



TRIBHUVAN UNIVERSITY
INSTITUTE OF ENGINEERING
PULCHOWK CAMPUS

Thesis No: 075MSCCD002

**ASSESSING THE POTENTIALITY OF RAINWATER
HARVESTING VIA ZONING IN THE CORE CITY LIMITS OF
THE KATHMANDU METROPOLITAN CITY**

BY

ANKITA SINGH
075MSCCD002

A THESIS

SUBMITTED TO THE DEPARTMENT OF APPLIED SCIENCES AND
CHEMICAL ENGINEERING
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR
THE DEGREE OF MASTERS IN SCIENCE IN
CLIMATE CHANGE AND DEVELOPMENT

DEPARTMENT OF APPLIED SCIENCES AND CHEMICAL
ENGINEERING
PULCHOWK CAMPUS, INSTITUTE OF ENGINEERING
TRIBHUVAN UNIVERSITY
NEPAL

SEPTEMBER 2021

COPYRIGHT

The author has agreed that the library, Department of Applied Sciences and Chemical Engineering, Pulchowk Campus, Institute of Engineering may make this thesis freely available for inspection. Moreover, the author has agreed that permission for extensive copying of this thesis for scholarly purpose may be granted by the professor(s) who supervised the work recorded herein or, in their absence, by the Head of the Department wherein the thesis was done. It is understood that the recognition will be given to the author of this thesis and to the Department of Applied Sciences and Chemical Engineering, Pulchowk Campus, and Institute of Engineering in any use of the material of this thesis. Copying or publication or the other use of this thesis for financial gain without approval of the Department of Applied Sciences and Chemical Engineering, Pulchowk Campus, Institute of Engineering and author's written permission is prohibited. Request for permission to copy or to make any other use of the material in this thesis in whole or in part should be addressed to:

Head
Department of Applied Sciences and Chemical Engineering
Institute of Engineering
Pulchowk Campus
Lalitpur, Nepal

CERTIFICATE

This is to certify that the work contained in this thesis entitled “ASSESSING THE POTENTIAL OF RAINWATER HARVESTING VIA ZONING IN THE CORE CITY LIMITS OF THE KATHMANDU METROPOLITAN CITY”, in partial fulfillment of the requirement for the degree of Master of Science in Climate Change and Development, as a record of research work, has been carried out by Ms. Ankita Singh (075MScCCD002) under my supervision and guidance in the Institute of Engineering, Pulchowk Campus, Lalitpur, Nepal. The work embodied in this thesis has not been submitted elsewhere for degree.

Supervisor

Assistant Prof. Neeraj Adhikari
Department of Mechanical
and Aerospace Engineering
IOE, Pulchowk Campus

Program Coordinator

Prof. Dr. Khem Narayan Paudyal
Department of Applied Sciences
and Chemical Engineering
IOE, Pulchowk Campus

Committee Chairperson

Prof. Dr. Ram Kumar Sharma
Head of Department
Department of Applied Sciences
and Chemical Engineering
IOE, Pulchowk Campus

External Examiner

Assoc. Prof. Dr. Rajeshwar Man Shrestha
Department of Applied Sciences
and Chemical Engineering
IOE, Pulchowk Campus

DECLARATION

I hereby declare that the thesis entitled “Assessing the potentiality of rainwater harvesting in the core city limits of the Kathmandu metropolitan city” has not been previously accepted in substance for any degree and is not being concurrently submitted in candidature for any degree. I state that this thesis is the result of my independent work/investigation, except where otherwise stated. I, hereby, give consent for my thesis, if accepted, to be available for photocopying and understand that any reference to or quotation from my thesis will receive an acknowledgement.

Ankita Singh
075/MSCCD/002
2021

ABSTRACT

Rapid and haphazard urbanization, alarming population growth, and climate change are causing a huge stress in water management in Kathmandu Metropolitan City (KMC). Without proper alternative source of water supply, and the time and again failure of Melamchi water Supply Project, the demand and supply gap is continuously expanding in the Valley, and in KMC. Over exploitation of ground water with a motive to meet the demand of water has caused a great decline in ground water level. But, not just the water scarcity monsoon flooding in the valley has also become topic of concern because of increased intensity and frequency of urban flooding in the city affecting daily livelihood of the people and also causing a huge human, financial, and physical damage here. Rainwater harvesting (RWH) is considered as a potential solution in addressing water stress and aiding water management in different parts of the world. So, this study is carried out to assess the potential of Rainwater Harvesting in urban context of KMC and the potential runoff volume that could be harvested.

Study delineates the **Rainwater Harvesting Potentiality Index** via zoning within KMC. Analytical hierarchy process (AHP) based multi-criteria decision making is applied establishing rainwater harvesting potentiality index (RWHPI). The study also required hydrological modelling of basin of the study area in rainfall-runoff simulation to estimate the runoff coefficient of the sub-basins. Drainage density, roof area density, basin slope, and runoff coefficient are considered for assessing RWHPI. Results showed that 28.78% of the total basin area has good RWHPI, 46.30% has moderate, and only 24.90% has low RWHPI. Also, Roof Rainwater harvesting (R-RWH) is alone able to meet nearly 23% of the total domestic water demand of the city.

ACKNOWLEDGEMENTS

This work would not have been possible without the support provided by my adviser, Mr. Neeraj Adhikari, Assistant professor in the Department of Mechanical and Aerospace Engineering. I would also like to thank Dr. Khem Narayan Poudel for the constant encouragement throughout the degree program. I would also like to remember all the professors that I had privilege to interact with during this masters program, without them the program would not have been as fruitful as it has become.

I would like to thank all my colleagues for direct and indirect support through out the last two years. I would also like to thank Mr. Rajendra Bahadur Chettri, Asst. Professor of Thapathali Campus for his guidance in due course of this research whenever needed. Further, I would like to express my gratitude to Bikram Maharjan, Parasar Ghimire, Aasish Sumsher Rana, Nirmal Ruwale, Surendra Maharjan, and Ajay Yadav for their guidance in various technical aspects of this project, which truly enabled me to complete this work. And finally, I would like to extend deepest gratitude to my parents, my sister, my in-laws and my husband for their constant encouragement and support in every step of the process.

Table of Contents

Copyright	i
Certificate	ii
Declaration	iii
Abstract	iv
Acknowledgements	v
Table of Contents	vi
List of Figures	viii
List of Tables	ix
List of Abbreviations	x
1 Introduction	1
1.1 Background of the study	1
1.2 Need for Rainwater harvesting in Kathmandu	2
1.2.1 Water Demand	2
1.2.2 Ground water recharge	2
1.2.3 Urban Flooding	3
1.3 Potential of Rainwater harvesting in Kathmandu	3
1.4 Rationale of the study	4
1.5 Objective of the study	4
1.6 Limitations of the study	5
2 Literature review	6
2.1 Literature review on the historical perspective of water management in Kathmandu Valley	6
2.2 Literature review on the present day water situation in Kathmandu Valley	7
2.2.1 Drinking water crisis	7
2.2.2 Floods during rainy season	8
2.3 Literature review on rainwater harvesting	10
2.4 Brief description of software and applications used in study	12
2.4.1 HEC-HMS	12
2.4.2 Geographic Information System (GIS)	12
2.4.3 Open Street Map (OSM)	12

3	Study area	13
3.1	Brief overview on Kathmandu Valley and KMC	13
3.2	Urbanization trend of KMC	14
3.3	Climate in Kathmandu	15
4	Methods	17
4.1	Input Data	18
4.1.1	GIS input	18
4.1.2	Model input	19
4.2	Hydrological Modelling	23
4.2.1	Model Setup	23
4.2.2	Model performance measures	24
4.2.3	Model performance evaluation criteria	26
4.3	Roof area calculation	26
4.4	Multi-criteria decision analysis	27
4.5	Quantity runoff from catchments	28
5	Results and Discussions	30
5.1	Validation of the HEC-HMS model for rainfall runoff simulation	30
5.2	Rainwater harvesting potentiality	32
5.2.1	Roof areas	33
5.2.2	Drainage density	34
5.2.3	Runoff coefficient	35
5.2.4	Basin slope	36
5.2.5	Rainwater harvesting potentiality index	36
5.3	Potential quantity rainfall for harvesting and meeting city demands	39
5.3.1	Quantity rainwater harvest from roof catchments	39
5.3.2	Quantity rainwater harvest from KMC - catchment	40
5.3.3	City water demand management	40
6	Conclusions and Recommendation	42
6.1	Conclusions	42
6.2	Recommendations	43
	References	46

List of Figures

2.1	Picture representing the water scarcity in Kathmandu.(Konstantinos Mavroudis 2009, Wikimedia Commons)	7
2.2	A soldier carries a child to safety in the flooded urban region (New York Times 2019).	9
2.3	Floods during the recent week-long rain, destroying fruits at a market. (The Kathmandu Post 2021).	10
3.1	Map of Nepal showing the location of KMC	13
3.2	Historical and projected population of KMC, Source: Macrotrends (2021)	14
3.3	Expansion of built up area in Valley.	15
3.4	Climate graph by month in Kathmandu, Source: climate-data.org	16
4.1	A flow chart of the methods for the study.	17
4.2	DEM of Bagmati basin under study	18
4.3	Monthly mean temperature of Kathmandu Valley wrt Airport Station	20
4.4	Plot showing precipitation in Kathmandu valley and discharge at Khokana station	20
4.5	Curve Number generated by GIS	22
4.6	HEC-HMS model setup, with the inset showing the detail of the core city limits.	23
5.1	Daily discharge of observed vs simulated for Khokana	30
5.2	Monthly discharge of Observed vs simulated data for Khokana	31
5.3	Correlation of observed vs simulated monthly discharge (2000-2002)	32
5.4	Correlation of observed vs simulated monthly discharge (2003-2007)	32
5.5	Computed roof areas using OSM for the study.	33
5.6	Sub-basin wise roof area percentage within KMC.	34
5.7	Sub-basin wise drainage density within KMC	35
5.8	Sub-basin wise runoff coefficients within KMC	36
5.9	Sub-basin wise average basin slope	37
5.10	Computed rain water harvesting potential.	37
5.11	Status of supply-demand in Kathmandu Valley	41

List of Tables

2.1	Water Demand, Production, and Distribution detail (2077/78) as per KUKL (2021)	8
4.1	Rainfall stations in the valley	21
4.2	Monthly mean PET	21
4.3	Model performance evaluation criteria	26
5.1	Summary of model performance	31
5.2	Sub-basin wise roof area percentage within KMC.	34
5.3	Weights of selected criteria and their features	38
5.4	Runoff volume from buildings roof of KMC	39
5.5	Basin wise annual runoff within KMC	40

List of Abbreviations

AHP	Analytical Hierarchy Process
CN	Curve Number
DEM	Digital Elevation Model
DHM	Department of Hydrology and Meteorology
GIS	Geographic Information System
HEC-HMS	Hydrologic Engineering Center's – Hydrologic Modeling System
KMC	Kathmandu Metropolitan City
KUKL	Kathmandu Upatyaka Khanepani Limited
MCM	Million Cubic Meter
MLD	Million Liters per Day
NSE	Nash-Sutcliffe Efficiency
OSM	Open Street Map
PET	Potential evapo-transpiration
RWH	Rainwater Harvesting
RWHPI	Rainwater Harvesting Potentiality Index
RCM	Regional Climate Model
RCP	Representative Concentration Pathways
RRWH	Roof-RainWater Harvesting
SCS	Soil conservation Service
USGS	United States Geological Survey

Chapter 1: Introduction

1.1 Background of the study

Rainwater Harvesting is the collection and utilization of the rain that falls on the rooftops and other surfaces of a given area, for either immediate or future usage. Rainwater harvesting can be done mainly by two ways—using reservoir/storage tanks or recharging the rainwater to the underground sources as tube wells. Far from a new idea, rainwater harvesting is one of the oldest technologies that has been used in water management scenarios in areas with water crisis.

