adpc

Water Harvesting Assessment:

Strengthening Water Security in Nepal

Climate Adaptation and Resilience (CARE) for South Asia Project

Water Harvesting Assessment:

Strengthening Water Security in Nepal

ASSESSMENT REPORT

adpc

SM Tower 24th Floor No. 979/66-70 Phahonyothin Road,
Phaya Thai Sub-District Phaya Thai District, Bangkok 10400
Telephone: +66 2 298 0681-92
Website: www.adpc.net

Citation: Sharma, L., Gupta, N., & Basnayake, S. (2023). Water Harvesting Assessment:Strengthening Water Security in Nepal. Bangkok: Asian DIsaster Preparedness Center.

Cover photo credit: Dr. Niladri Gupta, and DoWRI, Govt. of Nepal

Layout: Lakkhana Tasaka

Document No: ADPC/CARE/WAT/NP-02

Date of Publication: September 2023

Message

Water resources development in Nepal is key to our prosperity. We have good overall availability of water and land resources that could be pivotal in enhancing our overall productivity and development. However, the availability of water resources is constrained by topography and natural variability in precipitation. This poses questions on our present and future water securities as we lack adequate quantity and quality of water at the times when we need them.

In this context I welcome this publication by the Asian Disaster Preparedness Center (ADPC) ***Water Harvesting Assessment: Strengthening Water Security in Nepal.*** In an era of unprecedented environmental challenges and climate change impacts the nexus of water resources management and climate change adaptation is important for sustainable development and resilience. It is important to address how we can best use the seasonally available water for year-round irrigation, sustainable water supply and other vital uses of water essential for growth and development. Water harvesting is one of the important solutions to meeting our seasonal shortages and spatial deficits in water availability.

Water security is a vital issue and our policies direct us to adopt various water harvesting and storage options, redistributing water from surplus basins to arid basins and newer approaches in irrigation including conjunctive uses of groundwater and water conservation approaches in enhancing water security. The recommendations in the report for a water harvesting or water storage strategy resonates strongly with the Department's priorities in improving irrigation coverage and assuring water supply to the users.

I congratulate the authors, ADPC and The World Bank for this publication and thank all other officials and experts who have contributed to this study as this work complements our department's effort towards a better water resource management and irrigation services.

Thank you.

Churna Bahadur Wali
Director General
Department of Water Resources and Irrigation, Government of Nepal

February 2024

ACKNOWLEDGMENT

This publication, ***Water Harvesting Assessment: Strengthening Water Security in Nepal***, is a product of the Asian Disaster Preparedness Center (ADPC), developed under the project titled “Climate Adaptation and Resilience (CARE) for South Asia,” funded by the World Bank (WB Reference: P171054). ADPC extends its gratitude to the Ministry of Energy, Water Resources and Irrigation and the Water Energy Commission Secretariat, Government of Nepal, for their support and collaboration to develop this report.

The authors would like to thank Dr. Kapil Gnawali of Water and Energy Commission Secretariat, Dr. Santosh Kaini and Mr. Sanjeeb Baral of Department of Water Resources and Irrigation for their support and facilitating our work. We are grateful to them for pointing out documents and resources and ideas on the topic.

We also thank Mr. Churna Bahadur Wali, Director General of the Department of Water Resources and Irrigation, for his foreword and continuous encouragement. ADPC also wishes to acknowledge the tireless efforts of its national team in Nepal and Headquarters in Bangkok in the development of this document. We extend our sincere thanks to all stakeholders, partners, and contributors whose valuable input and feedback were instrumental in shaping this report.

Table of Contents

1. INTRODUCTION **9**

1.1 Relevance and Objective 9

1.2 Methodology 12

2. WATER HARVESTING **14**

2.1 Introduction and definition 14

2.2 Types of Water Harvesting 14

2.3 Advantages or Need of Water Harvesting 17

2.4 Risks and disadvantages of water storage structures 18

3. WATER HARVESTING NEEDS OF NEPAL **20**

3.1 Background Information 20

3.2 Surface Water 20

3.3 Groundwater 22

3.4 Rainfall Patterns 22

3.5 Climate Change Forecasts 24

3.6 Water needed for irrigation and hydropower 25

4. GOOD PRACTICES **28**

5. CONCLUSION **34**

6. REFERENCES **37**

List of Figures

Figure 1: Components of a typical water harvesting system on a catchment basin for agricultural use 11

Figure 2: Analytical Framework for Water Harvesting Needs Assessment 12

Figure 3: Overview of water harvesting storage systems 15

Figure 4: Map of (a) Physiographic zones. (Rai et al., 2023), and (b) Schematic of ecological zones along a typical North-South Transect of Nepal. (Source: Nepal et al., 2021) 21

Figure 5: Mean annual precipitation of Nepal (Aryal et al., 2022) 22

Figure 6: Mean precipitation in different river basins in Nepal for different seasons (basic data obtained from WECS, 2019 and further analyzed) 23

Figure 7: Distribution of mean precipitation for various seasons (Source: DHM, 2015) 24

Figure 8: Dhap Dam and reservoir (left) in the head-reaches of Bagmati River and the Concrete Face Rockfill Dam (on right) (Source: DoWRI, GoN). 28

Figure 9: Small earthen dam for water storage in Dang Valley storing flood waters primarily for irrigation. (source: D Bhatta, DoWRI) 29

Figure 10: A Pyne conveying water to farms (left source: India Water Portal) and a revived system running full capacity. (right, source: WHH) 30

Figure 11: Cascade Tank System in Sri Lanka with a sketch showing tanks at different levels (left) and a schematic diagram of the system compromising of sequential tanks and paddy fields. (source: adapted from IUCN, 2015 as cited in Melles and Perera, 2020) 31

Figure 12: The Water Harvesting: Guidelines to Good Practice provides a comprehensive information on water harvesting around the world (Source: Mekdaschi-Studer & Liniger, 2013) 32

Figure 13: The Field practitioners guides and a feasibility study on Rainwater Harvesting (WFP, 2018 and FAO, 2014) 33

1. INTRODUCTION

The Asian Disaster Preparedness Center (ADPC) and the Regional Integrated Multi-Hazard Early Warning System (RIMES) are jointly implementing a five-year (2020-2025) regional project called 'Climate Adaptation and Resilience (CARE) for South Asia with support from the World Bank. The overall objective of the project is to contribute to an enabling environment for climate resilience policies and investments in agriculture, transport, water, and policy & planning, and finance sectors in South Asia. Initially, the national-level activities are being implemented in Bangladesh, Nepal and Pakistan.

The project has two parallel but distinct components: RIMES is implementing the first component which focuses on promoting evidence-based climate smart decision-making; ADPC is implementing the second component which focuses on enhancing policies, standards, and capacities for climate-resilient development in South Asia. ADPC is looking specifically into 1) Advisory services for policy and investment interventions; 2) Promoting climate resilient design and standards; and 3) Implementation support to climate-risk management solutions: capacity building and technical support.

Climate change impacts in Nepal, as well as around the globe, primarily manifest through water; changes in the precipitation pattern alter the availability of water (Pörtner, et al., 2022). Impacts can be on the frequency as well as the intensity of precipitation events (Chaturvedi, et al., 2022; Trenberth, 2011; MOFE, 2019), form of precipitation events, with changes ranging from snowfall to rainfall (Sharma and Goyal, 2020), delayed onset of the rainy season, or even extended periods of drought/ the period between successive rain events (Mondal et al., 2021; Pörtner, et al., 2022). While irrigated areas can be considered to be better positioned to adapt to these changes in precipitation, rain-fed agricultural lands or those that have limited water for irrigation are severely impacted.

Arable lands in arid and semi-arid regions with physical water scarcity (Molden, 2013; Yu et al., 2021) are more vulnerable to climate change. Even areas in the tropics or sub-tropics that have extreme seasonal variations in precipitation or have limited supplementary irrigation facilities can be exposed to hazards like drought impacting crop yield and production. The National Adaptation Plan of Nepal (GoN, 2021) also lists water stress and lower water availability during the winter season, causing water shortages in rural and urban areas, as a major climate risk that need to be addressed with priority. Climate change trends of increasing temperature and decreasing annual rainfall in all seasons reported for Nepal in the period 1971 to 2014 (DHM, 2017) while the rainfall extremes are increasing (Karki et al., 2017). Climate change impacts are believed to be responsible for the reduction in flow or even drying-up of springs in Nepal (Adhikari, et al., 2021; Shrestha et al., 2017) as well as in the Eastern Himalayas (Tambe et al., 2012) limiting water supply for domestic and agriculture purposes.

All of these highlight the need for adopting measures to increase the availability of water resources round the year by seeking to store or harvest water when it is available and release later when required. These measures are known as water harvesting, which is defined as the collection and management of floodwater or rainwater runoff to increase water availability for domestic and agricultural use as well as ecosystem sustenance (Mekdaschi-Studer and Liniger, 2013; WOCAT, n.d.). This report assesses the need for water harvesting in Nepal, especially in view of its strength to adapt to climate change impacts and develop resilience in the water sector.

1.1 Relevance and Objective

The Constitution of Nepal (2015) states food sovereignty as a fundamental right along with the right to a clean and healthy environment, relating to water and the environment. Nepal's 25-year long term economic vision of prosperity, the current (15th) 5-Year Plan 2019-2024 (NPC,2020), and the Sustainable Development Goals Status and Roadmap 2016–30 (GON, 2017) all recognize sustainable utilization of resources along with climate change adaptation and mitigation as key strategies to accelerate and safeguard economic growth. The overall goal of the nation, stated in these primary policy documents, is to achieve prosperity and happiness with sustainability.

There are a number of sectoral and integrative policies promulgated recently that are related to use of water and addressing climate change. There are no dedicated policies and directives specifically only for water harvesting in Nepal. The National Adaptation Plan (GoN, 2021), the latest climate change-related policy document lists water stress and lower water availability during the winter season as a major climate risk that needs to be addressed with priority. The Vulnerability and Risk Assessment exercise (MoFE, 2021) done for the water resources sector recommends addressing climate adversities such as high seasonal fluctuation of river flow; risks from climate-induced disasters; spatial and temporal water scarcity be addressed, and benefits from the water sector be maximized. These climate related actions guide towards the necessity of water harvesting.

The National Water Plan 2005 strongly states that due to extreme seasonal variations in water availability in the Nepalese rivers, all future programs will have to focus on the storage of water during the rainy season and its proper utilization during dry periods. Nepal recently released the National Water Resources Policy, 2020; whose stated goal is "to sustainably conserve, manage and to carry out multipurpose development of the available water resources contributing to the economic prosperity and social transformation of the country."

The National Climate Change Policy (2019), in terms of water resources and energy, states that energy security will be ensured by promoting multiple uses of water resources and the production of low carbon energy. The policy says that the following strategies and working policies shall be included:

- Technologies for storage, multiple purpose uses and efficient usage of water will be developed and promoted in risk-prone areas and settlements considering the effects of climate change on the availability of, and access to, water.
- Rainwater harvesting ponds will be constructed for groundwater recharge and their multiple uses.

All of this suggests that water harvesting is accepted one of the solutions to combat climate change impacts and help in the necessity to increase storage capacity of water to meet the seasonal water scarcity impacted by climate change and to meet the scattered demand of water service areas.

Increasing water security, especially in rural agrarian societies, is an appropriate strategy towards adaptation and building resilience in the battle against climate change, as highlighted in the Asian Water Development Outlook, 2020 (Panella et al., 2020). Water harvesting, including storage, strengthens water security which can further translate to food security, through irrigated agriculture and increased production, and energy security through the adoption of hydropower generation. Hydropower is a clean renewable energy which is expected to replace energy derived from fossil fuels and help in meeting nations' carbon reduction targets.

This report assesses the need for water harvesting in Nepal adopting an analytical framework introduced in this report. The objective of this report is to:

- Introduce the concept of water harvesting in tackling water scarcity. (*Chapters 1 and 2)*
- Determine if water harvesting is a priority action through an analysis of the national policy and goals. *(Chapter 1)*
- Assess and establish further the need of water harvesting in Nepal, if required. *(Chapter 3)*
- Provide best practices examples and additional information on water harvesting (*Chapter 4*) followed by a conclusion recommendations arising from the assessment above. *(Chapter 5)*

This document aims to be a resource material for the development practitioners and planners. It will be useful to the government offices related to water and development planning in general and specifically to MoEWRI, MoFE, WECs, Provincial governments and local governments in Nepal as well as other climate related offices in understanding the approach and the related policy scenario currently. The document can also be the basis to guide decisions on water harvesting paving way for detailed analyses and feasibilities for rain-fed and water deficit areas.

The document being an assessment is valid till the moment when the issues of water scarcity and stress are addressed in the field or are removed from the priority action areas from the government policies.

Rainwater harvesting from rooftops and built-up areas is well-known and is a well understood and practiced method of water harvesting. This scope of this report is geared more towards the micro to macro-catchment approaches of utilizing stream runoff and flood flows to address seasonal water scarcity by building up primarily surface storage, e.g., as depicted conceptually in Figure 1.

