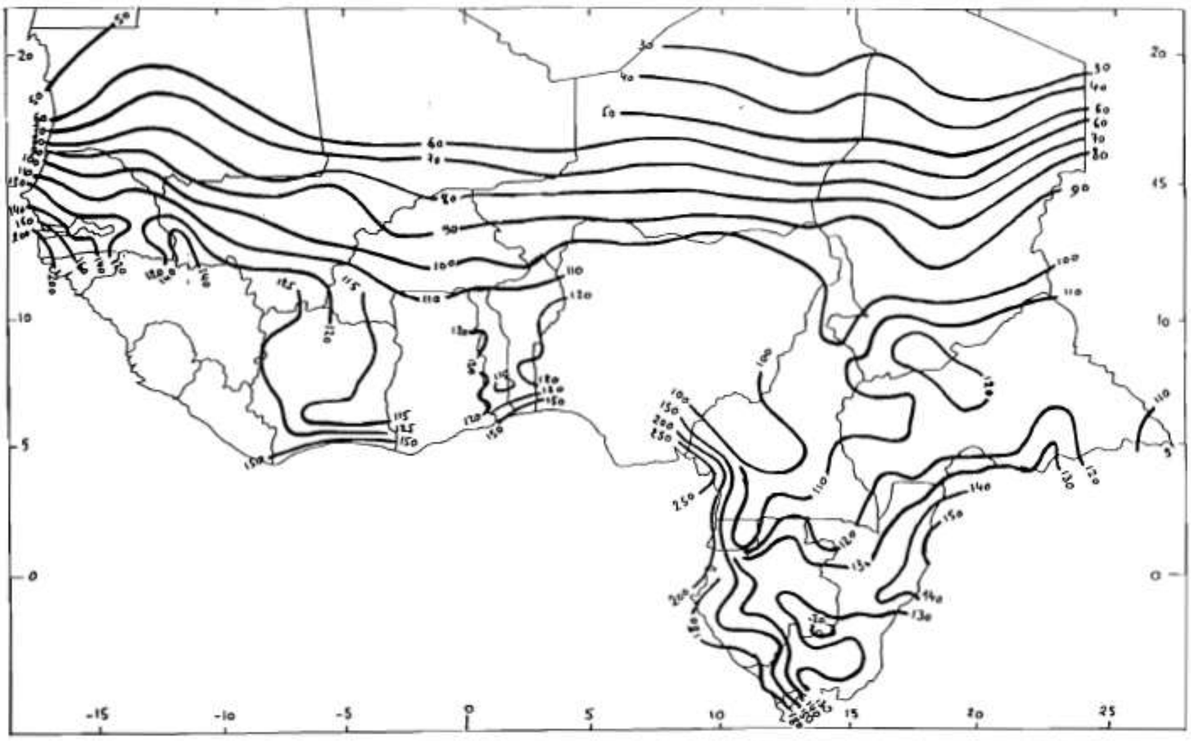


Appendix D: Isohyet maps for obtaining the values of decennial annual rainfall (Pan) and decennial daily rainfall (P_{10})

Decennial annual rainfall (Pan)



Decennial daily rainfall (P_{10})



Appendix E: BUDGET

S/No.	Item	Quantity	Unit price in FCFA	Total price in FCFA	Total price in USD	Link to Research Activity
1	Printing of the questionnaire	8	50	800	1.45	Collection of information for adopting water harvesting
2	photocopy of the questionnaire	900	50	45,000	81.81	Collection of information for adopting water harvesting
3	Printing and binding of the thesis and internship report	327	50	16,350	29.72	For submission to pauwes
4	Internet recharge	105	2000	210,000	381.81	Download of online papers
	Sub Total			**272.15**	**494.79**	
1	Rainfall data	1	150,000	150,000	272.7	Rainfall analysis
2	Soil data	1	50,000	50,000	90.9	Soil characteristics check before considering water harvesting
3	Water consumption data	1	120,000	120,000	218.18	To give an idea of whether to adopt water harvesting in the study area
	Sub Total			**320,000**	**581.78**	
1	Flight from Tlemcen to N'Djamena	1		770,000	1,400	Data collection
	Sub Total			**770,000**	**1,400**	
1	Field transportation					
1.a	N'Djamena-Abéché	2	50,000	100,000	181.81	Field visit of water harvesting structures
1.b	Abéché-Guereda	2	40,000	80,000	145,45	Field visit of water harvesting structure
1.C	Guereda-Iriba	2	30,000	60,000	109.09	Field visit of water harvesting structure
1.D	Abéché-Abougoudam	2	20,000	40,000	72.72	Administration of the questionnaire for water harvesting adoption
	Subtotal			**280,000**	**509.07**	
TOTAL				**1,642,150**	**2985.04**	
	1$= 550 FCFA					