While the population of Nepal has only been increasing by $\approx 2\%$ in the past decades, the urban population has been increasing much more rapidly. In fact, even though it is one of the least developed nations, Nepal ranks in the top ten list of countries in the world when it comes to the rate of urbanization. The urban population growth rate in Nepal almost doubled from 3.6% in 1991 to 6.5% in 2001, along with the increase in the number of urban centers from 58 in 2013 to 293 in 2017 (Timsina et al., 2020). Kathmandu valley is one of the fastest growing urban center in the world. The urbanization of Kathmandu valley started from 1940s. But, the valley lacks proper planning and management in various sectors. There is increasing gap between the supply and demand of water within the valley. As of now, only 91 million liters a day (MLD) of water has been supplied by Kathmandu Upatyaka Khanepani Limited (KUKL, the government agency responsible for water supply to the valley) while the demand is much higher at 470 MLD (KUKL, 2021). To cover this gap, population of valley have been relying of different sources, main source being ground water. There have been over-extraction of water to meet the increasing water demand. Many different studies (Dixit and Upadhya, 2005; Pandey et al., 2010; Gautam and N Prajapati, 2014), shows the heavy rate of groundwater extraction as compared to the recharge. The overall rate of groundwater extraction exceeds the rate of natural recharge capacity by 6 times, thus causing the decline in the groundwater table by approximately 2.5 metres per year (Shrestha et al., 2009). In year 1991 and year 2001, the ground water recharge rate was 9.6 MCM/year while the rate of extraction was as high as 40 MLD (or 14.6 MCM/year) and 59.06 MLD (or 21.56 MCM/year) respectively (Pandey et al., 2010). Unmanaged urbanization has increased the water demand, and consequently increased the extraction of ground water. Not only this, it has also reduced ground water recharge, which has led to many cases of flooding in the urban cities in recent years, most prominently in the capital city of Nepal, which lies in the Kathmandu Valley itself.

1.2 Need for Rainwater harvesting in Kathmandu

1.2.1 Water Demand

Within Nepal, the Kathmandu Valley, home of the capital of the country and the largest city, has a permanent population of nearly 2.5 million people, and is growing even further at an astonishing 6.5% per year. The development however has been completely haphazard. The unmanaged nature of the urbanization process has left the citizens of the valley without the necessary amenities for a healthy life. One such critical issue for the residents is the lack of adequate water for daily necessities. The vast majority of the population of the valley do not have access to enough water in general for living, let alone potable water. With the lack of water supply from the municipal sources, the residents have been, for decades, left to their own devices when it comes to meeting their water demand. While in the past, when the population density of the valley was low, residents relied on community based wells and stone spouts for their water needs, the explosive growth in population in the decades that followed has been unable to quench their thirst from the traditional sources. According to the recent annual report for the year 2021 published by Kathmandu Upatyaka Khanepani Limited (KUKL), the current water demand within Kathmandu Valley is 470 MLD, but its supply is as low as 91 MLD on average, creating a huge supply-demand gap.

1.2.2 Ground water recharge

In the present day, many people rely on individual bore-wells for their normal water needs. Groundwater from both shallow and deep aquifers (more than 200 metres) is being heavily extracted by small- to large-scale users, including KUKL itself. In the present situation, KUKL owns more than 107 deep tube wells (DTWs), 19 dug wells, and 32 pumping stations (KUKL, 2021). Not just KUKL, most of the individual households have dug their own wells to meet their water demand. For potable water needs, people are forced to buy water in packaged jars from water processing plants. In the most dense of the areas, even this is starting to become a huge problem as the ground water level keeps dropping, and the water that people can access is of low quality. The unregulated extraction is depleting the aquifers, even in a situation where the deep aquifers are not easily rechargeable due to the valley's impermeable black clay (JICA, 1990). As of now, nearly 80% of the current demand in the valley can be met by groundwater (Duwal et al., 2019). However, the situation will not remain the same in the future. The water table level has been dropping in the past decades. Study on ground water environment has showed that urbanization, population growth along side increasing tourism has caused a huge gap in ground water extraction and recharge (Pandey et al., 2010). This had a decline in ground water level by 1.38–7.5 m during 2000–2008 (Pandey et al., 2010). It is absolutely critical that we mon-

itor water levels regularly underground, and find ways to recharge the water table. One way to recharge groundwater may be rainwater harvesting (Ganesh et al., 2018). It would be useful to study the value of rainwater harvesting in terms of recharging groundwater, and the calculation of the potential of rainwater harvesting can be useful for planning for the future.

1.2.3 Urban Flooding

Urbanisation and climate change collectively impose the threat of urban flood. The rapid and unmanaged urbanization of the Kathmandu valley has also made the urban environment unsafe in many ways for the residents. One such way the urban environment has been unsafe in the past decades, is during the monsoon season when there is urban flooding within the core areas. Year after year, the residents of the valley have been subjected to flash floods in case of heavy rains which typically results from unmanaged and severely inadequate drainage systems. The few months of monsoon in any given year is a nightmare for many of the residents of the city. The situation has only been getting worse with time, thanks to the effects of climate change. The unpredictability of the changing climate has affected Nepal just as it has affected many other countries. It is in fact the fourth most vulnerable country to the changing climate. Not only are the summers getting hotter, but the natural calamities such as abnormally heavy rainfall is also getting worse. This, coupled with the unmanaged nature of urbanization, has accentuated the effects of heavy rainfall with regards to urban floods. The concerned authorities typically do too little, too late. And so, there must be a study for alternative solutions that address these problems.

1.3 Potential of Rainwater harvesting in Kathmandu

The most important factors for rainwater harvesting are rainfall and catchment area. The average annual rainfall in Kathmandu is 1455 mm average taken from 1981-2010 (Central Bureau of Statistics, 2019). Also due to urbanization most of the area within the valley now falls under concrete built up areas including buildings roofs, parking, roads, pavements, etc. The built up area of Kathmandu Metropolitan City (KMC) has increased from 30% in year 1996 to 60% in year 2006 (Bajracharya et al., 2015). The built up areas have high runoff coefficients, thus giving high runoff volume. According to study (Shrestha et al., 2009), a building with 100 m^2 roof area is able to collect 200 m^3 rainwater in a given year, even if only 80% of the water is collected. This amount is enough to meet the water demand of a family with an average number of 5 members (Shrestha et al., 2009). But it is not feasible to collect and store all the rainfall falling into the building area. Thus, the collected water could be then directed towards the wells for ground water recharge. Since, there are many ancient shallow to deep tube wells, and also many modern wells dug to meet water demand in individual household, it will further help in recharge of the

ground water. There should be adequate study and research for artificial recharge well and their implementation in the field. If proper filtration media and storage wells are planned, rainwater harvesting has the potential to be very fruitful in the urban context of Kathmandu when it comes to meeting the water demand, along with the side benefit of ground water recharge.

1.4 Rationale of the study

The two faced problem of water scarcity and flood management is a recurring problem in the city that will only keep getting worse if left without intervention. The rain, while the certainty can be predicted - the amount of rain can hardly be predicted. We must try and find solutions to the constant problem. As the population of the valley keeps growing, the number of people facing water issues will keep increasing, and even the ones who are currently not facing the issues, they will start facing water crisis as well. In the meantime, increased urbanization will increase the number of people who struggle due to urban floods as well. We must therefore find potential solutions.

The rain is not only the source of the problems, but can also be a solution via rainwater harvesting. Rainwater harvesting is the collection of the rain that falls, and the thus collected rainwater can be used for potential solutions to our problems. Understanding how much rainwater can be harvested can help the city planners plan for solving the two major issues we have at hand, both at once. If enough groundwater can be recharged from the rain water to meet the resident's needs, the problem of lack of water would be solved. If rainwater can be harvested properly and sent to recharge ground water, then the issue of standing water and flash floods would also be solved. Therefore, it would be very useful to study the potential of rainwater harvesting in major areas of Kathmandu valley.

1.5 Objective of the study

Main objective

1. To map the rainwater harvesting potential zones with calculated rainwater harvesting potential index using Analytical Hierarchy Process(AHP) within the Kathmandu Metropolitan City (KMC).

Specific objective

1. To estimate the sub-basin wise runoff coefficient through hydrological modelling of the basin
2. To assess the estimate quantity runoff volume that can be obtained from roof catchments
3. To assess the sub-basin wise quantity runoff volume from KMC

1.6 Limitations of the study

1. Due to the require filtration system to process the harvested rainwater for domestic use, economic factors may make the solution undesirable
2. The roof area is assessed through open source - Open Street Map, which might not give as accurate results.
3. Rainwater harvesting potential can be dependent on various different parameters, among which only 4 are selected for our study.

Chapter 2: Literature review

2.1 Literature review on the historical perspective of water management in Kathmandu Valley

The Kathmandu Valley hosts the capital of the country. It is divided into three major administrative regions in the current day, in the form of three districts: the namesake and largest district of Kathmandu, Lalitpur, and the smallest Bhaktapur. While Kathmandu is the largest, and most populous district, the two neighbors are catching up fast. Urbanization is happening in all three districts and the issues relating to water and water management hits the entire valley. To begin, the section gives an outlook on the present and historical status of water supply in the Kathmandu Valley.

From the days of the Lichhavi period in the Kathmandu valley, spanning from 300 AD to 800 AD, communal water distribution and management has existed. The earliest stone spout for drinking water was constructed in 550 A.D. at Hadigaun, Kathmandu, while in Patan the oldest spout dates to 570 A.D. It is still in use and is known as manga hiti (located in Mangalbazaar, Patan durbar square) (Jalsrot Vikas Sanstha, 2018). There are many such stone spouts all over the country. Many of these stone spouts are actually still in use to this day in the Kathmandu valley. While even just a decade ago, they were in use 100% of the time, lack of groundwater in the aquifers has relegated them to seasonal use. They can only supply water during the wet rainy seasons, but are completely dry in the winter season.