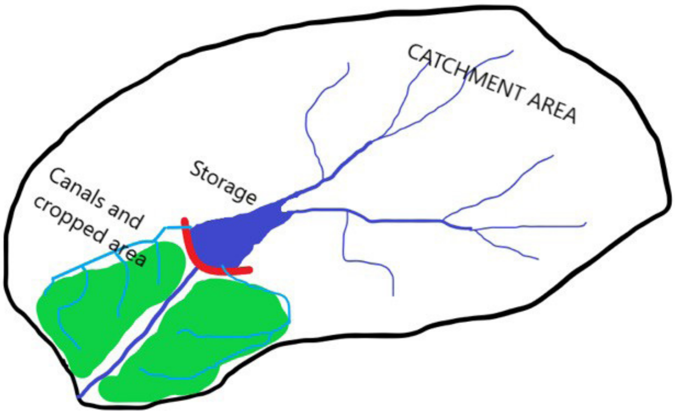


Figure 1: Components of a typical water harvesting system on a catchment basin for agricultural use

The document supports the objectives of the policy documents, mainly the National Water Resources Policy (2020), National Climate Change Policy (2019), the National Water Plan 2005 while executing actions recommended by the National Adaptation Plan (2021) and SDGs in terms of addressing climate change impacts of water stresses and scarcity. It builds upon the policy documents, further elaborating on the needs and suitability of the proposed methods in addressing water shortage which is going to be exacerbated by climate change in the future. Water harvesting also supports the national goals of increasing agricultural productivity in rainfed areas, thereby supporting the government's long-term economic goals of prosperity and happiness. The document identifies the opportunity for further work in developing a water harvesting strategy within the short term, by year 2024, and developing an appropriate action plan.

Water harvesting can also be an integral part of climate-smart agriculture, providing opportunities for attracting private investment in small-scale water storage interventions building in adaptation and resilience as well as in improving the resilience of the poor and vulnerable as described in the key pathways for adaptation and resilience in the Country Climate and Development Report: Nepal (WB, 2022). This document will also be useful to the rural development experts, local adaptation planners and policy makers.

This report describes the need for the study with relevance in Chapter 1 describing briefly the Project, policy relevance and the need for the study tying in with the ADPC's CARE for South Asia Project. A basic assessment framework for carrying out this study is also introduced. Chapter 2 provides the definition and introduces the concept and types of water harvesting along with their applicability in Nepal. Chapter 3 goes on to provide the fact-based requirement of water harvesting in Nepal analyzing the precipitation patterns and the need for water harvesting. The document ends with a concluding chapter summarizing the findings of this need assessment.

Water harvesting resonates well with building resilience and adaptation to climate change. This study supports the objectives of the CARE for South Asia project in providing advisory services for policy towards building resilience and adapting to climate change in the water sector and adds to supporting the policies and program initiatives of the Government of Nepal.

1.2 Methodology

The assessment is carried out by a formative process evaluation adopting the general assessment framework evident in Figure 2.

Gaps and need assessments are carried out by first defining the desired situation of what should be, and the existing condition what is present. The difference between these two states yields the gap in the system or the needs that is to be addressed with some actions or interventions.

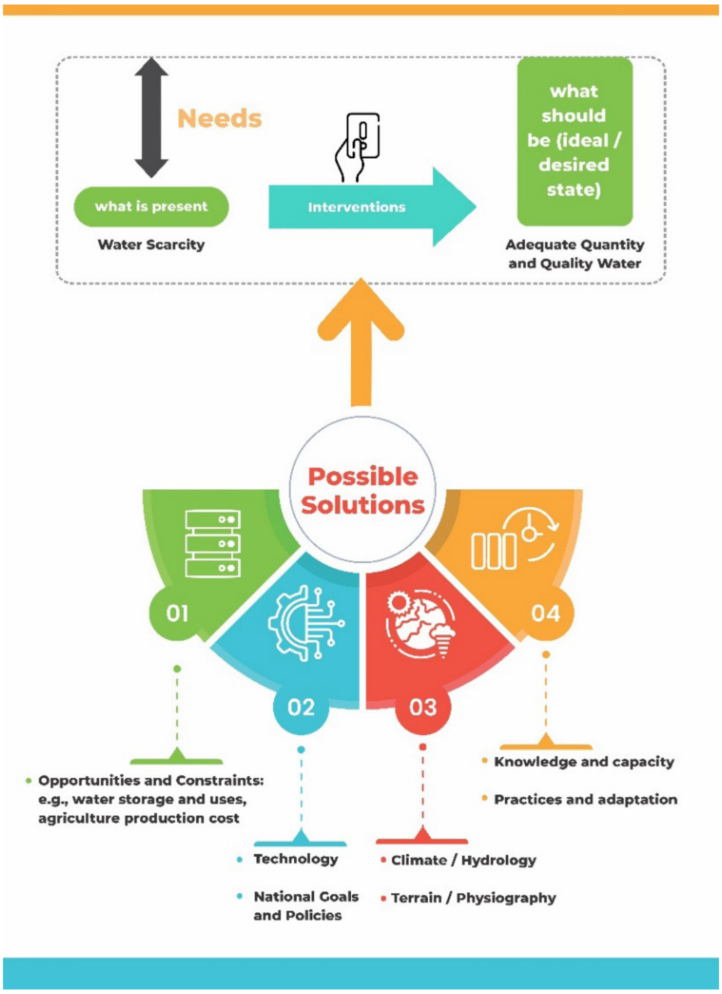


Figure 2: Analytical Framework for Water Harvesting Needs Assessment

These interventions are drawn from a pool of possible solutions which is defined by a set of constraints ranging from policies to physical parameters such as climate, hydrology, terrain and physiography. The capabilities to design and implement actions as well as the opportunities and other constraints further define the possible solutions. These possible solutions guide the watershed interventions required to develop water harvesting systems in the catchment.

Additionally, the methodology also includes a review of literature and best practices in water harvesting, and these are referenced in this document. No actual field work, surveys of existing systems and their types and operational status were made due to resource constraints and limitations imposed by restrictive COVID-19 protocols. Secondary data is used in the assessment through a desk study drawing in on field experiences of experts involved.

The existing practices were primarily determined to be rainwater harvesting systems for augmenting water supply for personal uses, live stocks and limited to kitchen and small scales of agriculture. For example, the size of ponds used in studying 141 rainwater harvesting adopters in mid-hills of Nepal ranged from 1 m^3 to 75 m^3 only (Kattel and Nepal, 2022) while the average storage capacity of 180 farmers in another study was less than 50 m^3. This indicates the relatively low adoption of water harvesting schemes in Nepal, despite the potential irrigation areas that can be developed for irrigation is 11,800 km^2 as per the latest irrigation master plan (DWRI, 2019). This presents a very large opportunity for water harvesting limited only by constraints of topography, geology, climate and storage limitations. Therefore, the current scale of operation is negligible in Nepal when compared to the opportunities of potentials of development. There is a very large gap in what is present and what could be done ideally.

2. WATER HARVESTING

2.1 Introduction and definition

Water harvesting is a practice used to harvest or collect water and make it available for crops and other needs. It is an adaptation to water-stressed conditions (Mekdaschi-Studer and Liniger, 2013). This has been practiced since ancient times around the world to address water shortages for varied uses. Water harvesting is the concentration of rainfall and runoff from roofs, watersheds or built-up areas for beneficial use and is formally defined (Mekdaschi-Studer and Liniger, 2013; WOCAT, n.d.) as follows:

> *The collection and management of floodwater or rainwater runoff to increase water availability for domestic and agricultural use as well as ecosystem sustenance.*

The above definition makes it clear that all forms of collecting rainwater, directly from rooftops and pavements to tanks or by redirecting runoff from catchment surfaces to ponds, lakes or reservoirs, or directly to concentrating run-off to field applications are all water harvesting practices. Therefore, water harvesting is a general term that encompasses rainwater harvesting as well as runoff or floodwater harvesting. harvesting.

The components of a water harvesting system include a catchment or collection area, a storage part and a distribution or abstraction system for the targeted use (Figure 1). An additional conveyance system may also be required in larger systems. Water harvesting includes collecting runoff during times of excess and storing it on surface tanks, reservoirs or even in sub-surface aquifers or groundwater and abstracting it when required. This requires impeding, channeling and collecting surface runoff as well as increasing storage to make more water available for domestic, irrigation or use of livestock. The stored water will provide resilience against droughts or periods of no rain. It can, for example, provide a critical supply of water for planting seeds or raising seed beds in the dry months before the onset of monsoon in Nepal for paddy cultivation.

Water harvesting enhances water security and provides coping mechanisms against shocks introduced by increased climate variability under a changing climate. UN-Water (2013) defines water security as follows:

> *The capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability.*

This demonstrates that water harvesting is an important activity and is therefore included in various policies and development plan documents in Nepal, as was described in Chapter 1.

2.2 Types of Water Harvesting

Water harvesting have been categorized into different types depending upon the purpose, source of water, storage methods and structures (Mati, 2012; Mekdaschi-Studer and Liniger, 2013; Prinz, 1996; Oweis, 2017; etc.). A simple classification is based on the type of harvesting systems. These different types in general are described below and shown in Figure 3. Water harvesting has been a traditional practice also in many arid and semi-arid regions around the world and different local names for different styles of farming also exist (Prinz, 1996) but these are excluded for brevity from the discussion below. Commonly understood types of water harvesting systems are listed below, while Figure 3 shows various storage systems;

- Rainwater harvesting
- Runoff water harvesting and/ or Floodwater harvesting

- Subsurface dams; aquifer recharge, storage and recovery
- In-situ water harvesting

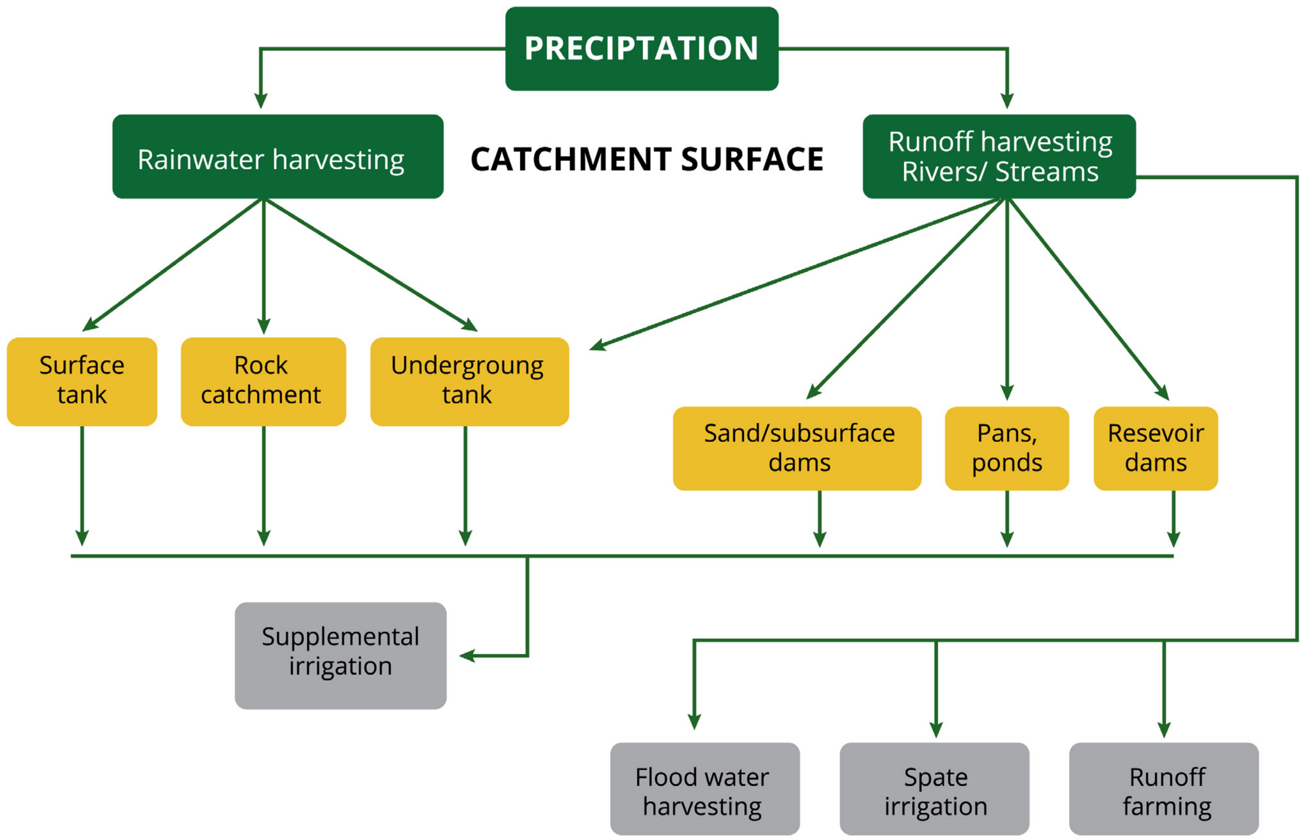


Figure 3: Overview of water harvesting storage systems

Rainwater Harvesting

Rainwater harvesting is commonly understood to be collecting water from rooftops and pavements/ built-up areas in vessels or tanks, either above or below the ground, to be used for supplying water for domestic purposes including livestock and limited gardening or irrigation uses. These are typical household or micro-catchment activities, widely applicable in Nepal and around the world. This is well understood by all, has been traditionally practiced and advocated in Nepal for quite some time.

Runoff water harvesting and/or floodwater harvesting

This type of water harvesting is a group of catchment level activity, both macro and micro, that collects or impounds flood waters or runoff in streams, lakes or rivers, or diverts flood waters with the use of structures in the rivers to farms and required areas. The flow regime is primarily turbulent runoff and channel flow through rivulets, gullies, streams and rivers. Spate irrigation is a form of floodwater harvesting where the flood is diverted and spread over agricultural land. Runoff farming channels water from upland catchments to lower-level agricultural areas, thus concentrating rainfall collected to a smaller area.

In basin or sub-basin scales, rivers and streams or their high flows can be stored behind dams in reservoirs and the water is withdrawn when required. The predominance of turbulent runoff and channel flow of the catchment water is a characteristic of these systems.