Appendix F: Work Plan

Status	Deliverables	Date	Days	2019																							
				January			February			March			April			May			June			July			August		
				Q1	Q2	Q3	Q1	Q2	Q3	Q1	Q2	Q3	Q1	Q2	Q3	Q1	Q2	Q3	Q1	Q2	Q3	Q1	Q2	Q3	Q1	Q2	Q3
√	Abstract and budget submitted to PAUWES	07.01.2019	2																								
√	1st Draft of the proposal submitted to PAUWES	26.01.2019	7																								
√	1st Draft of the proposal submitted to supervisor	28.01.2019	1																								
√	**1st Skype call between Ramadan and Bakhodir**	**28.01.2019**																									
√	**Beginning of Research activity**	**01.03.2019**																									
√	Revised proposal submitted to supervisors	10.03.2019	7																								
	Reviewal and feedback of the proposal from the supervisors	11.03.2019	1																								
	Final version of the proposal submitted to PAUWES and supervisors	12.03.2019	1																								
	2nd Skype call scheduled with supervisors	**13.03.2019**																									
	Proposal review and evaluation by PAUWES	13.03.2019	1																								
	1st draft of Questionnaires submitted to supervisors	20.03.2019	7																								
	Final version of the questionnaire approved by the supervisors	22.03.2019	2																								
	Internship at the Bank(30 hours per week)	25.03.2019																									
	Field visit in Chad	27.03.2019																									
	interview and questionnaire reponse from the instittutions	30.03.2019	7																								
	interview and questionnaire reponse from the community	06.04.2019	7																								
	Analysis of the questionnaire using SPSS	11.04.2019	4																								
	3rd Skype call Scheduled	**15.04.2019**																									
	Internship and research continuation in Abuja	18.04.2019																									
	Completion of data collection	20.04.2019	3																								
	Draft chapter 1 and 2 submitted to supervisors	23.04.2019	14																								
	Final Chapter 1 and 2 submission	**07.05.2019**	**2**																								
	Data synthesis and analysis completed	09.05.2019	2																								
	Submission of draft chapter 3 to the supervisors	11.05.2019	10																								
	Final chapter 3 submission	21.05.2019	5																								
	4th Skype call Scheduled	**26.05.2019**																									
	Technical analysis of the selected structures completed	27.05.2019	5																								
	Cost-benefit analysis of the structures completed	02.06.2019	5																								
	Social acceptability analysis completed	07.06.2019	5																								

Status	Deliverables	Date	Days	2019																							
				January			February			March			April			May			June			July			August		
				Q1	Q2	Q3	Q1	Q2	Q3	Q1	Q2	Q3	Q1	Q2	Q3	Q1	Q2	Q3	Q1	Q2	Q3	Q1	Q2	Q3	Q1	Q2	Q3
	Draft chapter 4(Results and Discussion) submission to supervisors	13.06.2019	14																								
	Final submission of Chapter 4	27.06.2019	3																								
	5th Skype call Scheduled	**30.06.2019**																									
	Conclusion and Recommedations completed	01.07.2019	7																								
	Draft Chapter 5 submission	08.07.2019	1																								
	Final chapter 5 submission	09.07.2019	3																								
	1st draft of master's thesis and internship report submitted to supervisors	11.07.2019	14																								
	Reviewed and feedback of MSC thesis and report from the supervisors	25.07.2019	5																								
	Face to face meeting with supervisors	**Not defined**																									
	Revised MSC thesis and report internship submitted to supervisors	26.07.2019	2																								
	1st draft of the research paper and policy submitted to supervisors	28.07.2019	3																								
	Revised research paper and brief policy submitted to the supervisors	29.07.2019	1																								
	Final submission of MSC thesis and Internship reports to supervisors	30.07.2019	1																								
	Submission of final master thesis to PAUWES	**31.07.2019**	**1**																								
	1st draft of the power point presentation to the supervisors	01.08.2019	7																								
	Revised version of the power presentation by Ramadan	08.08.2019	3																								
	Final submission of the power presentation	11.08.2019	3																								
	Pe-thesis defence with supervisors	20.08.2019	1																								
	Research and Internship Completion	31.08.2019																									