In Kathmandu Valley, the Malla period began after the Lichhavi period. In the Malla period, water resources were developed and managed by the communities for drinking and agricultural purposes during the Golden Era. There are several well-known constructions of that period, including the Raj Kulos (irrigation canals) in Kathmandu and irrigation canals/Nahar/Kulos in the hills (Jalsrot Vikas Sanstha, 2018). The communities continue to manage some of these. To provide drinking water facilities inside and outside Kathmandu valley, more stone spouts, pokharies, wells, kuwas, Naulos, and Jal Dronis were constructed. They not only serve for water, but also hold importance with architectural and art point of view. The most famous stone spouts from this period include Dhunge Dharras in Hanuman Dhoka Palace, Tusa Hiti in Patan Durbar, and Thatu Hiti in Bhaktapur Durbar. Water spouts from Balaju and Naulos (spring protections) in Baitatdi, Darchula, Dadeldhura and other districts of the Far Western region, which were built during this period, are still in use today (Jalsrot Vikas Sanstha, 2018).

Bir Shumser introduced a piping system for the first time in 1891 in the Kathmandu valley (Jalsrot Vikas Sanstha, 2018). The ruling families were the only ones who had access to it. It was then considered a status symbol to have a piped water supply (Jalsrot Vikas Sanstha, 2018). British engineers constructed the first piped water scheme in Nepal, which

tapped the headwaters of the Bishnumati River in the Shivapuri hills north of the Kathmandu valley(Jalsrot Vikas Sanstha, 2018). Other Rana prime ministers such as Chandra Shumser, Bhim Shumser, Padma Shumser, Dev Shumser and Judha Shumser extended it to Lalitpur, Bhaktapur and other districts(Jalsrot Vikas Sanstha, 2018). Water systems were designed, constructed and maintained by Pani Goswaras, which were manned by a khardar and an overseer(Jalsrot Vikas Sanstha, 2018). After the introduction of piped water supply, stone spouts, wells, and ponds gradually disappeared. Up until 1950s, dhunge dhara (stone spouts), well, ponds, were the main sources of drinking water in Nepal(Jalsrot Vikas Sanstha, 2018). It was only after 1951, when Nepal overthrew the centuries old autocratic rule. Thus, in Nepal's First Five-Year Plan (1956-61), modern planning and development of public water supply and sanitation was initiated (Jalsrot Vikas Sanstha, 2018). The Department of Water Supply and Sewerage was established in 1972 as the lead agency(Jalsrot Vikas Sanstha, 2018). Following the world declaration of 1981-1990 as the International Water Supply and Sanitation Decade, international donor agencies and Non-governmental organizations supported Nepal in its Water and Sanitation Program with fair financial help.

2.2 Literature review on the present day water situation in Kathmandu Valley

2.2.1 Drinking water crisis

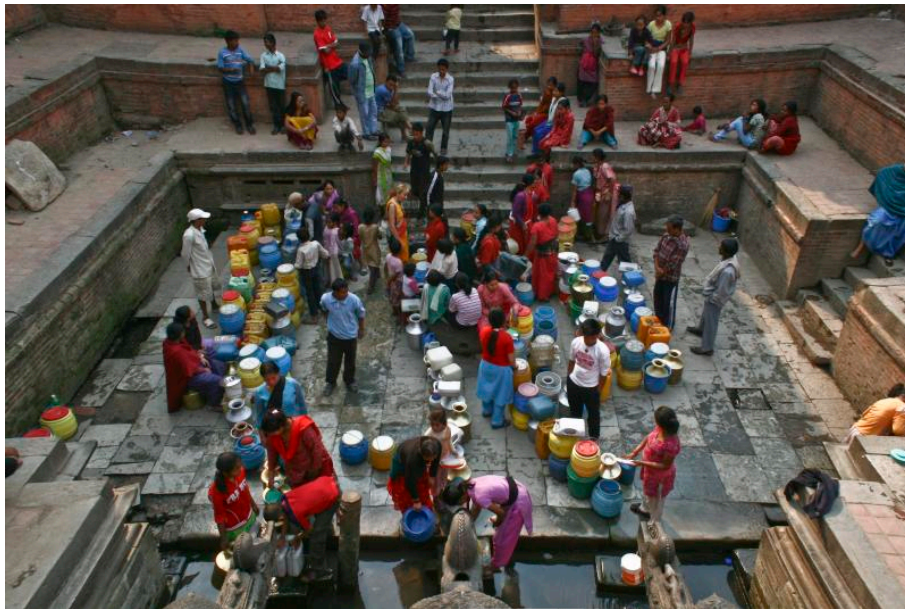


Figure 2.1: Picture representing the water scarcity in Kathmandu.(Konstantinos Mavroudis 2009, Wikimedia Commons)

The problem of water scarcity in the valley is not new and has its traces to back in the 1980s. The condition has been only getting worse since then. In the present day, Kathmandu Valley is in massive water supply deficit and suffering a lot more than ever. The

estimated water demand if the valley is about 470 million litres per day (MLD), but the Kathmandu Upatyaka Khanepani Limited (KUKL) can only supply about 80 MLD during the dry period and 106 MLD during the wet period as shown in table 2.1. With the motive to bridge the supply demand gap not just individual families or private sectors even governmental bodies are extracting groundwater from both shallow and deep aquifers (more than 200 metres) with out proper regulations. This unregulated extraction is causing depletion of the aquifers; especially the deep aquifers which are not easy to recharge due to impermeable black clay lying in the Valley (JICA, 1990). Due to the difference in the rate of extraction and recharge, extraction being much higher(almost 6 times the rate of natural recharge), the groundwater table is declining by approximately 2.5 metres per year(Ministry of Physical Planning and Works, 2002). An immediate consequence of the depletion of shallow groundwater aquifers is that dug wells, hand pumps, and traditional stone spouts can no longer provide water as they once did. Searching for alternative to water by looking to the sky is also not new. In fact, a city in Bangladesh has also been studied in the context of rainwater harvesting and management for a similar purpose (Akter and Ahmed, 2015).

Table 2.1: Water Demand, Production, and Distribution detail (2077/78) as per KUKL (2021)

S.N.	Description	Quantity (Millions Liters Per Day)
1	Demand	470
2	Production	
a.	Minimum Production	100
b.	Maximum Production	133
3	Supply(Considering 20% real losses)	
a.	During month of Minimum Production	80
b.	During month of Maximum Production	106
c.	Average Supply	91

2.2.2 Floods during rainy season

Bagmati is the main river that drains through Kathmandu Valley for 25 km. The drainage basin morphology, geology, rainfall intensity, and duration are the key factors in maximizing the rainfall-runoff. For instance, heavy rainfall in the central valley influences the volume of runoff and enhances flash floods in the Bagmati River and its tributaries due to the majority of land being covered by built-up area and road networks (Khatakho et al., 2021).

The original drainage system in Kathmandu valley was designed for 200,000 people (Mohanty, 2011). The construction of the sewerage system in the Kathmandu valley

started around 1920s, that included a 55km long brick channel to collect and dispose within a combined sewer system along with rainwater runoff in Kathmandu and Patan (Nyachhyon, 2006). Later, as an extension and replacement of the channels additional concrete pipes were laid. This combined sewage system worked as sewage drainage as well as storm drainage during rainfall. Though the original system worked just fine for then conditions, but the system is no longer adequate for the population the valley holds at present as the population and built up area of the valley grew with time.



Figure 2.2: A soldier carries a child to safety in the flooded urban region (New York Times 2019).

The inadequate drainage system has led to the occurrence of urban flooding, which has been more frequent in Kathmandu valley during heavy rainfall events (Pandey and Dugar, 2019; Pradhan-Salike and Pokharel, 2017). Extreme precipitation due to climate change and global warming is attributed as the main cause behind the increased frequency of floods Devkota and Shrestha (2021). According to a recent study, the precipitation in the Bagmati basin will follow an increasing trend of 2.9 mm/year and 4.97 mm/year in two different respective scenarios of Representative Concentration Pathways (RCP) under climate change, namely RCP4.5 and RCP8.5 Dahal et al. (2016). Monsoon precipitation is dominant in Nepal which is a major predictable cause of flood in Kathmandu Valley. In addition, improper land use plans, unplanned settlement distribution, and deforestation in the watershed increase the extent and intensity of flood devastation. With the source of the floods being consistent year after year, proper solutions must be sought in order to prevent these floods. The economic loss due to flood disaster is considerably high in Nepal.



Figure 2.3: Floods during the recent week-long rain, destroying fruits at a market. (The Kathmandu Post 2021).

2.3 Literature review on rainwater harvesting

Rainwater has been used for various purposes all over the world, from drinking, to irrigation, to domestic use, to industrial use (Shrestha et al., 2009, 2011). In South Australia, 42% of the population drink rainwater. In Bangladesh, rainwater is a major alternative source of drinking water in arsenic-affected areas. At Singapore's Changi Airport, 63,500 tonnes of rainwater is used for flushing toilets and cooling the terminal buildings each month, about 33% of the total water used, saving approximately USD 390,000 a year. In China's Gansu Province, the annual precipitation of 300 mm caters to 2 million people and supplies supplementary irrigation for 236,400 hectares of land. In India, direct recharge of rainwater into the ground (Mahnot et al., 2003) resulted in groundwater level increases of up to 5 to 10 metres in just two years. Given such successes around the world, it is clear that rainwater harvesting has great potential to address some of today's water crises in many of the world's urban areas.

Mahmoud et al. (2014) investigated the rainwater harvesting potential in Khartoum, the capital of Sudan. The study area is Khartoum City Center, which is an urban area susceptible to not only drought but also flood during heavy showers. Lack of pervious surfaces for water infiltration has increased frequency dust storms in summer and flooding in rainy season. This has raised not only environmental and health concerns, but also economic burden. Hence, for urban runoff and storm management, they investigated the rainfall behavior in the region. They started with rainfall variability, seasonal distribution, number of days with rain, daily rainfall probability, maximum daily rainfall and deficit/surplus of rain, which they discuss in detail within the article. They used United

States Natural Resources Conservation Services method (US-NRCS) to compute the potential runoff in the 6.5 sq. km. area. Weighted Curve Number (CN) estimated was 94% which shows high imperviousness of the area. Rainfall threshold for runoff generation was 3.3 mm. The drainage capacity of the area corresponds to rainfall with 80% probability and one year return period and an extreme rainfall can produce a runoff of four times the capacity. They showed that the rainfall could be harvested by the rational method from 18% of rooftops of the commercial and 80% of rooftops in business area. They chose six potential sites for rainwater harvesting based on results and concluded that it would solve the drought problem and manage the storm water.