Depending upon the volume of the storage it can be tanks, pans, ponds, lakes or reservoirs. The availability of water, location and headwater available can provide opportunities for multipurpose uses including drinking, irrigation, hydropower, recreation, the preservation of the ecosystem and biodiversity. Smaller scale pans and ponds can also be constructed to utilize the local topography to aid in local water supply, irrigation and livestock use. Such storage can be given in Nepal in river valleys, depressions, old ponds and abandoned flood plains or even upslope of road embankments or constructing embankments in suitable locations.

Subsurface Dams

Subsurface dams are barriers built in sandy rivers/beds to capture subsurface flows and extract them for consumptive uses: for drinking, livestock and irrigation. These are feasible in certain sandy river beds and alluvial fans with high permeability, even though there may not be visible water on the river beds. Arjun Khola in the Dang area of Lumbini Province are known to have such suitable conditions in Nepal. Other and other flashy river beds in the Terai and valleys with shallow conglomerate or sandy gravel beds can be suitable locations for constructing subsurface dams and diverting flows to use the collected water as required.

Aquifer Recharge, Storage and Recovery

Sub-surface aquifers or groundwaters can also be recharged by delaying runoff, infiltration ponds, spreading runoff over large areas and delaying flood propagation. Injection wells and boreholes can also be constructed to store water during excess flows, store water in underground mounds in suitable aquifers and retrieve them as required using mechanical pump sets. The water thus injected, stored and extracted, generally termed artificial recharge or aquifer storage and recovery (ASR), is well understood (Sharma and Ray, 2011) and developed in USA, Australia, Europe and other countries around the world to bank water, though there may be some physio-chemical changes to water as surface water mixes with the groundwater in the aquifer.

Recently, in the Indian subcontinent, groundwater infiltration has also been suggested for storing floodwaters and alleviating flood problems downstream (Pavelic, 2015) as well as addressing water scarcity in post-monsoon season (Sundaravadivel, 2001). Pavelic (2015) introduced and demonstrated the concept of 'Underground Taming of Floods for Irrigation' (UTFI) as a possible approach for addressing both floods and droughts at the river basin scale. Flood waters upstream were directed to infiltration ponds and wells and the groundwater was recharged; this could be tapped during the subsequent dry season, proving to be beneficial in disaster reduction as well as in aiding crop production. Such practices can be feasible in the Terai and wider valleys in the hilly regions where the soil horizon has good water storage and transmissivity properties. The cost of the operation and the extent and hydraulic gradient of the aquifer may limit storage and retrieval.

In-situ Water Harvesting

In-situ water harvesting is often practiced in arid and semi-arid areas where rain water is collected where it falls, at the field itself or adjacent to the plant itself. Bunding, terracing, furrow bed system, contour farming, etc. are examples of in-situ water harvesting. Sheet flow or rill flow occurs from the rain-catchment area adjacent to the run-on agricultural areas, and the moisture is stored in the root zone for direct use of the plants (Prinz, 1996; Oweis, 2017). Extensive literature exists (Prinz, 1996; Critchley and Scheierling, 2012; Oweis, 2017; Mekdaschi-Studer, R. and Liniger, 2013; Yu et al., 2021) regarding this type of water harvesting, and it is often coupled with in-the-field soil and water conservation activities.

A type of in-situ rainwater harvesting with construction of tanks, called *Tajamares* in Paraguay as well as in Brazil, and Argentina can be best implemented in low relief areas with clayey soils that limit infiltration losses (Umazano et al., 2004) even in areas with less than 500 mm of rainfall could practice sustainable farming providing supplemental irrigation.

Some forms of in-situ water harvesting (bunding, half-moon furrows, contour bunds and ridges) can be beneficial in drier parts of Nepal that have long dry spells and/ or a long dry season. These would be good for trees and plantations, crops and even fodder for cattle. Possible areas in Nepal are the dry areas in in the rain shadow areas beyond the Western Himalayas in Mustang, Dolpo and

Karnali regions, or even in the hills and terai region where the annual precipitation is lower than 1000 mm and the dry season rainfall is as low as 100 mm as depicted in Figures 4 and 6.

2.3 Advantages or Need of Water Harvesting

The following are the advantages or the reasons why water harvesting is essential in tackling climate change impacts, addressing livelihood of the rural population and supporting in achievement of the national goals of productivity and prosperity.

Enhances water and food security reducing vulnerability to climate variability

Water harvesting provides water in areas and times of need if the system is carefully planned and operated. It provides drinking water (after treatment), for livestock and agriculture. The large population and related rise in demand for food means that greater pressures are exerted on arable land and water.

Rain-fed agriculture provides a major role in food production and sustaining livelihoods around the world (Rost et al., 2009; Rockström et al., 2010). It constitutes 80% of the world's cropland and produces more than 60% of the world's cereal grains, generating livelihoods in rural areas while producing food for cities (Molden et al., 2011). Rain-fed areas, in most arid and semi-arid zones, with no access to water for supplementary irrigation, are deficit in terms of overall water required to support the cultivation of crops customary in the region.

The rainfed and upland crops even in humid and sub-humid areas are likely to fail or yield lesser when the rainfall is not adequate to support the optimum plant physiology and crop yield (Critchley and Scheierling, 2012) when the dry seasons are too long or the rain-intervals are longer, as evidenced by the climate trends of Nepal (DHM, 2017) or is expected due to the climate change impacts in Nepal (MoFE, 2019). These pose direct impacts to the livelihoods of farmers, more so for the small farmers. Rainwater harvesting is evidenced as being very useful in climate change adaptation and for community resilience in the hills of Nepal (Kattel and Nepal, 2022).

Water harvesting, through storing of water during times of excess runoff, provides a relief in times of water shortages. This reduces vulnerability to climate change impacts and improve water and food security.

Augments groundwater

The basic principle of holding on to rainwater or runoff water provides greater opportunities for water to infiltrate and augment groundwater. This provides additional benefits to the users in the area or further away in restoring depleting groundwater levels, increasing access to, and safety of, water. Water harvesting diverts the portion of the rain that would be lost to streams and rivers by overland flow and runoff aids retains it in storage or augments subsurface storage. This enhances the groundwater recharge and availability as evidenced in the drought-prone Barind Tract of Bangladesh (Rahaman et al., 2019) or traditionally practiced in India in recharging shallow groundwater aquifers or via anicuts (Glendenning et al., 2012).

Availability of groundwater or enhancing recharge to it, aids in combatting droughts and addressing water shortages by supplementary usage of groundwater. It is also a spread out and established r esource readily available to farmers and villages for water supply.

Aids integrated water resources management

The activities of planning, executing and operating water harvesting require that the community and different sectors of land-use, forest conservation, watershed conservation, utilities, local user groups and rural and municipal governments come together and deal collectively on various issues coming up. Water harvesting is These can include the use of upland catchment area resources, reforestation and soil conservation, water quality, waste disposal and management, water scheduling and usages, agriculture practices and production, marketing and distribution of products as well as credits and agriculture inputs, etc., such as demonstrated in Bangladesh (Rahaman et al., 2019) where the rural population benefitted by water harvesting in terms of IWRM practices such as inclusion and sustainability.

Re-greening agricultural and rangeland ecosystems:

The water harvesting systems in arid and semi-arid help in retaining water within the catchments and rangeland through suitable measures such as bunds, benched terraces, semi-circular or triangular bunds, eye-brow terraces, stone dams, hill slope catchments, planting (*zai*) pits or etc. (Prinz, 1996). In-situ water harvesting or in-slope micro-catchments also offer tanks or ponds for collection of storm water at the bottom of the slope and the adjacent slopes and bunds can be planted with shrubs, vegetables and trees. Livestock production is supported through the pasture and rangeland areas where water spreading, soil and water conservation, water harvesting are the options used to regreen pastures. This supports important sources of livelihoods in the high hills and the mountain region.

Rural economy is uplifted with more jobs

Water harvesting reduces the drudgery in fetching water and improves the economic activities at rural areas that are increasingly left vacant by urbanization and migration. It helps retain labor and youth in rural areas creating jobs in spin-off benefits, such as those used in the processing of agriculture products, and greater opportunities in agro-forestry enterprises, tourism and travel industries, which could be attracted by means of good watershed and water harvesting activities. Positive impacts of rain water harvesting are documented in Palpa, Nepal where crop diversification occurred from cereal based to vegetable based cropping pattern and enhanced income to the water harvesting practitioners (Subedi et al., 2020). Similarly, Kattel and Nepal (2022) show that the adoption of rainwater harvesting and crop diversification was highly beneficial economically in four mid hill districts of Nepal.

2.4 Risks and disadvantages of water storage structures

There are certain risks and disadvantages associated with water harvesting structures and applicable for Nepal. These include safety and accidents at the water bodies – storages, ponds and reservoirs. There also exist risks of dam failures or flooding downstream or harboring pests and vectors such as mosquitoes for increased incidences of malaria and other bio-chemical contamination.

The primary disadvantage of water harvesting systems, especially when practiced for larger system or areas, is that it may curtail the traditional uses of unimpeded water along the river bodies or generate conflicts between upstream and downstream users as the water used at one stretch will always undermine availability at the other end. The upland watershed, which may need to be managed to prevent erosion and pollution of water which is being stored, may be controlled or prohibited from carrying out other developments such as urban construction, tillage agriculture, uses of pesticides, herbicides and fertilizers, or other underground storage tanks for chemicals or gasoline products, etc.

Another disadvantage, especially from large storage sites include the inundation of fertile valleys, settlements, displacements and even affecting the riverine ecology as the dam will create a barrier in the watershed preventing fish and aquatic species traveling up and down stream. Increased salinity due to upwelling of groundwater and possibility of pollution of water bodies including the groundwater resources are also potential risks that need to be managed.

The adoption of water harvesting systems could be costly or labor intensive to most of the rural farmers already practicing subsistence farming. Adopting new technology, capacity to take risks and invest are also limiting factors that impede widespread adoption of water harvesting.

Water harvesting at the larger catchment scale, requires better information on rainfall parameters, soil horizons and geo-hydrology, estimation of water requirements, sizing of the water harvesting structures, conduits and conveyances, siting harvesting systems, use of appropriate materials and construction of the system. Knowledge on undertaking feasibility analyses and assuring the technological know-how to design, construct and implement water harvesting systems are real issues and risks at the ground level.

These disadvantages and risks are the major factors facing the rural farmers in Nepal, who are already facing acute problems due to shortage of labor, agriculture inputs, credit facilities and technical extension.

3. WATER HARVESTING NEEDS OF NEPAL

The analytical framework in Figure 2 shows that the possible solutions to design the intervention to implement water harvesting requires the knowledge of technology with enabling policies supporting national goals. Chapter 1 has introduced the need for water harvesting along with the relevant government policies supporting national goals. The technology is briefly explained in Chapter 2 describing the types of water harvesting systems. Chapter 2 also explains the relative advantages and risks that can be translated into opportunities and constraints for water harvesting. This section describes the physical requirements of climate and the physiography with an introduction into the .

3.1 Background Information

The physiographic distribution of Nepal and its ecological zones are shown in Figure 3 with a typical North-South transect with climatic zones along the transect. Out of the total area of 147,516 km^2 almost 86% of the nation is covered by hills and mountains. Forests cover about 43.4% of the area of the country while agricultural land is 24.1%, almost half of the latter is in Terai – southern flat lands. The average annual precipitation ranges from less than 200 mm to more than 5000 mm with the average value estimated to be 1830 mm (MOFE, 2019). The spatial distribution of annual values is shown in Figure 4 from a DHM (2015) report, the primary rainfall is driven by the summer monsoon emanating from the Bay of Bengal.

The middle mountain region (Figure 4), with an elevation from 1,000 to 3,000 masl and a temperate climate, averages 275-2300 mm of rainfall. It is intersected by large rivers flowing north to south. The High Himalaya region includes the Himalayan Range and the areas north of it. The climate here is of the tundra and arctic variety. It has an extremely rugged terrain with steep slopes and deep valleys. Precipitation is estimated to be 150-200 mm, and a major portion of it occurs as snow in higher altitudes.

The Terai and the valleys in the middle mountains are prime areas of agriculture and residential areas. The Irrigation Master Plan (IMP, 2019), states that, out of the total net agricultural lands of 35,610 km^2, about 64% of this land or only 22,650 km^2 has the potential for irrigation, while the rest is not economically irrigable. Of the total agricultural land, about 63.6% is potentially irrigable. Irrigation facility is extended to only about 30.5 % of the agricultural area and the irrigation infrastructure could be further developed on an additional 33.1% of the agriculture area as per the Master Plan. Currently almost 70% of the agricultural area is rain-fed.

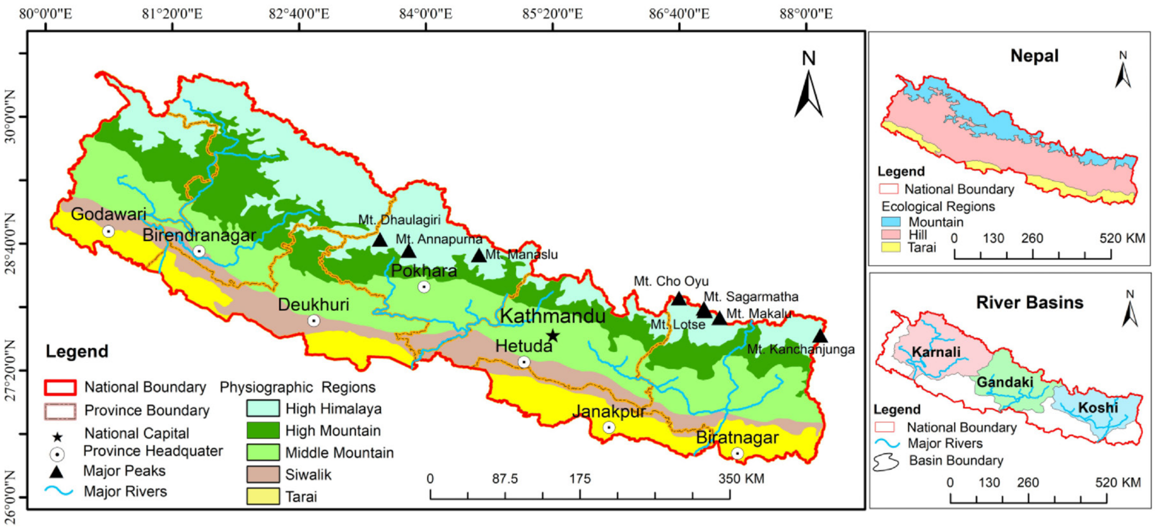
The present population of Nepal is estimated to be about 29.192 million (Central Bureau of Statistics (CBS), 2021). Agriculture is the mainstay of Nepalese, 60% of the population list agriculture as their prime occupation (CBS, 2012) contributing to a quarter of the gross domestic product (GDP). The GDP per capita is estimated to be USD $1,085 for FY 2019/20 (CBS, 2020).