Akter and Ahmed (2015) estimated the potential of rainwater harvesting in the South Agrabad, which is south-western part of Chittagong city of Bangladesh. The Chittagong city is the second largest city of Bangladesh, and South Agrabad is an urban area as of Kathmandu. South Agrabad is experiences water scarcity as well as urban floods with an average annual precipitation of 3000 mm. They adopted Analytic Hierarchy Process based multicriteria decision analysis technique. They considered the roof area and slope, drainage density and runoff coefficient. They also used HEC–HMS to model the runoff of precipitation. The simulation showed that Rainwater Harvesting could minimize storm water up to 26%. Further it can supplement 20-liter water per person per day. As such, the Rainwater Harvesting potential of the study area was verified. They used the results to divide the study area into three potential zones with good, moderate and poor potentials. They used AHP in HEC–HMS for a study like ours in an urban area with a sub-basin or basin context.

Gado and El-Agha (2020) on their study regarding feasibility of rain water harvesting (RWH) in sustainable water management in urban context of Egypt have put forward RWH as promising solution for the existing problem of water demand deficit and inundation problem in Urban context. It is stated that limited resources, rapidly increasing population, and climate change are major factors in making the water demand and supply gap wider. Feasibility of rainwater harvesting for urban area was assessed in 22 cities of the Egypt. To estimate the infiltration coefficients of the study area, land cover classification maps of given areas were created by using the ArcGIS® software. The study concluded that, infiltration of RWH into an aquifer can play an meaningful role in water management for urban environments, as this might lead to a sound reduction in risks of flooding and expenses related to municipal drainage systems installation. A recent research study was carried out with a motive of assessing the integrated impact of climate change and urbanization on flooding in Kathmandu metropolitan city(KMC), using personal computer Storm Water Management Model (Saurav et al., 2021). Future rainfall was projected using three Regional Climate Model (RCMs) under two scenarios of Representative Concentration Pathways. It showed that the impact on flooding is likely to be more intense with relatively higher contribution of the climate change. It showed that despite

less contribution of urbanization in intensifying flooding, it can be a stimulant for emphasizing other factors and in the implementation of management measures. For example, the application of small-scale rainwater harvesting, and storage of the overflow reduced the runoff, ultimately reducing the volume of flood by 20–35%. These studies discuss and verify the potential of rainwater harvesting for runoff management during surplus and water utilization during deficit in urban areas as of Kathmandu.

2.4 Brief description of software and applications used in study

2.4.1 HEC-HMS

The hydrologic modeling system (HEC-HMS) is a modeling technique that to simulate the precipitation-runoff processes of drainage basins. It simulates the complete hydrologic processes of given watershed systems. It includes many different traditional hydrologic analysis that includes: infiltration, unit hydrographs, and hydrologic routing. HEC-HMS is also capable of doing continuous as it accounts the processes like evapo-transpiration, snow melt, and soil moisture. HEC-HMS is a product of the Hydrologic Engineering Center in the U.S. Army Corps of Engineers. It is designed to be applicable in a wide range of geographic areas for solving the widest possible range of problems. This includes large river basin water supply and flood hydrology, and small urban or natural watershed runoff.

2.4.2 Geographic Information System (GIS)

A geographic information system (GIS) is a conceptualized framework that provides the ability to capture and analyze spatial and geographic data. GIS applications (or GIS apps) are computer-based tools that allow the user to create interactive queries (user-created searches), store and edit spatial and non-spatial data, analyze spatial information output, and visually share the results of these operations by presenting them as maps (Maliene et al., 2011).

2.4.3 Open Street Map (OSM)

OSM is a collaborative project to create a free and user editable map of the world. Increasingly restrictive usage on proprietary satellite maps were the primary reasons for development of OSM. OSM relies on aerial photography, primary knowledge by users, and GPS (Global Positioning System) data. While this project generates maps that are primarily free and open source, it has another benefit. Given that the maps have contributions from local people, it gets updated far more than maps provided by companies that use satellite images.

Chapter 3: Study area

3.1 Brief overview on Kathmandu Valley and KMC

Bowl shaped Kathmandu valley is situated between $27^{\circ}31'55''$ to $27^{\circ}48'56''$ north latitude and $85^{\circ}11'11''$ to $85^{\circ}31'52''$ east longitude. It is surrounded by four different mountain ranges: Shivapuri, Phulchowki, Nagarjun, and Chandragiri hills. The central lower part of the valley stands at an altitude of 1,425 metres (4,675 ft) above sea level. The major river flowing through the Kathmandu Valley is the Bagmati. The valley is made up of the three districts: Kathmandu District, Lalitpur District and Bhaktapur District with an area of 220 square miles (570 km²).

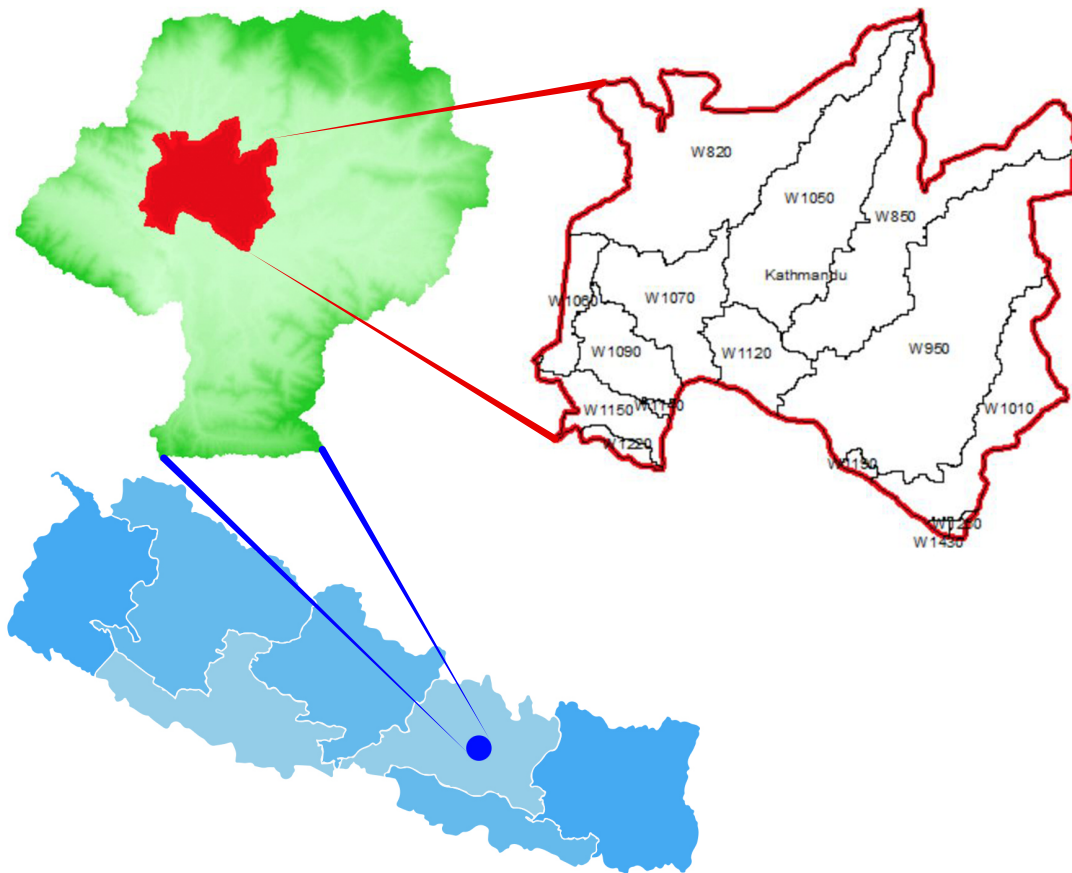


Figure 3.1: Map of Nepal showing the location of KMC

Kathmandu metropolitan city (KMC) is the oldest metropolitan city in Kathmandu District, Nepal. The city stands at an elevation of approximately 1,400 meters (4,600 ft). The city is located at $27^{\circ}42'06''$ north latitude and $85^{\circ}19'14''$ east longitude. KMC is a fast growing city in Nepal, also in South Asia. The metropolitan city area is 49.45 square kilometers and has a population density of 19,726 per km². KMC is divided into 32 wards, bordered with Lalitpur Metropolitan City and Kritipur Municipality in the South, Nagarjun Municipality in the West, Budhanilkantha, Tarkeshwor, and Tokha Municipalities in

the North and Kageshwari Manohara, Gokarneshwor, and Bhaktapur Municipalities in the East.

While this study is focused in KMC for assessing its potentiality in RWH, the study needs the modelling of the Bagmati basin considering the Khokana outlet for better reliability in the model performance through calibration and validation of discharge data. The figure 3.1 shows the focus area of our study.

3.2 Urbanization trend of KMC

Kathmandu Valley is one of the fastest growing urban center in south Asia. It has an estimated population of 2.54 million with the growth rate 6.5% per year (Timsina et al., 2020). This massive population growth trend in valley is the result of in-migration due to employment opportunities, urban facilities and services, and also being the Federal Capital City of Nepal. Almost 38% of migrants go to the central hill, out of which 34% accounts the migration in Kathmandu valley (Suwal, 2014).

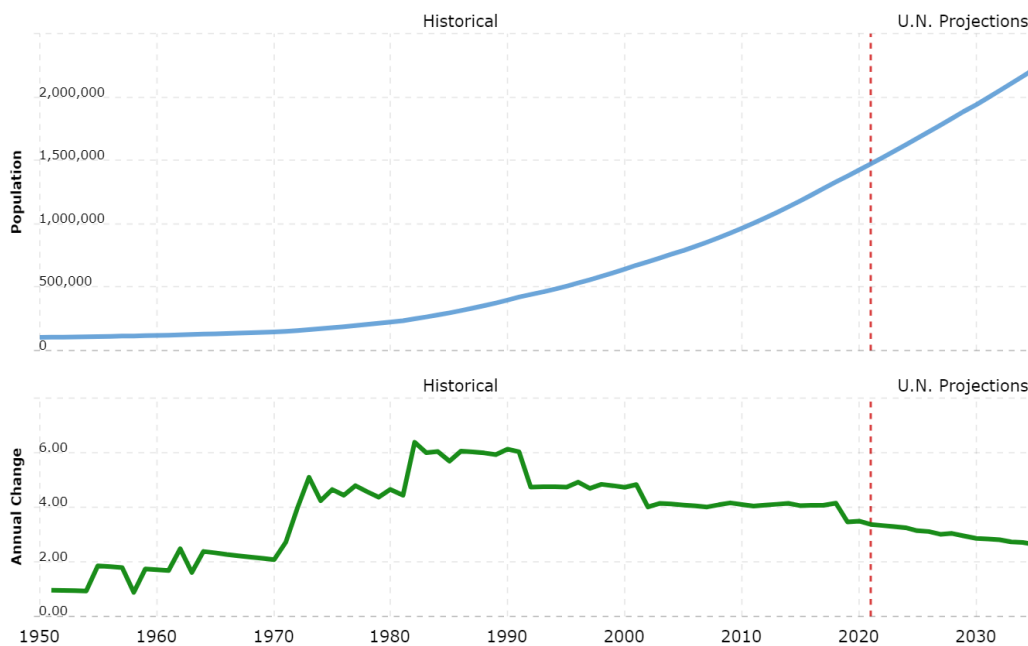


Figure 3.2: Historical and projected population of KMC, Source: Macrotrends (2021)

Figure 3.2 shows the trend of the population of KMC. The graph clearly shows the distinct and rapid increment in the population, and it is expected to further increase in the future. The figure also shows the annual change in population, where it is seen that the maximum increment was during 1990s. Though the rate of increment is projected to be little stable to slightly decreasing, there still is good space for population growth.

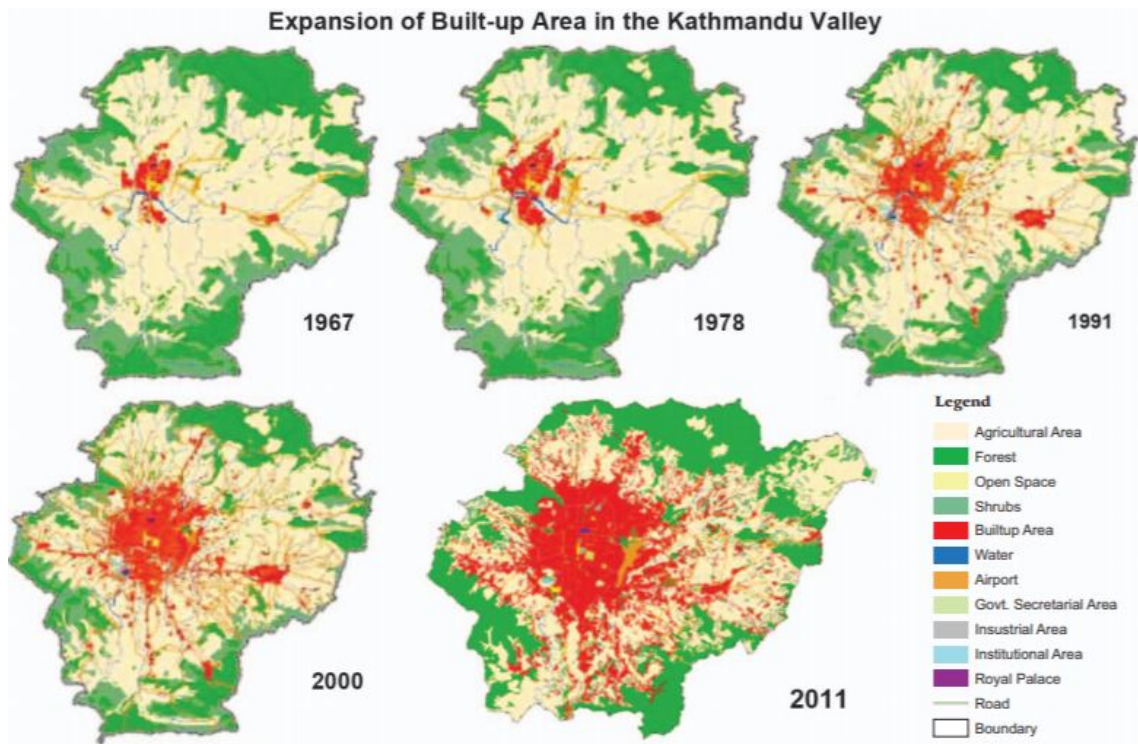


Figure 3.3: Expansion of built up area in Valley.

It is known that the increase in population will lead to expansion of built-up areas. KMC is no exception to it. From past till present, the trend in built-up area of KMC shows a huge expansion. It is proportional to increasing trend of the population due to migration. The historical data and the path traced by the KMC in reaching present state reveals that the growth of the built-up area in KMC has substantiated an unparalleled increment in recent decades. Figure 3.3 gives the visual summary of the extent of urbanization that the valley has had in the past decades. It is clear that the growth is unprecedented, also we can see that that the major growth has happened in central area of valley, Kathmandu.

3.3 Climate in Kathmandu

Kathmandu Valley lies in the Warm temperate zone with the elevation ranging from 1,200-2,300 meters. However, the climate experienced here is fairly temperate. About 80% of its total annual rainfall in the valley falls during monsoon. The monsoon in the valley lasts for only four months of summer—June through September—with an average of 110 precipitation days. For the base years as 1981-2010, the annual average rainfall is 1455 mm. The average monthly precipitation is lowest in December with an average of 26 mm, while the maximum monthly rainfall is in month of July with as average of 778 mm. Similarly the average annual maximum and minimum temperature is 29.1 °C 2.4 ° in the month of December and June respectively. With recorded average monthly temperature of 20.5°, June is the hottest month and the lowest monthly average temperature is 9.2° in the

month of December. The average relative humidity is accounted as 73% and the average monthly sunshine hours of the valley is 213.

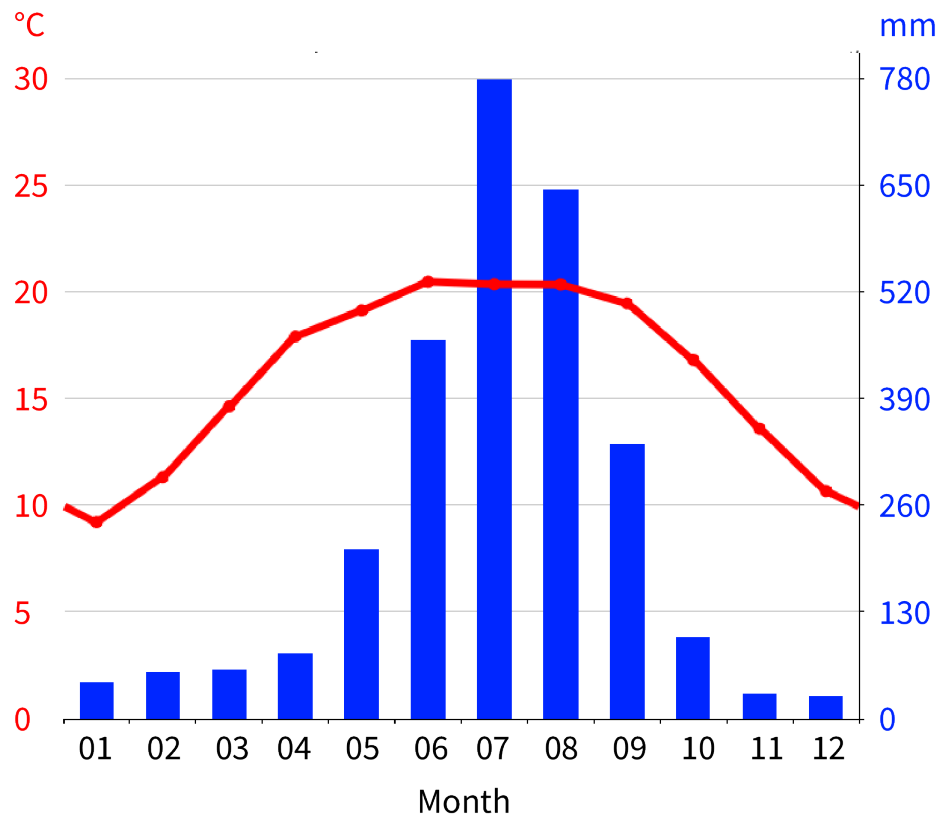


Figure 3.4: Climate graph by month in Kathmandu, Source: climate-data.org

Chapter 4: Methods

The flowchart included gives the general direction of the study. It shows the logical progression of the steps taken in the project to meet the main objective the research. After the selection of the study area for which the research is well justified, thorough review on different literature were done which helped model the structure of the research properly. The chart gives the surface information on the major input data required with their respective sources. Further, how these input are used to obtain basin characteristics like roof area, runoff coefficient, drainage density, and basin slope. Finally using AHP based multi criteria decision analysis RWHPI is computed for study area.

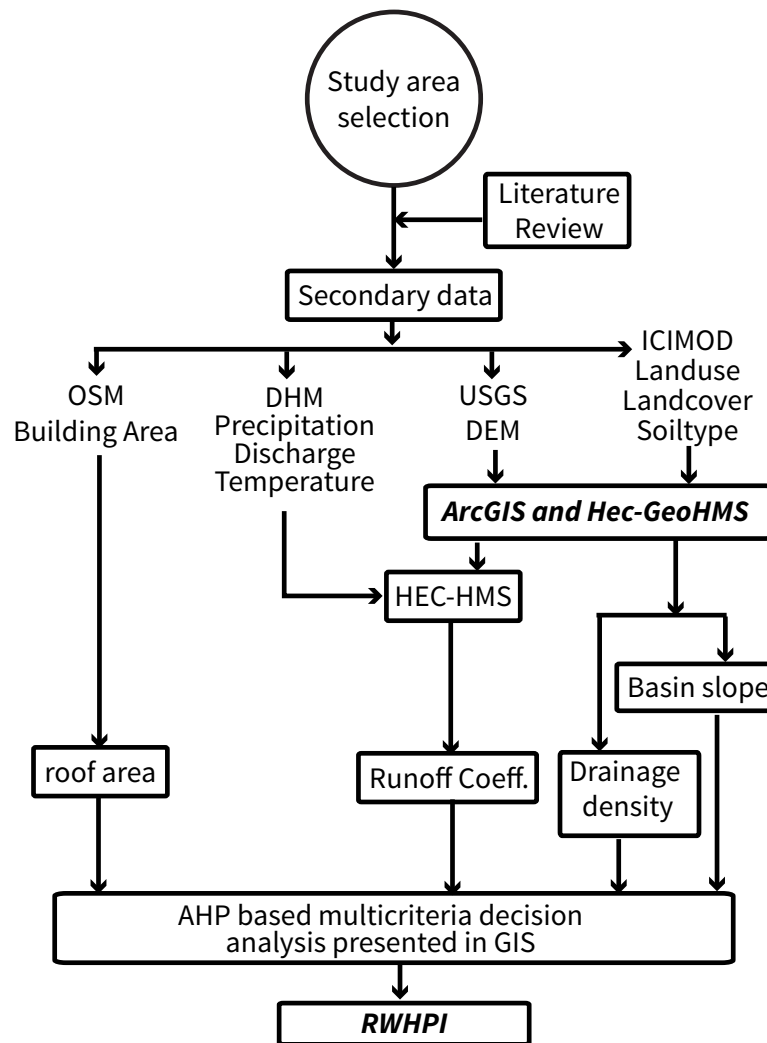


Figure 4.1: A flow chart of the methods for the study.

The details on the steps involved for the research work are discussed in the subsequent sections.