Availability of reliable supply of water or soil moisture to enhance crop production, is essential to combat not only climate change induced impacts of rain deficits but also to build resiliency to face losses incurred from floods, landslides and storms. Water harvesting aids in providing that additional source of water for crops.

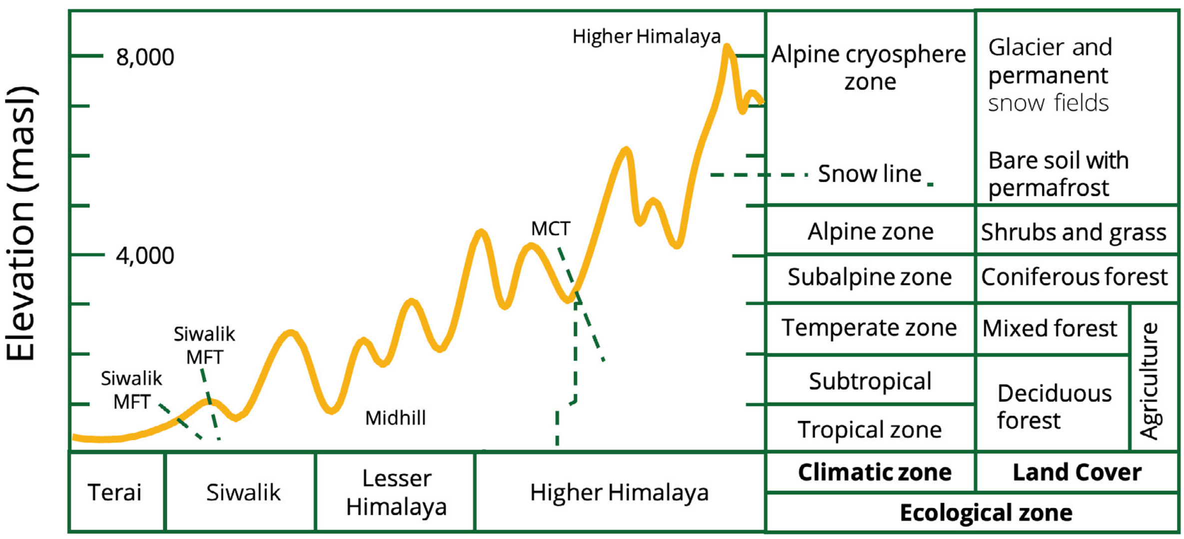
3.2 Surface Water

The average annual total surface water available in the country is estimated to be 225 billion m^3. Nepal's freshwater accounts for an estimated 2.27% of the total world supply (WB and ADB, 2021). The major river systems of Nepal are Mahakali, Karnali, Narayani (Gandaki) and Koshi. These rivers originate from the Himalayas and beyond, are fed from snow and glaciers and have appreciable dry season flow. These four river systems drain almost 73% of the land mass and account for 78% of the average annual run-off volume. In annual averages, these are water surplus basins, but the seasonal variations are extreme and the rivers flow in deep valleys such that the mountain terraces have no feasible reliable sources of water for irrigation and other usages.

The other rivers, Babai, West Rapti, Bagmati and Kankai drain only 8% area of the country, with large flows during rainy seasons but very low to almost no flows in the dry season. These are water deficit basins. The rest of the nation is drained by Mechi, Kamala and other southern rivers in the Terai. These are extremely seasonal flow rivers with high floods in the summer monsoon and almost no flows during the dry season.



(a)



(b)

Figure 4: Map of (a) Physiographic zones. (Rai et al., 2023), and (b) Schematic of ecological zones along a typical North-South Transect of Nepal. (Source: Nepal et al., 2021)

The large seasonal variation in rivers suggests that the optimum utilization of the water resources requires water harvesting storage or reservoir projects that store annual floods and provide water round the year to required areas. This can be equally true at the local micro-catchment to basin scales where suitable sites exist. Inter-basin diversions are also a strategy to supply water to deficit areas. The Terai basins, especially the areas within the basins of rivers originating from the Mahabharat Ranges or the Siwaliks, comprise of good agricultural lands but scarce water for irrigation for year-round supply due to the seasonal low flows in these basins. These areas are seasonal water deficit basins and require water from storage schemes or inter-basin transfers from surplus basins.

3.3 Groundwater

Nepal has good resources for groundwater in the Terai region, the net total recharge is estimated to be 13 billion cubic meters per year. Groundwater has been used for drinking water and irrigation development, through the use of shallow tube wells (STW), and deep tube wells (DTW). Inner valleys and hill slopes also provide local groundwater that has been used for drinking water, irrigation and industrial usage at places. The Kathmandu Valley groundwater abstraction has exceeded sustainable yield so that it has drastically lowered, drying up natural springs and ponds.

Similar cases have also been reported to dry up hillside springs and water sources in the hills and mountain areas in the Himalayas, where changes in land use patterns reportedly couple with climate change impacts; reducing flows or even drying up springs in (Adhikari, et al., 2021; Shrestha et al., 2017; Tambe et al., 2012.) It is also understood that the change in consumption patterns may have increased water demands in these hill springs and caused over-exploitation. Climate change-related changes in precipitation causes increased intensity, but the reduced number of events of rainfall would reduce the net infiltration to soil profile and recharge of the groundwater. Reduced but intense rain events accelerate runoff and limit subsurface recharge.

Suitable water resource management activities at the local levels need to be implemented to maintain healthy watersheds to arrest erosion, thereby improving water quality as well as arresting nutrient and soil loss, and retarding overland runoff to augment the recharging of groundwater.

3.4 Rainfall Patterns

Figure 5 shows the distribution of mean annual precipitation in Nepal (Arya et al., 2022) and Table 1 shows the precipitation for different rain seasons. The precipitation ranges from less than 200 mm to more than 5000 mm, and the majority of this aggregate takes place during the 4 months (June -September) of monsoon.

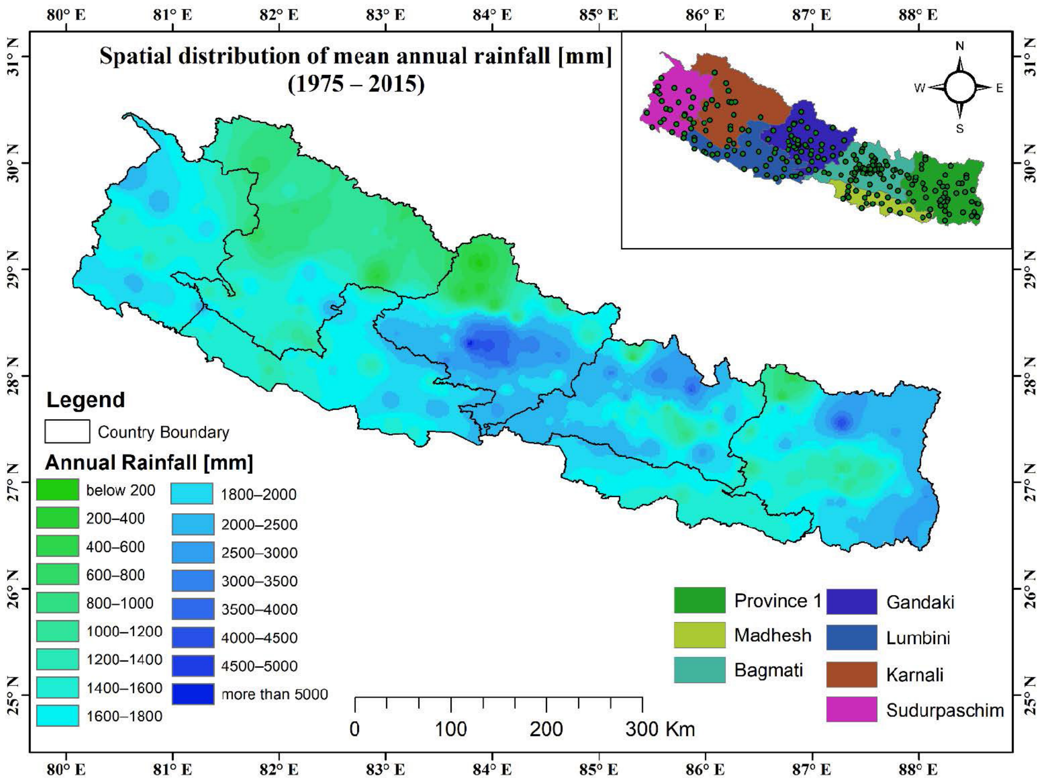


Figure 5: Mean annual precipitation of Nepal (Aryal et al., 2022)

The areas with annual rainfall less than 1200 mm are typical areas in Figure 5 where water harvesting will be feasible given the suitability of other factors like terrain physiography and suitability of climate and soils for agriculture. These areas need water harvesting mechanisms to optimize rainfall collection directly or storing surface runoff and storm flows in suitable locations to allow usage during low or no rain periods

Figures 6 and 7, and Table 1 show the seasonal rainfall distributions which can also be used to assess water harvesting needs. It shows that the bulk of the rainfall, about 76-83%, occurs during the summer monsoon period – four months of June-September. The rest of the eight months is with quite sparse rainfall. Table 1 shows the annual precipitation amounts in mm for different river basins in Nepal and is shown in percentage for monsoon (June-Sept, 4 months) post-monsoon (Oct-Nov, 2 months), winter (Dec-Feb, 3 months), pre-monsoon (Mar-May, 3 months). The last column shows the rainfall for 8 months (Oct-May) and it is seen that this ranges from about 250 mm to 400 mm; approaching the semi-arid rainfall values. Typical water requirements for winter crops is about 250 mm to 700 mm.

Table 1: Mean Annual Precipitation and seasonal distribution for different River Basins in Nepal (basic data obtained from: WECS, 2019 and further analyzed)

River Basins	Total Mean Annual Precipitation	Monsoon (June – Sept)	Post-monsoon (Oct- Nov)	Winter (Dec- Feb)	Pre-monsoon (Mar-May)	Non-monsoon (Oct -May)
	(mm)	4 months (%)	2 months (%)	3 months (%)	3 months (%)	8 months (mm)
Kankai	1998.9	79.6	4.9	1.9	13.6	408.2
Koshi	1666.7	76.6	4.6	3.0	15.7	389.3
Kamala	1628.9	80.1	5.0	1.9	13.0	323.8
Bagmati	1794.9	81.6	4.2	2.3	11.8	330.3
Gandaki	1823.0	78.7	3.9	4.1	13.4	388.9
West Rapti	1586.6	82.8	3.9	4.2	9.1	273.6
Babai	1513.6	83.2	4.1	4.6	8.1	254.5
Karnali	1225.1	75.8	4.2	8.0	12.0	297.1
Mahakali	1924.8	79.2	3.0	6.5	11.3	399.9

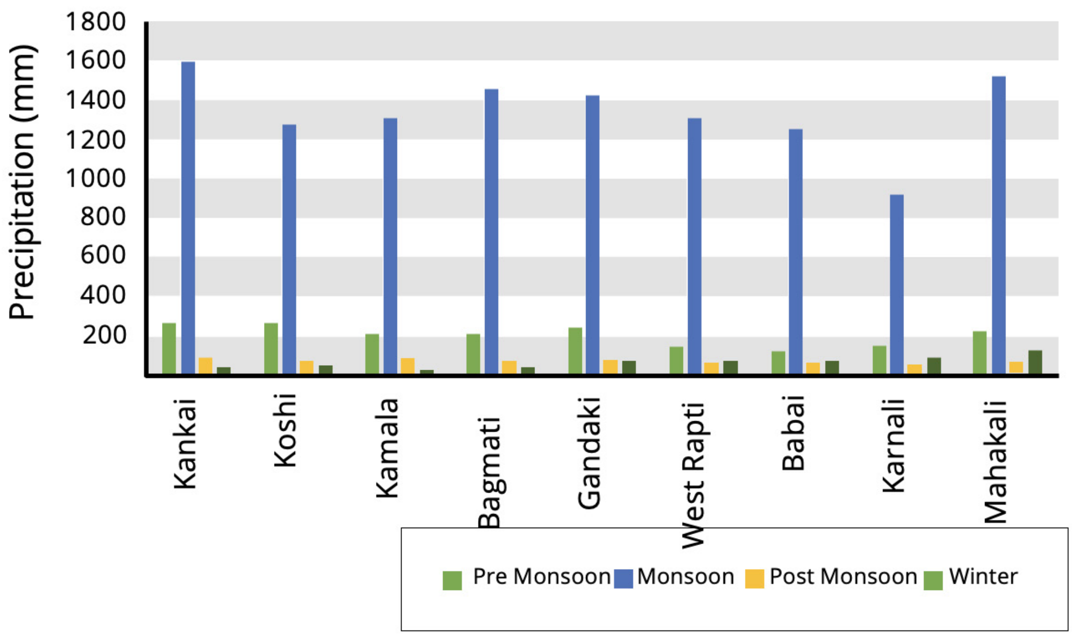


Figure 6: Mean precipitation in different river basins in Nepal for different seasons (basic data obtained from WECS, 2019 and further analyzed)

It is seen that areas with high mean annual precipitation have low values for 8 months of the year ranging from about 400 mm to less than 300 mm. This rainfall depth is less than the potential evapotranspiration requirements for most of the winter crops. This suggests that, we need to cultivate winter crops such as wheat, oilseeds, vegetables, potatoes, sugar cane, etc. are to be cultivated, we need to resort to supplemental irrigation. Supplemental irrigation would be possible only through stored water if water harvesting practices are adopted. Otherwise there would be insufficient water for the crops which would drastically reduce crop productivity. The dry land agriculture only becomes feasible or profitable if there is assured water supply.