4.1 Input Data

4.1.1 GIS input

Digital Elevation Model

A DEM is a digital representation of any area that includes the elevation information of a given area. A DEM is a 3D computer graphics representation of elevation data that represents a terrain. DEMs are most often used in geographic information systems (GIS). We obtained the DEM data from the USGS - United States Geological Survey. USGS

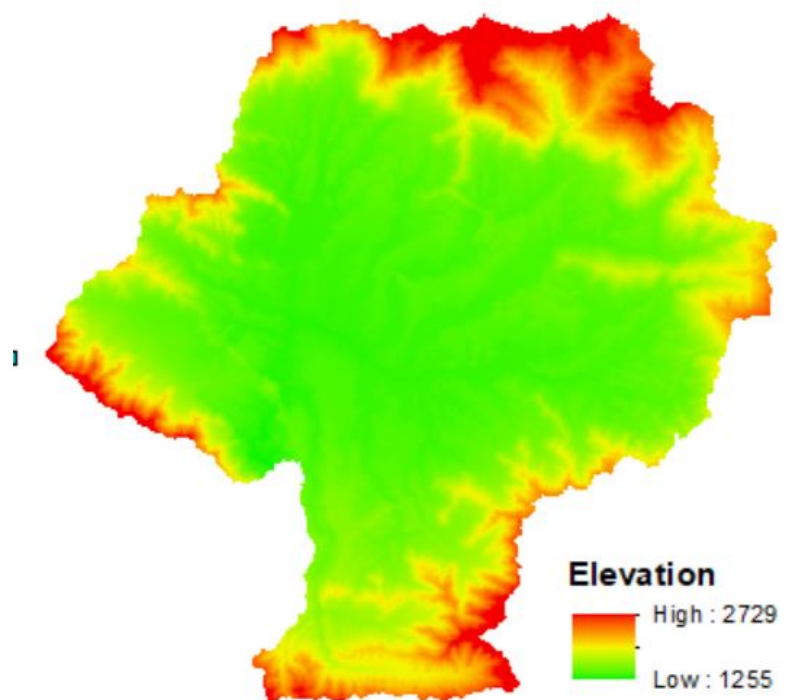


Figure 4.2: DEM of Bagmati basin under study

is one of the many scientific agencies of the federal government of the United States of America. For this study, the DEMs acquired from USGS had a resolution of 30 m x 30 m.

4.1.2 Model input

Hydrological data

For this study, daily precipitation and discharge data for the Kathmandu Valley were obtained from the Department of Hydrology and Meteorology (DHM) of the Government of Nepal. For the temperatures of the basin, the centrally located Tribhuvan International Airport station was taken under consideration. Figure 4.3 shows the monthly mean of maximum, minimum, and average temperature recorded in Airport station of Kathmandu valley. Precipitation data from 21 different stations within the Bagmati river basin was accounted and discharge at Khokana outlet was taken, which is the main outlet for water from the valley. The information of the rainfall stations used in this study is as shown in the table 4.1. To account for the better spatial distribution of precipitation in the study area, Thiessen polygon method was followed. Precipitation distribution was obtained as area weighted factor of different precipitation stations in the study area. If there are n number of stations accountable for the value of precipitation in the given area, then the precipitation value for the given sub-basin can be derived using the following formula:

$$P_b = \frac{P_1 * A_1 + P_2 * A_2 \dots P_n * A_n}{A} \quad (4.1)$$

where,

P_b = Precipitation for the given sub-basin,

A_1, A_2, \dots, A_n represent areas of polygon with precipitation values P_1, P_2, \dots, P_n respectively of n number of stations contributing to the sub-basin, and

A is the total area of the sub-basin.

Figure 4.4 plots the average rainfall in the valley alongside the discharge observed at Khokana station.

The potential evapo-transpiration is calculated using temperature-based evapo-transpiration equation as defined by Hargreaves(1985).It is temperature-based method.

$$PET = 0.0023 \times S_o p \delta T (T + 17.8) \quad (4.2)$$

Where,

S_o = water equivalent of extraterrestrial radiation (mm/d)

T = air temperature (°C)

δT =daily air temperature range (°C)

Other hydrological properties and losses of the basin like- Baseflow, canopy loss, and surface loss were carried out by recession, simple canopy, and simple surface method respectively. Initialization of these parameters were derived from Devkota and Shrestha (2021) for Bagmati river basin. The Curve number was generated and basin wise average

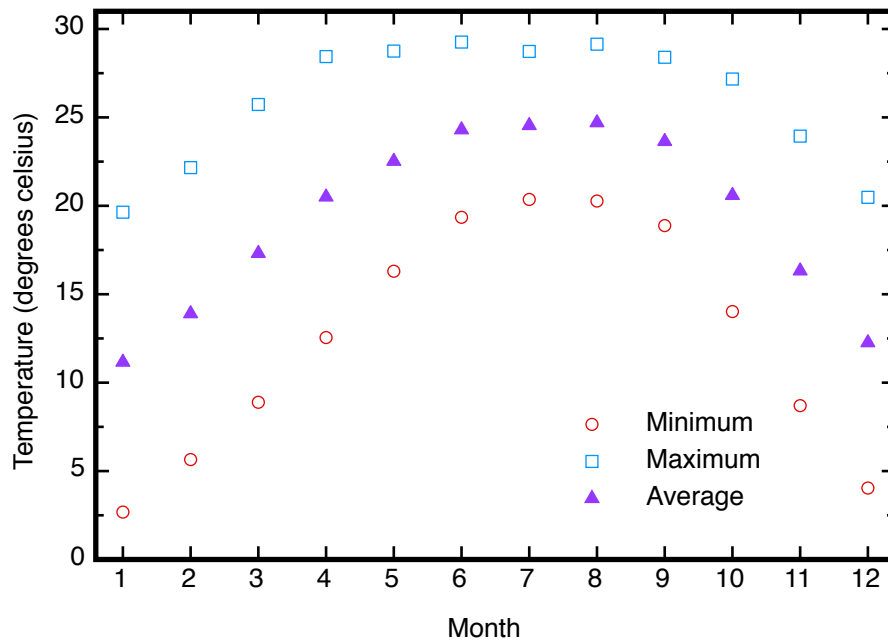


Figure 4.3: Monthly mean temperature of Kathmandu Valley wrt Airport Station

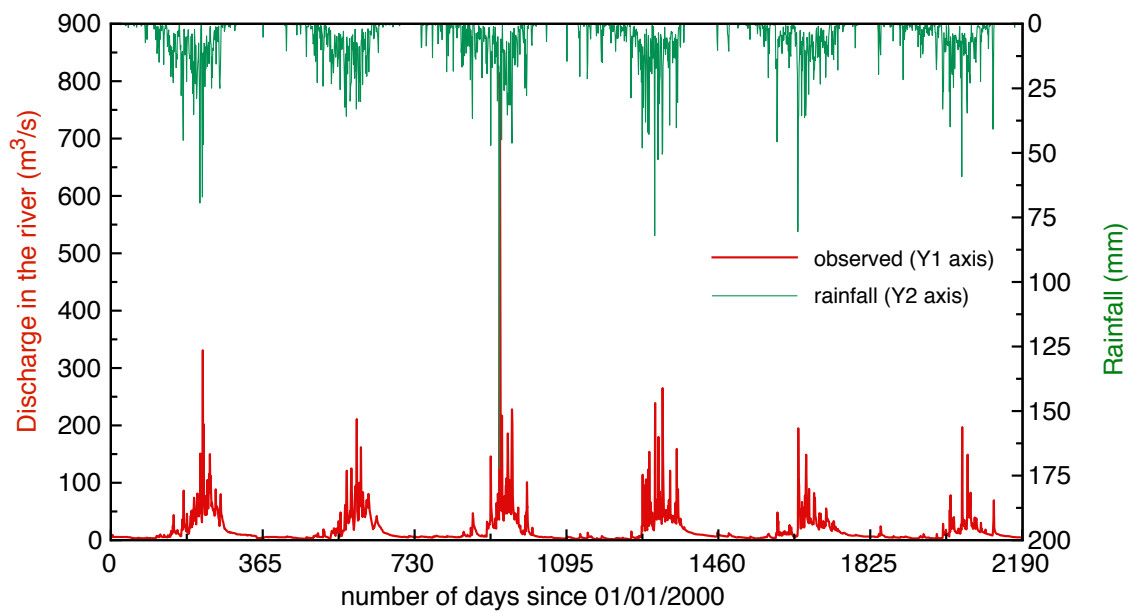


Figure 4.4: Plot showing precipitation in Kathmandu valley and discharge at Khokana station

curve number (*CN*) was calculated, using the available latest land use and soil map data were used from ICIMOD (2010).

Table 4.1: Rainfall stations in the valley

SN	Station Name	Station ID	District	Latitude	Longitude
1	Kakani	1007	Nwuakot	27_48	85_15
2	Thankot	1015	Kathmandu	27_41	85_12
3	Godavari	1022	Lalitpur	27_35	85_24
4	Khumaltar	1029	Lalitpur	27_40	85_20
5	Kathmandu airport	1030	Kathmandu	27_42	85_22
6	Sankhu	1035	Kathmandu	27_45	85_29
7	Pani Pokhari	1039	Kathmandu	27_44	85_20
8	Nagarkot	1043	Bhaktapur	27_42	85_31
9	Bhaktapur	1052	Bhaktapur	27_40	85_25
10	Changu Narayan	1059	Bhaktapur	27_42	85_25
11	Chapagaun	1060	Lalitpur	27_36	85_20
12	Budhanilkantha	1071	Kathmandu	27_47	85_22
13	Khokana	1073	Lalitpur	27_38	85_17
14	Sundarijal	1074	Kathmandu	27_46	85_25
15	Lele	1075	Lalitpur	27_35	85_17
16	Naikap	1076	Kathmandu	27_41	85_15
17	Sundarijal	1077	Kathmandu	27_45	85_25
18	Nagarjun	1079	Kathmandu	27_45	85_15
19	Tikathali	1080	Lalitpur	27_39	85_21
20	Jitpurphedi	1081	Kathmandu	27_47	85_17
21	Nangkhel	1082	Bhaktapur	27_39	85_28

Table 4.2: Monthly mean PET

Month	Average Potential Evapo-transpiration (PET)
	mm
January	75.72
February	97.34
March	131.45
April	159.04
May	159.03
June	151.64
July	138.4
August	135.64
September	121.91
October	111.58
November	88.92
December	73.44

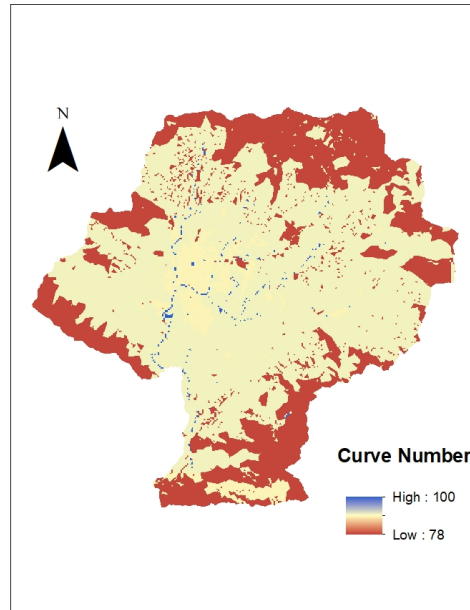


Figure 4.5: Curve Number generated by GIS

Curve Number

The curve number is simply stated as CN and also popularly referred as SCS- curve number, because it was developed by soil conservation service. It is an empirical constant used in hydrological studies for the prediction of direct runoff or infiltration from excess precipitation.