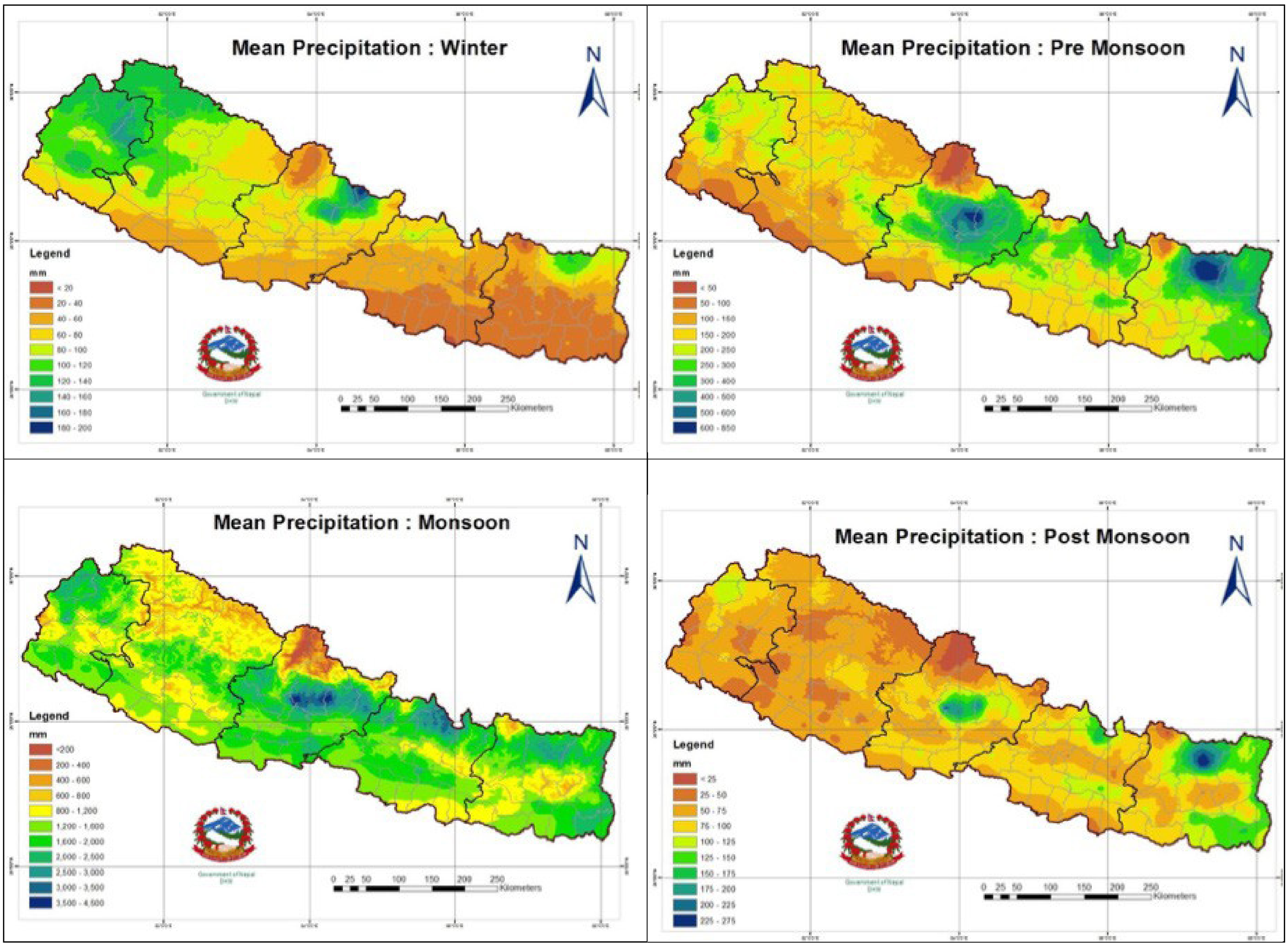


Figure 7: Distribution of mean precipitation for various seasons (Source: DHM, 2015)

3.5 Climate Change Forecasts

The climate change impacts in Nepal related to temperature and precipitation. Sea-level rise does not directly impact Nepal being a landlocked country.

Temperature rise in Nepal is projected to exceed the global average. Nepal is projected to be warmer by 1.2°C–4.2°C by 2080, under the highest emission scenario, RCP8.5, as compared to the baseline period 1986–2005 (CRCP Nepal, 2021). The maximum and minimum temperatures are expected to be increasing at a higher rate than the average temperature.

There exists considerable uncertainty in future precipitation, as the variability is compounded by the influence of El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole (CRCP Nepal, 2021). These two phenomena affect occurrence of intense rainfall as well as droughts in the region. Using Coupled Model Inter-comparison Project Phase 5 (CMIP5) models and the four Representative Concentration Pathways (i.e. RCP2.6, RCP4.5, RCP6.0, and RCP8.5) it estimated that the projected precipitation will decrease in the 2050s and increase for the 2090s (CRCP Nepal, 2021). Nonetheless, occurrence of extreme events will cause intensity of rainfalls to increase.

The latest modeling updates using the CMIP6 and the Shared Socioeconomic Pathways (SSPs), shown by the World Bank's Climate Change Knowledge Portal, show the projected precipitation for 2020-2039, compared to reference period 1995-2014. It is seen that the median values of monthly precipitations for the months of November to March for all SSPs will likely be decreasing (from about 5% to 15%) while the wetter months will be increasing with a smaller amount of about 5%. The drier periods will be drier. For the next time horizon of year 2040-2059, the median monthly precipitations will increase marginally for the wet months of June to October and remain similar for the rest of time compared to the reference period.

The portal outputs also show that the maximum number of consecutive dry days are also expected to increase marginally for the same dry winter periods of November to March. The maximum number of consecutive dry days ranging from 69 days to 79 days.

3.6 Water needed for irrigation and hydropower

These figures and data suggest that for Nepal to enhance food productivity by growing more crops in a year, it is essential that there exist some storage systems that stores water and provide irrigation water. There are severe shortages in rainfall or stream flows in Nepal for winter or spring crops. The aggregate March river flows in Nepal are adequate to provide irrigation only to an area of 750,000 hectares while the irrigable area is 2.265 million hectares (DWRI, 2019), thus requiring additional water to irrigate 1.515 million hectares (equal to 15,150 km^2) if 100% crop coverage is desired even in the dry season.

This suggests, with a preliminary estimate, that about 1,800 million cubic meters storage water would be required just for the single month of March assuming a crop requirement of 0.6 l/s/ha without any provisions for irrigation system losses (rough estimates). This value would be considerably higher if additional spring paddy is cultivated, which is often advocated for enhancing cereal production. Cumulative storage requirements would be further more. This shows that that there is huge storage requirement for increasing cropping intensity and agricultural production in areas that are or could be irrigable. Not practicing water harvesting would lead to seasonal shortages of water, preclude the efficient use of water resources at various scales, enhance aridity and land degradation, and increased vulnerability and risks of climate change impacts.

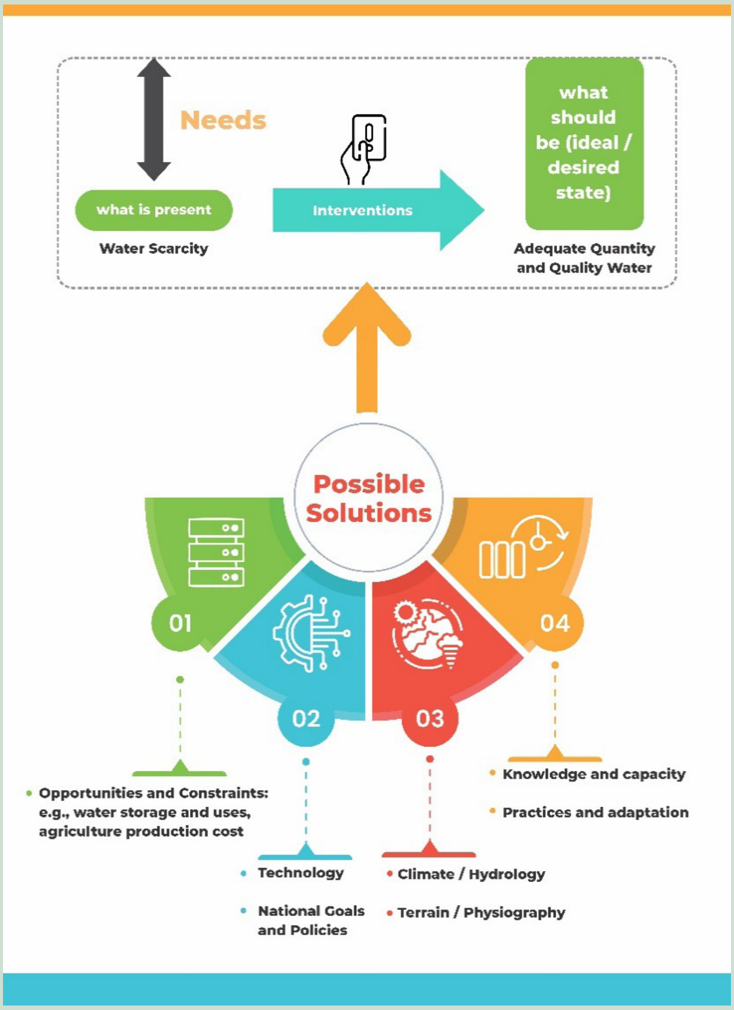
The nation has primarily run-of-the-river hydropower schemes and only one reservoir (storage) hydropower scheme, the Kulekhani Hydropower Project with an installed capacity of 60 MW. This is a 114 m high rockfill dam with a storage volume of 85.3 million cubic meters. The current hydropower mix is primarily runoff the river schemes, with low production during the low flow season in winter. Low winter flow reduces the power generation from the run-of-the-river hydropower plants schemes and jeopardizes electricity supply and the country needs to import electricity from India. Water harvesting structures at larger catchments and basins can help store water providing opportunities for reliable hydropower generation and augment supply of water during low flow periods.

Energy security is a prime objective of Nepal's, and a number of storage and run-of-the-river are in various stages of implementation. The government's approach is stated to be, in principle, the adoption of multipurpose projects that accrue multiple benefits for the nation. Water harvesting can help towards fulfilling this approach.

There are a few storage schemes planned such as Budhigandaki Hydropower Project with a gross storage capacity of 4,467 million cubic meters, and the Dudhkoshi Storage scheme with 1,581 million cubic meters. The nation's goals are not only to be hydro-electricity sovereign, but also plays an important role in meeting its NDC requirements of adopting clean energy and reducing fossil fuel usage. It also looks forward to export electricity to the neighboring countries, offset fossil fuel driven electricity and earn hydro-dollars. To support its road to prosperity. Therefore, a storage system that accumulates monsoon flows and provides opportunities for hydropower generation is a dire necessity. This could be alleviated, to some extent, by water harvesting storage systems that indirectly contribute to increased flows in the rivers or even operate hydropower schemes in different parts of the country.

The benefits, at local scale with constructions of ponds and lakes will also be beneficial to a variety of uses such as for livestock, aquaculture, and recreation as well as preservation or restoration of ecosystems. It must also be recognized that the water harvesting can be useful and needed not only for human-centric developments, but also are equally important in terms of preservation of the ecosystem (Yu et al., 2021), rejuvenation of wetlands and ponds as well as reviving water bodies impacted by human developments and compounded by climate impacts.

Box 1. Application of Criteria for fulfilling water harvesting needs (with reference to the Analytical Framework for Water Harvesting Needs Assessment)



1. There are conducive national policies and goals that promote adoption of water harvesting practices. The technology is suitable for Nepal where there exists rainfall variability and agricultural land availability.
2. Annual rainfall exceeds 700 mm for a large part of the country, whereas the 8 months rainfall falls below 350 mm therefore, seasonal climate and hydrology favors water harvesting.
3. Since there is a very large area that is rain-fed, about 24,756 km^2, there exist more than enough locations with suitable terrain, physiography and soil profile where water harvesting can be practiced and be beneficial.
4. There exists sufficient knowledge within Nepal and knowledge from arid and semi-arid areas

where rainwater harvesting is being practiced on a larger scale, e.g. in India, Bangladesh and even the Sub-Saharan region in Africa, practices and lessons learnt can be adapted.

5. Opportunities with suitable water yielding catchments, storage locations, farming lands crop varieties and cost of implementation is attractive, and it also addresses the national goals of increasing employment as well as adopting green environment friendly initiatives.
6. Various types of solutions can be prescribed depending upon the geographical locations, agroclimatic zones and topographical relief. Spate irrigation in river valleys, gully plugging to slow water flow to retain sediments and moisture, eyebrow terracing with live fencing, micro-basin approach to in-situ runoff capture, cross slope barriers to induce infiltration are already proven practices in Nepal. These, along with good practices around the world, can guide future interventions and provide water harvesting facilities in greater number of locations and a larger aggregate area maximizing benefits, building resilience to climate change impacts and adapting to the threats.

4. GOOD PRACTICES

Water harvesting has been practiced traditionally in Nepal and elsewhere globally throughout history. The practices became more evolved and dominant in the arid and semi-arid regions around the world (Biazin *et al.*, 2012 and Mati, 2012) as farmers needed to adapt to the local climate patterns and agricultural practices evolved.

Terraced farming in Nepal, ponds, *Raj Kulo* systems in the Kathmandu Valley[1], farmer managed irrigation systems that practiced traditional flood harvesting and canal systems. These systems retained water, nutrients and conserved soil; built up in-situ soil moisture or diverted water from water bodies, transferring it inland and feeding water tanks, ponds and groundwater in wells. The traditional irrigation systems, such as the *Rani Jamara Kulariya*[2] or the *Chhattish Mauja* practiced floodwater harvesting, diverting water from rivers into an intricate network of channels and ditches to provide irrigation water to thousands of hectares of land. They had an excellent community institution set up for operation and management of water distribution including maintenance.

The following are some examples of the currently established practices or initiatives on water harvesting in Nepal and beyond.

Dhap Dam, Bagmati River Basin Improvement Project (BRBIP), Nepal

This project was implemented by the Government of Nepal to improve water security and resilience to potential climate change impact in the Bagmati River Basin with the support of the Asian Development Bank (ADB). One of the components of the project included building reservoirs, at Dhap and Nagmati on the Bagmati River, which flows through the Kathmandu Valley, to increase water availability in the basin during the dry season and recharge the Bagmati River downstream to restore the river environment in the Kathmandu valley. The Dhap dam has been completed (Figure 8) and design works for the Nagmati dam is ongoing.


Figure 8: Dhap Dam and reservoir (left) in the head-reaches of Bagmati River and the Concrete Face Rockfill Dam (on right) (Source: DoWRI, GoN).

The 24 m high Dhap dam reservoir at an elevation of 2090 m above mean sea level has a reservoir capacity of 1.2 million cubic meters and extending over an area of 12 hectares. The stored water provides additional water up to 400 liters per second to supplement low river flows during festivals, improve water quality and the riverine environment. The Nagmati dam located further downstream is under design and is expected to further improve water availability in the river during the dry season to raise the river's assimilative capacity. These interventions are carried out in tandem with other activities such as establishing capacity for integrated and participatory river basin management, watershed management, rainwater harvesting and groundwater recharge, improved riverbank environment in urban areas, early-floodwater warning system and establishment of decision support

[1] There were complex networks of water systems in Kathmandu Valley diverting water from streams through *Raj kulos to feed* water fountains (*hitis*), water tanks (*jarū hiti*), ponds (*pukhu*), groundwater wells (tū) and irrigating fertile lands.
[2] These are in fact three different irrigation channels off-taking from Karnali River, traditionally built by the local communities. (Sijapati & Paudel, 2010).

system for integrated river basin planning. The construction of the Dhap dam and the reservoir has also showcased the feasibility of water harvesting for multiple uses in Nepal.

Mega Dang Valley Irrigation Project, Nepal

The Department of Water Resources and Irrigation has been implementing the Mega Dang Valley Project with the primary aim to increase irrigation water availability and aid agricultural production. The Dang Valley is drained by the Babai River and it has one of the lowest annual water availabilities, at 0.89 million m^3/km^2, compared to other basins in Nepal. The project is implementing innovative ways to intercept and store wet season runoff for dry season use across all the streams in the valley. For this purpose, the project has identified some small dams and lowland storage schemes to store water and make it available later when required.

The project activities also include construction of small ponds, maintenance of wetland, rainwater collection, groundwater development, irrigation sprinkler and drip irrigation, flood water storage and utilization to enhance water utilization and resiliency against droughts. Figure 9 below, shows one of the recently completed small earthen dam reservoir storing monsoon excess water and using it later for irrigation and other uses. These systems also recharge the groundwater and help in raising groundwater tables for pumped tube-well irrigation.

Figure 9: Small earthen dam for water storage in Dang Valley storing flood waters primarily for irrigation. (source: D Bhatta, DoWRI)

Ahar and Pyne System South Bihar/ Jharkhand, India,

Ahar Pyne system is an indigenous irrigation technology of South-Bihar, Jharkhand and adjacent areas in India. The topography of these relatively dry areas with seasonal rainfall is gently sloping so the Ahar - a three-sided earthen embankment 1-2 m in height is fed by a Pyne – an earthen ditch or channel that would collect water from flooded rivers, streams or capture surface runoff from hilly areas. These system of ahars and pynes can also feed into the next set of ahars and pynes covering large extents of farmland and villages. These systems would even tap the streams completely of their flowing water and utilize all of it for agriculture purposes. Sometimes the emptied ahars would provide suitable moisture for winter crops. The extensive system thus diverted, stored water including groundwater recharge, flood protection in downstream areas apart from the irrigation benefits.

Figure 10: A Pyne conveying water to farms (left source: India Water Portal) and a revived system running full capacity. (right, source: WHH)

These systems were once a vibrant water harvesting and irrigation system, that provided irrigation to almost 35% of the 2.5 million hectares of cropped area in Southern Bihar in the early 20th century. Some of the bigger Pynes were even 20-30 km long, fed a number of branches and irrigated over 100 villages with an intricate system of ahars. The command area ranged from 400 ha to a few hectares. Ahars and Pynes were collectively maintained by the community, provided relief from drought to rain-fed areas and provided critical irrigation facility even to the early winter crops. These systems fell into dis-repair with the advent of state interventions in irrigation, changes in land-tenure systems and decline of community institution managing these systems.

In Palamu district of Jharkhand, India, Sampurna Gram Vikas Kendra, Jharkhand, India with support from Welthungerhilfe (WHH) and nominal funding from EU communities worked providing free labor to help revive or build 22 ahar-pyne systems of 15 villages to provide irrigation water to the community. Every 2-3 years the paddy crop would fail due to droughts or scant rainfall, but after the revival of the systems the farmers are getting reliable irrigation in about 485 ha of land and growing paddy without risk of crop failure. The harvested water is even available for irrigating some winter crops and increased productivity. Some of the ahars are used for fisheries, the farmers have started crop diversification into vegetables and cash crops which dramatically enhanced their incomes and livelihoods. Community engagement has increased with off-spin benefits in general awareness and rise in education, health, empowerment and climate resilience. Even the groundwater level has risen by 1-2 feet in 11 villages enhancing access to drinking water.

In the midland regions which feed these pynes, water and soil conservation activities have been adopted. One remarkable adoption is allocating 5% of the area of farm plots to make 8-10 feet deep pits to retain water which provide emergency access to irrigation water during dry spells, manage sediments and build overall soil moisture.

Cascade Tank System, Sri Lanka

In the dry zone of Sri Lanka, semi-arid north-central region of the island, reservoirs or tanks have served in collection, storage and distribution of rainfall and runoff, and provide irrigation water for cultivation of paddy for more than 2000 years. These systems consist of a series of interconnected tanks or reservoirs that are built on different elevations along the valleys. Water flows from higher tanks to lower ones through a series of channels or canals, allowing for the controlled distribution of water to crops in fields.

Figure 11: Cascade Tank System in Sri Lanka with a sketch showing tanks at different levels (left) and a schematic diagram of the system compromising of sequential tanks and paddy fields. (source: adapted from IUCN, 2015 as cited in Melles and Perera, 2020)

The cascading tank systems are known to have stood up to the climatic variations over centuries and demonstrated their potential as a tool for adapting to future climate change in Sri Lanka's dry zone and in other similar regions in other countries. Inadequate maintenance, poor management, or changes in land use patterns such as deforestation and growing population pressures may have put many of these systems defunct and neglected. Their restoration is now being actively pursued as a key to climate change adaptation and sustainable livelihoods for rural communities[3].

It must be noted that this cascading tank system are hydrologically interconnected series of tanks situated within the micro (or meso) catchments in a semi-arid zone landscape or sub-humid environments with seasonal rainfall. Mostly these exist on non-perennial streams. The system components include upland dry lands generating run-off that flows along streams and marshy wetlands with grass and reeds trapping sediments and pollutants into small tanks and water holes that trap sediments, provide for wild life and store and recharge groundwater which augments the tanks at the lower reaches. These tanks further release water through earthen spillways or sluices into farms and drain again into streams and further into other tanks.

The systems store, convey, use and reuse water enhancing water security for cultivation of paddy and other crops as well as multitude of community activities. This is an integrated system that addresses both water quality and quantity for semi-arid areas and incorporates nature-based solutions ensuring its sustainability, provided that it is supported by good management actions of the community.

Water Harvesting -Guidelines to Good Practices

This guideline to good practices (Mekdaschi-Studer & Liniger, 2013) offers a practical reference guide on good practices in water harvesting from around the world. The document describes different types of harvesting including an overview of the application of water harvesting such as floodwater harvesting, macro-catchment harvesting on a larger scale and micro-catchment harvesting with examples of these options in a book form. The different forms and options of water harvesting are presented with diagrams and are mostly flexible and can be adjusted to local context with due regard to climate, topography and soil horizons.

One of the important contents is the description on suitability and constraints of water harvesting based on applicability and the type of water harvesting classification. The guideline targets local and regional planners, watershed management consultants, government and project officials.

---

[3] The World Bank has been aiding in rehabilitating of some of these systems through the Climate Smart Irrigated Agriculture Project in Sri Lanka (P163742) and Sri Lanka Integrated Watershed and Water Resources Management Project (P166865) as this holds great promise in enhancing productivity and livelihood of the rural agrarian communities addressing water scarcity issues, adapting to and building resilience to climate change.

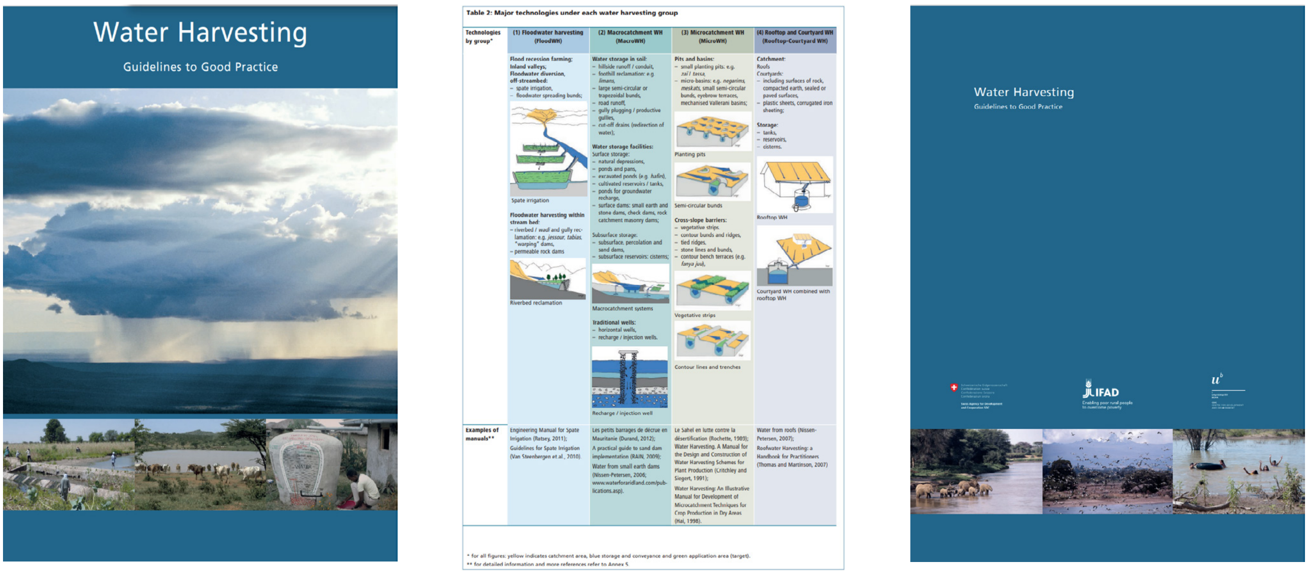


Figure 12: The Water Harvesting: Guidelines to Good Practice provides a comprehensive information on water harvesting around the world (Source: Mekdaschi-Studer & Liniger, 2013)

The document provides .In Part 1 of the guidelines the concept of water harvesting is introduced re introduced and a working definition proposed. The guideline further classifies the various systems into floodwater harvesting, macro-catchment harvesting as well as micro-catchment attempts. It is followed by an assessment of suitability, adoption and upscaling, and reflections on planning of water harvesting. In Part 2, an overview of four water harvesting classifications is presented and, for each classification, a selection of good practices in the form of case studies is included. These case studies are presented in the systematic, consistent and standardized format developed by the World Overview of Conservation Approaches and Technologies (WOCAT).

Additional Guidelines

The WFP and the FAO are both working in the areas of water harvesting water conservation and management. The field practitioners' guides (No. 1 and 2) describe various proven approaches from around the world (WFP, 2018). The Guide no. 1 discusses the adoption of water harvesting for rangeland rehabilitation, and goes on describe various methods of sustainable irrigation technologies for the arid zones. The second guide "Water Harvesting in Practice: Towards Building Resilient Livelihoods in Semi-Arid Zones" field practitioners guide no. 2 describes in clear details the runoff farming for crop productions such as Zai pits, lined farm ponds, water pans, and the sand and subsurface dams for water storage. The document attempts to follow similar descriptions on explaining the benefits, limitations and processes in implementing the desired interventions.