The curve number map is prepared in GIS using two maps of the study area - land use map and, soil type map. The map prepared has CN value for each grid as shown in the figure 4.5 In this study it is developed in GIS and further used as HEC-HMS input for the hydrological modelling of the basin.

To get the sub-basin wise curve number, area weighted CN is computed to each sub-basins by using the formula :

$$CN_b = \frac{CN_1 * A_1 + CN_2 * A_2 \dots CN_n * A_n}{A} \quad (4.3)$$

where,

$A_1, A_2, \dots A_n$ represent areas of polygon having CN values $C_1, C_2, \dots C_n$ respectively, and A is the total area of the basin.

4.2 Hydrological Modelling

4.2.1 Model Setup

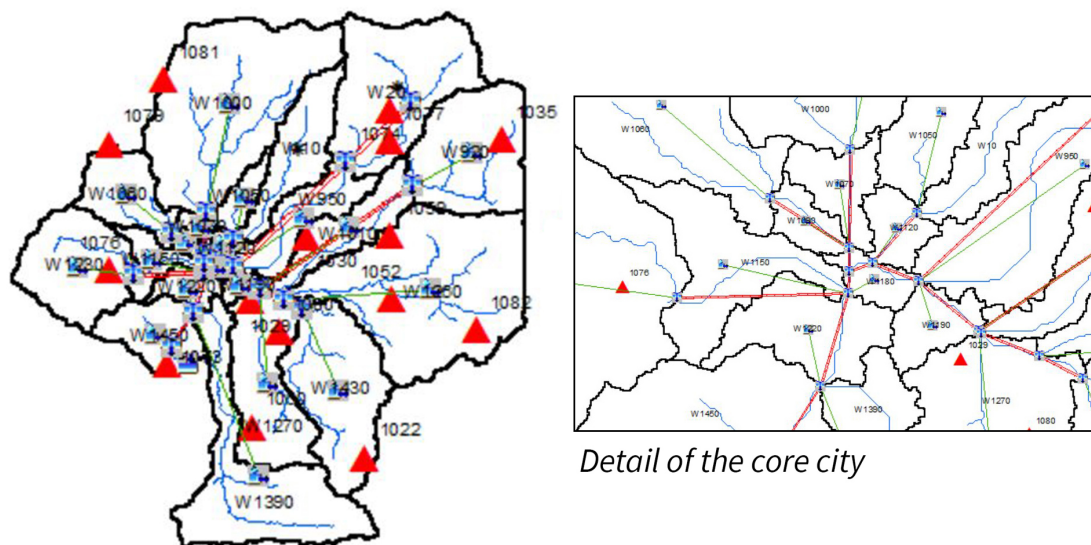


Figure 4.6: HEC-HMS model setup, with the inset showing the detail of the core city limits.

Hydrologic Engineering Center–Hydrologic Modeling System (HEC-HMS) v4.6 model was selected for this study. The DEM used as a secondary raster data was derived from USGS. Then the DEM was processed for a number of steps using Arc hydro tool. The threshold value used in stream grid development during ARC-hydro analysis tool was 4 km^2 .

The steps followed in ARC-hydro tool are as follows:

1. stream networks establishment by DEM reconditioning,
2. sink filling,
3. computation of flow direction,
4. computation of flow accumulation based on derive flow direction,
5. development of the stream grid with the threshold value of 4 km^2 in our study area,
6. stream segmentation,
7. generation of stream link grid using flow direction and stream grid as raster input,
8. catchment grid development,
9. polygon processing for turning catchment grid into a polygon per catchment,
10. drainage line processing, and

11. generation of the aggregated upstream catchments using Adjoint Catchment Processing tool.

Then, further processing was done in HEC-geoHMS 10.8 to prepare for the final hydrological model input required for HEC-HMS. The merging of sub basins were needed and done in a way that the the KMC limit had possible maximum numbers of sub-basins required for zoning. Total 25 Sub-basins were formed, 15 of them were either fully or partially under our study area, KMC.

The above steps finally allow extraction of basin characteristics, and generation of topographic characteristics of streams and sub-basins, including stream line length, stream line slope, basin slope, longest flow path, basin centroid (using center of gravity method), basin centroid elevation, and centroidal longest flow path.

The basin model prepared in HEC-geoHMS was imported into the HEC-HMS v4.6 environment. Input for the HEC-HMS modelling of the basin model generated in HEC-geoHMS is already discussed in the section 4.1.2 . Soil Conservation Service (SCS) curve number and the SCS unit hydrograph methods were used for calculating sub-basin loss and transform respectively. Transform method lag time was calculated as from the following equation Borah (1993):

$$Lag\ time\ (hour) = \frac{2.587 \times L^{0.8} \times (\frac{1000}{CN} - 9)^{0.7}}{1900 \times H^{0.5}}. \quad (4.4)$$

where,

L is the hydraulic watershed length,

CN is the curve number, and

H is the average watershed land slope.

In reach routing method, the lag time was calculated as Borah (1993):

$$Lag\ time\ (hour) = \frac{l^{0.65}}{83.4} \quad (4.5)$$

where,

l is the hydraulic length in meters.

Basin slope, river length were obtained from HEC-GeoHMS model for the basin, and then the drainage density for each basin is calculated. The runoff coefficient will be acquired from HEC-HMS model once the model is optimized for required performance level.

4.2.2 Model performance measures

After the model is set up, calibration and validation of the model is carried out for observed and simulated discharge data at Khokana. To access the reliability of the simulated results from the model, the uncertainty in results should be analyzed. To get the idea on the model

performance of any model, the results of the model have to be evaluated. This can be done by two methods-

1. visual comparison of observed and simulated plots
2. mathematical criterion to calculate the distance between observed and simulated data

From the very beginning of the hydrological modelling of a basin, there is need of of evaluating the results of a model in order to quantify the efficiency of a model in flow prediction. For this study, mathematical measures that are used to determine the model performance are-

1. **Nash-Sutcliffe Efficiency (NSE):**

NSE, Nash-Sutcliffe Efficiency, is normalized statistic which determines the relative magnitude of the residual variance (“noise”) as compared to the variance of observed data (“information”). NSE indicates how well the plot of observed versus simulated data fits the 1:1 line. NSE is computed as shown in equation,

$$NSE = 1 - \frac{\sum_{t=1}^T (Q_m^t - Q_o^t)^2}{\sum_{t=1}^T (Q_o^t - \bar{Q}_o)^2} \quad (4.6)$$

where,

\bar{Q}_o = the mean of observed discharges

Q_m^t = modeled discharge

Q_o^t = observed discharge at time t

The range of NSE is $-\infty$ and 1.0, with NSE = 1 being the optimal value. Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance. Higher the value of NSE, better is the performance of the model.

2. **Percent Bias (PBIAS):**

PBIAS is used to determine how well the model simulates the average magnitude of the model output as compared to the input. It is useful in continuous long term simulations. It is robust and commonly used criteria for evaluation of hydrological model performance and, help identifying average model simulation bias (over-prediction vs. under-prediction). PBIAS can give a deceiving evaluation of model performance in case the model over-predicts as much as it under predicts. In such case PBIAS will be close to zero even though the model simulation is poor. It is thus recommended that PBIAS should be used with other statistical and graphical criterion to determine model performance.

$$PBIAS = \frac{\sum_{t=1}^T (Q_m - Q_o)}{\sum_{t=1}^T (Q_o)} \times 100 \quad (4.7)$$

where,

Q_m = modelled discharge

Q_o = observed discharge

3. Coefficient of Determination (R^2):

Coefficient of determination (R^2) describes the degree of co-linearity between observed and simulated data. R^2 gives the proportion of the variance in observed data explained by the model. The value of R^2 ranges from 0 to 1. Higher values indicate less error variance and lower indicate more. Values greater than 0.5 are considered acceptable (Van Liew et al., 2003). Coefficient of determination is calculated as:

$$R^2 = \left[\frac{\sum_{t=1}^T (Q_m^t - \bar{Q}_m)(Q_o^t - \bar{Q}_o)}{\sqrt{\sum_{t=1}^T (Q_m^t - \bar{Q}_m)^2} \sqrt{\sum_{t=1}^T (Q_o^t - \bar{Q}_o)^2}} \right]^2 \quad (4.8)$$

where,

\bar{Q}_o = the mean of observed discharges

\bar{Q}_m = the mean of modelled discharges

Q_m^t = modeled discharge

Q_o^t = observed discharge at time t

4.2.3 Model performance evaluation criteria

The model performance evaluation is done as per Moriasi et al. (2015) for the mentioned model performance measures described in section 4.2.2. The recommended performance evaluation criteria for the 3 statistical performance measures—NSE, PBIAS, and R^2 for discharge is summarized in the Table 4.3 as adopted from Moriasi et al. (2015). The evaluation criteria for discharge simulation is taken as same for all three temporal scales—daily, monthly, and annually.

Table 4.3: Model performance evaluation criteria

Measure	Very Good	Good	Satisfactory	Not Satisfactory
R_2	$R_2 > 0.85$	$0.75 < R_2 \leq 0.85$	$0.60 < R_2 \leq 0.75$	$R_2 \leq 0.60$
NSE	$NSE > 0.80$	$0.70 < NSE \leq 0.80$	$0.50 < NSE \leq 0.70$	$NSE \leq 0.50$
PBIAS(%)	$PBIAS < \pm 5$	$\pm 5 \leq PBIAS < \pm 10$	$\pm 10 \leq PBIAS < \pm 15$	$PBIAS \geq \pm 15$

4.3 Roof area calculation

The fourth major part of the study data is obtained from Open Street Map (OSM). This study is focused in rainwater harvesting in urban setting. In the city area, a large chunk

of the actual area has buildings. And so, the roof area of the buildings become significant in determining the potential of rainwater harvesting. The most detailed and accurate way to get the rooftop area of given buildings would be to get individual building's municipal drawings, however that is extremely impractical due to the potential of time investment required, as well as legitimate privacy and safety concerns of the building owners. Instead, OSM output are used for this study. Specially for a developing country like Nepal, and for projects that do not have any fundings, open source alternatives to any software or service is a great, and encouraging solution.