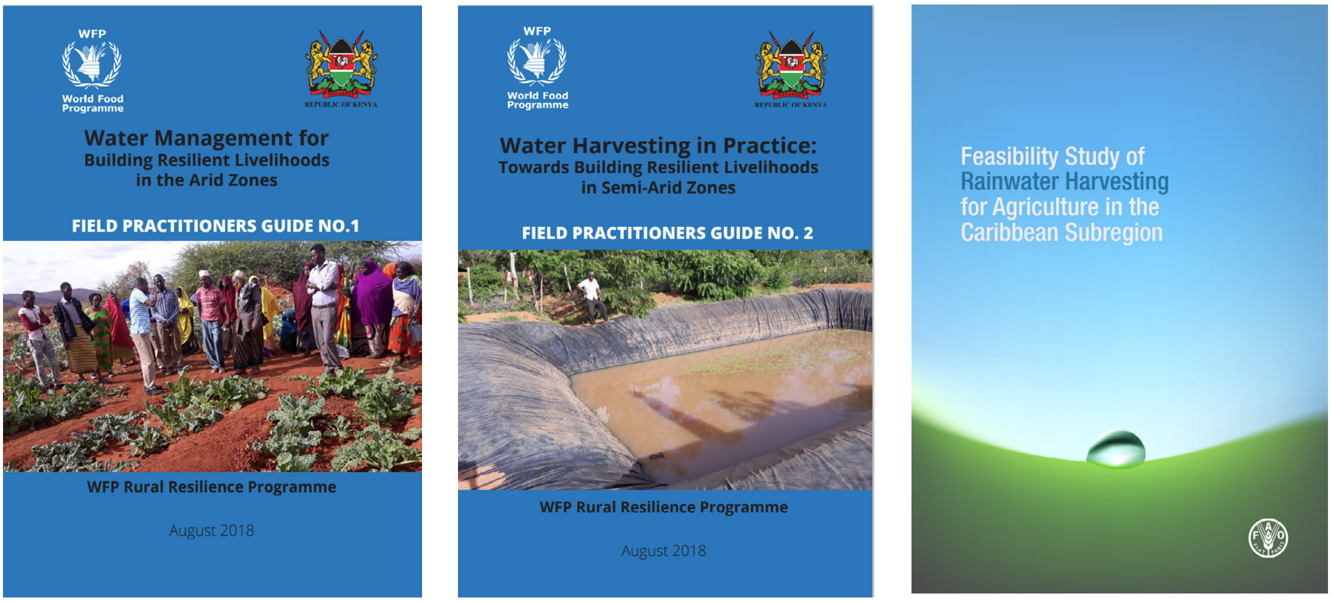


Figure 13: The Field practitioners guides and a feasibility study on Rainwater Harvesting (WFP, 2018 and FAO, 2014)

The FAO publication describes the feasibility study of rainwater harvesting for agriculture in the Caribbean subregion (FAO, 2014). These documents are simple to read and understand with illustrations. This document is an output of a study of the feasibility and potential benefits of rainwater harvesting undertaken within the scope of the Land and Water Programme of the FAO Sub regional Office in the Caribbean. The document describes the critical factors for rainwater harvesting for agriculture, potential for rainwater harvesting for agriculture, recommendations for rainwater harvesting systems for agriculture in the Caribbean subregion including design rainfall parameters for rainwater harvesting

5. CONCLUSION

Climate change impacts in Nepal, as well as around the globe, primarily manifest through water; with changes in the precipitation pattern altering the availability of water (Pörtner, et al., 2022). Impacts can be delayed onset of the rainy season or extended periods of drought or the period between successive rain events which can create water stress and create additional competition between different use. The average annual precipitation ranges from less than 200 mm to more than 5000 mm with the average value estimated to be 1830 mm (MOFE, 2019) with a very high spatial variability in rainfall. The wet monsoon season with four months of heavy rain and eight months of sparse rains introduces extreme temporal variations.

Agricultural sector is the largest user of water in the country stated to consume about 97% of the total 15 billion cubic meters of consumption (WECS, 2011). The data is old, but new information is not available but the consumption ratio would be similar. Agriculture is central to the national economy contributing to 21% of GDP in 2019 and providing employment to 64 % of the population (World Development Indicators, n.d.). Agriculture is critical for poverty reduction. A large portion of agriculture land about 24,756 km^2 is purely rain-fed land with no irrigation support. Increasing irrigation facility to a portion of these areas would help in raising agricultural production. Not only the productivity of a single crop increases, but also the cropping intensity also increases if irrigation facility is available round the year.

Water harvesting becomes feasible as there are conducive policies, rainfall variability leading to in-situ water scarcity and the existence of storage demand. The rainfed areas provide opportunities. The technical know-how and the capacity to implement water harvesting systems is also adequately present in the country. The crop variety, cropping yield and potential benefits of agricultural production are also existing in Nepal.

Furthermore, the climatic conditions do not require the storage to be extended beyond the dry season or the year and thus are relatively smaller in size, in comparison to multi-year storage dams required in other countries around the world.

The government's policies also direct people towards adopting water storage, inter-basin transfers, conservation ponds, water collection ponds, water recharge systems, and water reservoirs to augment water and food and energy securities at multiple scales. Nepal's 25-year long term economic vision of prosperity, the current (15^{th}) 5-Year Plan 2019-2024 (NPC, 2020), and the Sustainable Development Goals Status and Roadmap 2016–30 (GON, 2017) coupled with Water Resources Policy 2020, National Adaptation Plan 2021 provide necessary direction for implementing a water harvesting strategy. These policies need to be made more action oriented backed up by suitable budgetary outlays with programs and projects. Capacity building at all levels, federal, provincial and local governments should be carried out in tandem with professional inputs in identifying locations, designs, specifications and prototype developments.

The following points summarizes the needs, drawing upon the discussions made in the previous chapters, of a water harvesting or storage system.

Water Demand and Aspirations: Demand for water exists in Nepal due to the extended dry season, with low rainfall as well as the need to enhance water, food and energy securities. Communities are rather possessive of water and therefore the aspirations of the society will need to be scrutinized assessing the convictions and safeguarding our own environment and society.

Variability in precipitation: Extreme variability in precipitation creates water stress as well as provides an opportunity to adopt water harvesting so that the water can be stored and used as required.

Natural storage locations: It would be important that the topography and geological analyses yield suitable locations for storage. These include river valleys, pans, existing lakes and reservoirs, etc., which are available in Nepal.

Vulnerability to floods and droughts: The greater the vulnerability and risks of extremes of floods or droughts, the higher is the possibility of agreeing to a water harvesting or storage option. Storage options also retard floods, attenuate peaks and provide some relief to downstream areas exposed to floods. With climate change impacting severity of hydrological phenomena, the question of whether to build or not build storage reservoir may not be pertinent at all, the rhetoric may shift to what size of systems are required.

Capacity building for water harvesting: The capacity at various government levels to recognize, sensitize, plan, design, implement, construct, operate and monitor water harvesting systems at various scales is urgently required.

Policy Reference:

This Water Harvesting Needs Assessment in Nepal addresses the opportunities and directions set by the National Water Plan 2005, National Water Resources Policy 2020, the National Adaptation Plan 2021 and the National Climate Change Policy (2019). This document supports these policies.

Responsible Agencies: the following are the government agencies and stakeholders that can make use of this advisory document on Water Harvesting Needs Assessment in Nepal.

1. Ministry of Energy, Water Resources and Irrigation
2. Department of Water resources and Irrigation
3. Water and Energy Commission Secretariat
4. Provincial Ministries related to Water Resources and Irrigation
5. Local Municipalities

Recommendations for policy implementation

The existing policies, though proactive in terms of adapting to climate change and setting the context, have still not been able to excite and implement investments in watershed harvesting. The policies at the provincial and local municipalities level are either absent or lack enough prominence to be translated to practice. Watershed harvesting practices transect across different sectoral areas of land use and planning, forest and soil conservation, hydrology and water resources as well as the fields of water supply, agriculture and energy. These policies are in silos, addressing and concerned within their domains. These seldom complement efforts in other sectors which may be impacting their own spheres of influence and jurisdiction.

It is needed that the policies and directives be made more visible and followed with adequate fiscal outlays and programs to implement them. The need to recognize cross-sectoral role of watersheds and water harvesting systems need to be recognized and promoted by all sectoral policies. There are also needs to enlarge and strengthen capacity and develop technical skills to identify suitable locations, implement schemes at all levels of governments.

Governments are urged to create a water-secure society as one of the top priorities across the globe (UN-Water, 2013). Water harvesting is expected to provide that security and is recommended in Nepal's policy recommendations such as the National Water Plan 2005 (WECS, 2005), National Adaptation Plan (GoN, 2021) or national planning documents.

A careful analysis of storage options, sizing and location needs to be done to minimize the risks mentioned earlier as often the value of controlled and in-hand water will outweigh the costs and risks incurred with suitable planning and design. Water harvesting and storage are essential for Nepal to address its temporal and seasonal water shortages and year-round economic water scarcity.

ADPC recognizes the high priorities accorded to enhance water security by the Government of Nepal; and identifies water harvesting as a suitable strategy for it. This assessment will be used to inform and assist WECS and MoEWRI, as well as the latter's subsidiary Department of Water Resources and Irrigation (DWRI), with policy recommendations under the CARE for South Asia Project in medium term time scale. It is recommended, as a short-term target (by end of 2024), that the Government of Nepal, through its development partners or on its own, develop a water harvesting strategy for Nepal to address seasonal and spatial water scarcity in Nepal leading to an action plan for implementing water harvesting practices in Nepal.

Water harvesting should be taken up as an integral part of climate-smart agriculture, providing opportunities for attracting private investment in small-scale water storage interventions building in adaptation and resilience as well as in improving the resilience of the poor and vulnerable on a continuous rolling basis, from 2025 to 2045 to help achieve national goals of prosperity. The provincial governments and DWRI should take up the lead role in implementing the water harvesting strategy gradually building up the capabilities of the local governments to own and operate local watershed interventions.

This assessment also leads to the identification of water harvesting as an important topic to be included in the capacity building program under ADPC's CARE for South Asia Project. ADPC will, as an immediate follow up to this assessment, under CARE for South Asia, is designing suitable capacity building activities in water harvesting and will include it in the capacity building program it is carrying out next and planned to be completed by December 2024. This will contribute to developing the capacity to address climate change impacts in its programs and developing a resilient water sector for Nepal.

The ADPC, as a mandated organization working in the disaster and preparedness will continue to support Nepal in capacity building, enabling capabilities to address climate change and alleviate water stress and security leveraging its expertise and networking with international organizations.

The above assessment introduces the concept of water harvesting in tackling water scarcity and demonstrates that water harvesting is an attractive option for Nepal. It increases the amount of water available per unit cropping area, helps reduce drought impacts and enables beneficial use of run-off water thereby increasing the adaptive capability and resiliency of the water sector to impacts of climate change.

6. REFERENCES

Adhikari, S., Gurung, A., Chauhan, R., Rijal, D., Dongol, B. S., Aryal, D., & Talchabhadel, R. (2021). Status of springs in mountain watershed of western Nepal. *Water Policy, 23*(1), 142-156.

Adler, C., Huggel, C., Orlove, B., & Nolin, A. (2019). Climate change in the mountain cryosphere: impacts and responses. *Regional Environmental Change, 19*(5), 1225-1228.

Aryal, A.; Maharjan, M.; Talchabhadel, R.; Thapa, B.R. Characterizing Meteorological Droughts in Nepal: A Comparative Analysis of Standardized Precipitation Index and Rainfall Anomaly Index. Earth 2022, 3, 409–432. https://doi.org/10.3390/earth3010025

Biazin, B., Sterk, G., Temesgen, M., Abdulkedir, A., & Stroosnijder, L. (2012). Rainwater harvesting and management in rainfed agricultural systems in sub-Saharan Africa–a review. Physics and Chemistry of the Earth, Parts A/B/C, 47, 139-151.

CBS. (2012). *National Population and Housing Census 2011* (National Report). Central Bureau of Statistics, National Planning Commission, Government of Nepal, Kathmandu.

CBS. (2020). *Nepal in Figures 2020.* Central Bureau of Statistics, National Planning Commission, Government of Nepal, Kathmandu.

CBS. (2021). Preliminary Report of National Population Census 2021, Central Bureau of Statistics, National Planning Commission, Government of Nepal, Kathmandu.

Chaturvedi, S., Cheong, T. S., Luo, Y., Singh, C., & Shaw, R. (2022). IPCC Sixth Assessment Report (AR6): Climate Change 2022-Impacts, Adaptation and Vulnerability: Regional Factsheet Asia.

CRCP Nepal (2021): Climate Risk Country Profile: Nepal. The World Bank Group and the Asian Development Bank.

Critchley, W., & Scheierling, S. M. (2012). Water harvesting for crop production in Sub-Saharan Africa. Water Harvesting in Sub-Saharan Africa, 10.

Critchley, W., Siegert, K., Chapman, C., & Finket, M. (2013). Water harvesting: A manual for the design and construction of water harvesting schemes for plant production. Scientific Publishers.

DHM. (2015) *Study Report on Climate and Climatic Variation over Nepal,* Final Report prepared by Nepal Hydrological and Meteorological Research Centre and Consultancy Pvt. Ltd., Government of Nepal

DHM. (2017). Observed Climate Trend Analysis in the Districts and Physiographic Zones of Nepal (1971-2014). Department of Hydrology and Meteorology, Ministry of Population and Environment, Government of Nepal.

DWRI. (2019). *Irrigation Master Plan Preparation through Integrated River Basin Planning.* Water Resources Project Preparatory Facility, Department of Water Resources and Irrigation, Ministry of Energy, Water Resources and Irrigation, Nepal (accessed from website: https://dwri.gov.np on 19 September, 2021)

FAO, 2014. Feasibility *Study of Rainwater Harvesting for agriculture in the Caribbean Subregion*, available at https://www.fao.org/3/bq747e/bq747e.pdf

Garg, K. K., Anantha, K. H., Venkataradha, A., Dixit, S., Singh, R., & Ragab, R. (2021). Impact of rainwater harvesting on hydrological processes in a fragile watershed of South Asia. Groundwater, 59(6), 839-855.

Glendenning, C. J., Van Ogtrop, F. F., Mishra, A. K., & Vervoort, R. W. (2012). Balancing watershed and local scale impacts of rain water harvesting in India—A review. *Agricultural Water Management*, 107, 1-13.

GoN, (2021). *National Adaptation Plan 2021 -2050: Summary for Policy Makers*. Ministry of Forest and Environment, Government of Nepal.

GoN. (2017). *Sustainable Development Goals Status and Roadmap 2016–2030*. Kathmandu, National Planning Commission, Government of Nepal.

IMP. (2019). *Irrigation Master Plan Preparation through Integrated River Basin Planning*. Water Resources Project Preparatory Facility, Department of Water Resources and Irrigation, Ministry of Energy, Water Resources and Irrigation, Nepal

Karki, R., ul Hasson, S., Schickhoff, u., Scholten, T. & Bohner, J. (2017). Rising Precipitation learned and the way forward. Climate, 5(1), 4. http://dx.doi.org/10.3390/cli5010004

Kattel, R.R. and Nepal, M. (2022). Rainwater Harvesting and Rural Livelihoods in Nepal. In: Haque, A.K.E., Mukhopadhyay, P., Nepal, M., Shammin, M.R. (eds) *Climate Change and Community Resilience*. Springer, Singapore.

Mati, B.M. (2012). *Best Practices for Rainwater Harvesting from Open Surfaces with Storage in Structures*. Training Manual 2. NBI/NELSAP - Regional Agricultural and Trade Programme (RATP), Bujumbura, Burundi.

Mekdaschi-Studer, R. and Liniger, H. 2013. *Water Harvesting: Guidelines to Good Practice*. Centre for Development and Environment (CDE), Bern; Rainwater Harvesting Implementation Network (RAIN), Amsterdam; MetaMeta, Wageningen; The International Fund for Agricultural Development (IFAD), Rome.

Melles, G. and Perera, E.D., 2020. Resilience thinking and strategies to reclaim sustainable rural livelihoods: Cascade Tank-Village System (CTVS) in Sri Lanka. Challenges, 11(2), p.27.

MOEWRI, 2020. National Water Resources Policy, Government of Nepal, Singha Durbar, Kathmandu

MoFE, 2019. *Climate change scenarios for Nepal for National Adaptation Plan.* (NAP). Ministry of Forests and Environment, Kathmandu

MoFE. (2021). *Vulnerability and Risk Assessment and Identifying Adaptation Options in the Water Resources and Energy in Nepal.* Ministry of Forests and Environment, Government of Nepal. Kathmandu, Nepal

Molden, D. (2013).*Water for food water for life: A comprehensive assessment of water management in agriculture.* Routledge.

Molden, D., Vithanage, M., De Fraiture, C., Faures, J. M., Gordon, L., Molle, F., & Peden, D. (2011). 4.21-Water availability and its use in agriculture. Treatise on Water Science. Elsevier, Oxford, 707-732.

Mondal, S. K., Huang, J., Wang, Y., Su, B., Zhai, J., Tao, H., ... & Jiang, T. (2021). Doubling of the population exposed to drought over South Asia: CMIP6 multi-model-based analysis. Science of The Total Environment, 771, 145186.

Nepal, S., Neupane, N., Belbase, D., Pandey, V. P., & Mukherji, A. (2021). Achieving water security in Nepal through unravelling the water-energy-agriculture nexus. International Journal of Water Resources Development, 37(1), 67-93.

NPC, 2020. The fifteenth five-year plan (Fiscal Year 2019/20-2023/24), Government of Nepal, National Planning Commission, Singhadurbar, Kathmandu, Nepal.

Oweis, T. Y. (2017). Rainwater harvesting for restoring degraded dry agro-pastoral ecosystems: a conceptual review of opportunities and constraints in a changing climate. Environmental Reviews, 25(2), 135-149.

Panella, T., Fernandez Illescas, C., Cardascia, S., van Beek, E., Guthrie, L., Hearne, D., & Leckie, H. (2020). *Asian water development outlook 2020: advancing water security across Asia and the pacific,* Asian Development Bank, Manila, Philippines.

Pavelic, P., Brindha, K., Amarnath, G., Eriyagama, N., Muthuwatta, L., Smakhtin, V., ... & Kant, L. (2015). Controlling floods and droughts through underground storage: From concept to pilot implementation in the Ganges River Basin (Vol. 165). International Water Management Institute (IWMI).

Pörtner, H. O., Roberts, D. C., Adams, H., Adler, C., Aldunce, P., Ali, E., ... & Ibrahim, Z. Z. (2022). *Climate change 2022: impacts, adaptation and vulnerability*, IPCC AR6.

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

Rahaman, M. F., Jahan, C. S., & Mazumder, Q. H. (2019). Rainwater harvesting: practiced potential for integrated water resource management in drought-prone Barind tract, Bangladesh. *Groundwater for Sustainable Development*, *9*, 100267.

Rai, Mohan Kumar, Basanta Paudel, Yili Zhang, Pashupati Nepal, Narendra Raj Khanal, Linshan Liu, and Raju Rai. 2023. "Appraisal of Empirical Studies on Land-Use and Land-Cover Changes and Their Impact on Ecosystem Services in Nepal Himalaya" Sustainability 15, no. 9: 7134. https://doi.org/10.3390/su15097134.

Rockström, J., Karlberg, L., Wani, S. P., Barron, J., Hatibu, N., Oweis, T., ... & Qiang, Z. (2010). Managing water in rainfed agriculture—the need for a paradigm shift. Agricultural Water Management, 97(4), 543-550.

Sharma, A., & Goyal, M. K. (2020). Assessment of the changes in precipitation and temperature in Teesta River basin in Indian Himalayan Region under climate change. Atmospheric Research, 231, 104670.

Sharma, L., & Ray, C. (2011). A combined RBF and ASR system for providing drinking water in water scarce areas. In Riverbank Filtration for Water Security in Desert Countries (pp. 29-49). Springer, Dordrecht.

Sijapati, S. and Paudel, T., 2010. Participatory irrigation management: Lessons to learn from FMIS. In *National Irrigation Seminar-Challenges in Irrigation Development and Management.* Proceedings National Irrigation Seminar Challenges in Irrigation Development and Management (11-12 July, 2010). System Management and Training Division, Department of Irrigation, Jawalkhel, Lalitpur. (pp. 118-125).

Subedi, A., Kalauni, D., Khadka, R., & Kattel, R. R., & Yildiz, F. (Reviewing editor). (2020) Assessment of role of water harvesting technology in vegetable-based income diversification in Palpa district, Nepal, Cogent Food & Agriculture, 6:1, DOI: 10.1080/23311932.2020.1758374

Sundaravadivel, M. (2001). Concepts and Practices for Rainwater Harvesting. Resource Recycling Series RERES/5/2001-2, Central Pollution Control Board, Ministry of Environment and Forest, Government of India.

Tambe, S., Kharel, G., Arrawatia, M. L., Kulkarni, H., Mahamuni, K., & Ganeriwala, A. K. (2012). Reviving dying springs: climate change adaptation experiments from the Sikkim Himalaya. *Mountain Research and Development,* 32(1), 62-72.

Trenberth, K. E. (2011). Changes in precipitation with climate change. *Climate research,* 47(1-2), 123-138.

Umazano, AM, Adema, EO, & Aimar, SB (2004). Tajamares: an alternative technology for the arid-semiarid zone of La Pampa. https://ri.conicet.gov.ar/handle/11336/82004 retrieved 13 Jan 2023.

UN Water (2013). What is water security. Infographic: available at: https://www. unwater. org/publications/water-security-infographic/(last access: 4 March 2021).

WB and ADB., (2021). *Climate Risk Country Profile: Nepal (2021):* The World Bank Group and the Asian Development Bank.

WECS, (2011). Water Resources of Nepal in the Context of Climate Change. Water and Energy Commission Secretariat, Kathmandu, Nepal.

WECS. (2005). National Water Plan., Water and Energy Commission Secretariat, Kathmandu

WECS., (2011). Water Resources of Nepal in the Context of Climate Change. Water and Energy Commission Secretariat, Kathmandu, Nepal.

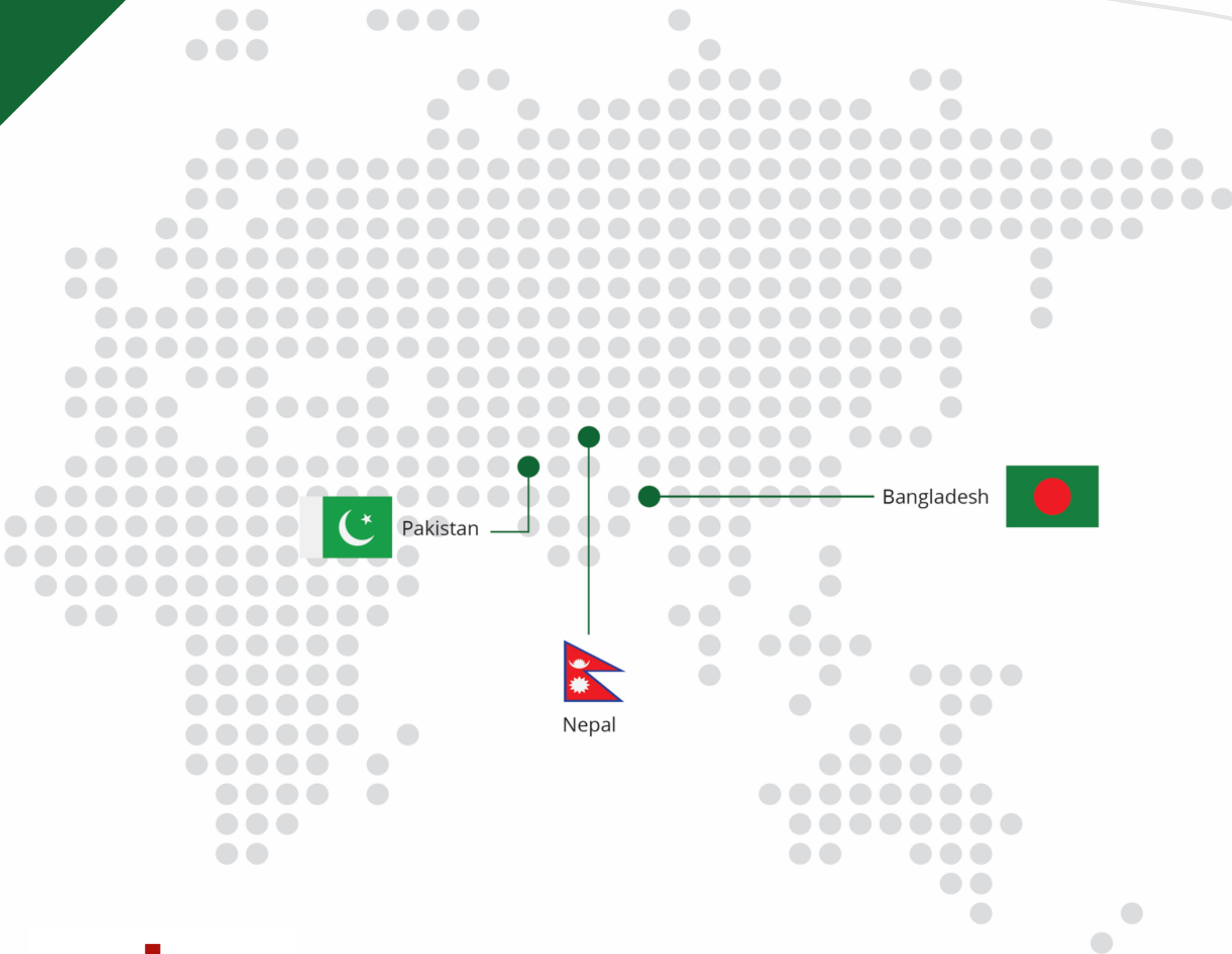
WFP, 2018. Water Harvesting in Practice: Towards Building Resilient Livelihoods in Semi-Arid Zones. Field Practitioners Guide No. 2. Rural Resilience Programme, World Food Programme, Nairobi.

WOCAT. (n.d.) Glossary. World Overview of Conservation Approaches and Technologies, (WOCAT), Retrieved April 25, 2022, from https://www.wocat.net/en/glossary

World Bank Group, (2022). Nepal Country Climate and Development Report. CCDR Series. World Bank, Washington, DC. https://openknowledge.worldbank.org/handle/10986/38012

World Development Indicators, (n.d.). accessed July 2022, https://data.worldbank.org/indicator

Yu, W., Rex, W., McCartney, M., Uhlenbrook, S., von Gnechten, R., & Priscoli, J. D. (2021). *Storing water: a new integrated approach for resilient development* (Vol. 13). Stockholm, Sweden: Global Water Partnership (GWP) Colombo, Sri Lanka; International Water Management Institute (IWMI)



Asian Disaster Preparedness Center
SM Tower, 24th Floor, 979/66-70 Paholyothin Road, Phayathai, Bangkok 10400 Thailand

Tel: +66 2 298 0681-92
Fax: +66 2 298 0012
Email: adpc@adpc.net

www.adpc.net
Asian Disaster Preparedness Center - ADPC
@ADPCnet
Asian Disaster Preparedness Center - ADPC