4.4 Multi-criteria decision analysis

Analytic Hierarchy Process-based multi-criteria decision analysis, as described by Wind and Saaty (1980) was used in this study. Here, RWH potential zones identification used four criteria, they are:

1. runoff coefficient
2. roof area
3. drainage density, and
4. slope

The runoff coefficients for all the sub-basins were obtained from the ratio of HEC-HMS simulated annual runoff and observed annual runoff at Khokana station. Slope calculation and drainage density is already discussed in previous sub-section. Drainage density was taken as the total length of the drains of each sub-basin divided by the respective sub-basin area. Based on the expert opinion and literature review on similar research weights were assigned for all of the criteria and their associated features as per 1–9 scale suggested by Wind and Saaty (1980). Thus, RWH potentiality consideration was reflected on assigned weights and pair-wise comparison matrices of the assigned weights, whereas those were constructed using the AHP by Wind and Saaty (1980). By using the eigenvector technique, the assigned weights were then normalized and examined for consistency by computing consistency ratio (CR) using equatin 4.9. The Consistency ratio should be below 15%.

$$CR = \frac{k_{max} - n}{n - 1} \quad (4.9)$$

where,

k_{max} = Principle eigenvector was computed by the eigenvector technique

n = number of criteria or factors

To delineate RWH potential zones with assigned RWH potentiality index (RWHPI), all the required four layers along with their normalized weights were integrated in ArcGIS[®], where the Weighted Sum acts as WLC method. This provides the ability for the assignment of different weighted value to different layers according to their importance. Multiple inputs were then combined to create an integrated analysis. The following approach was used for calculating the RWHPI,

$$RWHPI = (RC)_f(RC)_c + (RA)_f(RA)_c + (DD)_f(DD)_c + S_f S_c \quad (4.10)$$

Where,

$RWHPI$ = 'Rainwater Harvesting Potential Index' for a sub-basin.

RC_c = normalized weight of the runoff coefficient criteria.

RC_f = normalized weight of a feature of the runoff coefficient criteria.

RA_c = normalized weight of the roof area criteria.

RA_f = normalized weight of a feature of the roof area criteria.

DD_c = normalized weight of the drainage density criteria.

DD_f = normalized weight of a feature of the drainage density criteria.

S_c = normalized weight of the slope criteria.

S_f = normalized weight of a feature of the slope criteria.

4.5 Quantity runoff from catchments

Runoff from catchment is a function of the precipitation and the runoff coefficient of the catchment and the area of catchment. In this study, roof catchments and basin catchments are considered separately. Roof catchments can be of a wide variety depending on the design of the roof. In urban context of Nepal majority of roofs are cemented but there is a non-trivial proportion of corrugated sheets, and more recently, tiles. Thus, runoff coefficient for the roofs will vary accordingly. Since it was not practical to do the actual field survey to assess information, a study on the relevant topic was referred, where a sample survey was done for Ward 9 of KMC (Gautam, 2017). It showed that 85 percentage of the total houses had cemented roof, 13 percentage had tiles and only 3 percentage had corrugated sheet (Gautam, 2017). The runoff coefficient for roof catchment in the present study was scaled by the weighted average method from the study referenced. Runoff coefficient for cemented roof, tiles and corrugated sheet was found to be 80, 85, and 75 respectively (Shakya and Thanju, 2013).

On the larger scale, Rainwater harvesting is not limited to roof catchments but also accounts for the harvesting through extensive area in the city. Areas like lawns, roads, parks, streets are also potential areas for harvesting rainfall. The runoff coefficient of different sub-basins are estimated in the study itself after the hydrological modeling of in

HEC-HMS. It is obtained by the the total volume of rainfall in each sub-basin divided by the runoff volume from respective sub-basin as simulated from the modelling. The runoff quantity is then calculated by the equation:

$$R_v = \frac{A \times C \times P_v}{1000} \quad (4.11)$$

where,

C = runoff coefficient

R_v = Runoff volume (m³)

P_v = Precipitation (mm)

A = Catchment area (m²)

This study estimates the maximum available quantity of rainfall available for harvesting in both the cases:- Roof catchment within KMC, and entire KMC as catchment including roofs.

Chapter 5: Results and Discussions

5.1 Validation of the HEC-HMS model for rainfall runoff simulation

To get the estimate of basin wise runoff coefficient, rainfall runoff modelling was done in HEC-HMS. Before using the outputs from any model, one has to check on its skill to model any physical phenomena within desired efficiency. Thus, to check on the reliability of the HEC-HMS model to simulate the rainfall -runoff calibration and validation of the model was performed. Calibration of the model was done for the year 2000-2002 and validation was done for the year 2003-2007 using daily data for discharge at Khokana outlet. Observed discharge data for Khokana station were plotted against simulated discharge from model for the same outlet. Also, three different statistical criterion: Nash-Sutcliff Efficiency (NSE), percent bias (PBIAS), and coefficient of determination (R^2) of the best-fit line of observed and modeled discharge plot are accounted. The judgement on model performance evaluation as done by Moriasi et al. (2015). The table 4.3 adopted from Moriasi et al. (2015) summarizes the criterion which classifies the model performance as Very good, Good, Satisfactory, and Not Satisfactory.

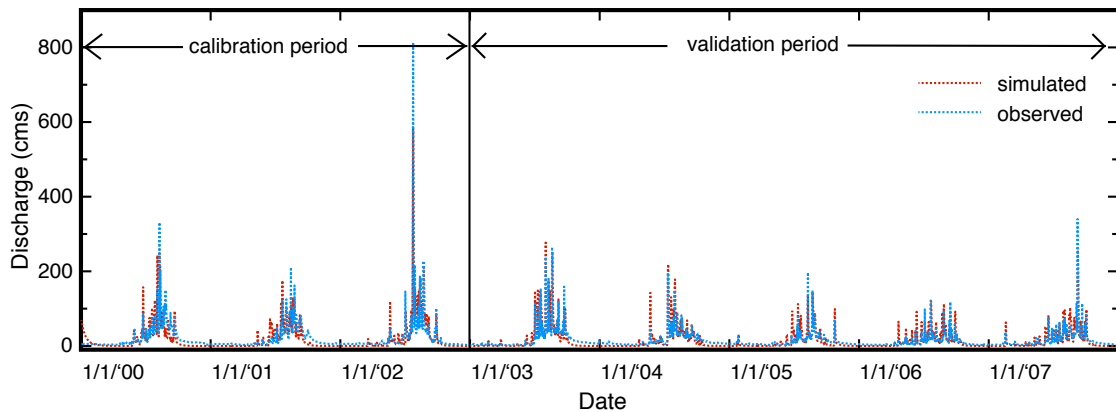


Figure 5.1: Daily discharge of observed vs simulated for Khokana

Figure 5.1 and figure 5.2 are the plots for observed and simulated discharge at Khokana station in the period of calibration and validation for daily and monthly temporal scale respectively. These plots give the visual examination on how good the model is in rainfall-runoff simulation of the basin. From the figures it is seen that the simulated discharges follows the observed discharges quite well in both of the temporal scale.

The table 5.1 is the summary of the three statistical criterion used in evaluation of the model performance skill on rainfall-runoff simulation using observed and simulated discharge at Khokana after the optimization. For daily temporal scale, the model had the NSE of 73.3% and 52% for calibration and validation respectively. The cumulative volume of observed and simulated discharge for calibration period was -8.48% i.e simulated discharge volume low by 8.48%, while in validation the simulated cumulative volume

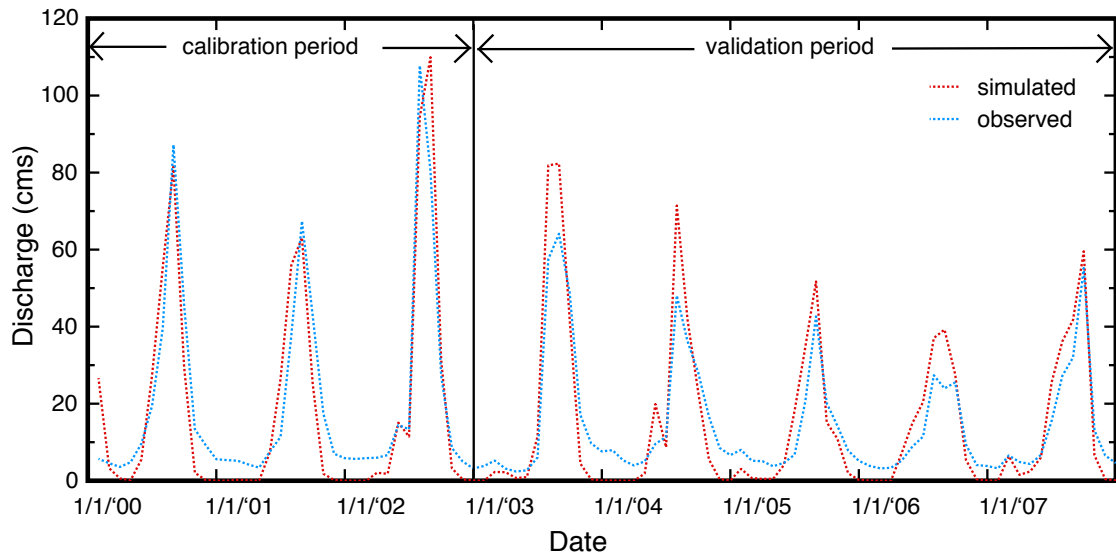


Figure 5.2: Monthly discharge of Observed vs simulated data for Khokana

Table 5.1: Summary of model performance

Criteria		Calibration (2000-2002)	validation (2003-2007)	overall (2000-2007)
Percent Bias in Volume (PBIAS)	D	-8.4	3.62	-3.05
	M	-8.49	1.38	-3.299
Coefficient of Determination (R^2)	D	0.744	0.741	0.725
	M	0.876	0.900	0.875
Nash-Sutcliffe Efficiency (NSE)	D	0.733	0.52	0.676
	M	0.842	0.79	0.865

exceeded the observed cumulative volume by 3.63. The R^2 value for for calibration and validation were 0.744 and 0.741 respectively. Similarly, the model performance evaluation criteria for monthly discharge showed that the model is able to simulate the discharge with NSE of 84.2% and 79% for calibration and validation respectively. While discharge volume was under predicted by model in calibration by 8.48% and slightly over predicted i.e 1.38% in validation years (2003-2007). The figure 5.3 and figure 5.4 is the plot of observed discharge against simulated discharge for calibration and validation period. It can be seen that the observed and simulated data have quite good correlation with the coefficient of determination (R^2), 0.876 and 0.906 in calibration and validation. The performance for daily discharge met satisfactory condition, while the model met good performance for monthly discharge. Thus, the results obtained from the model was okay to use in the

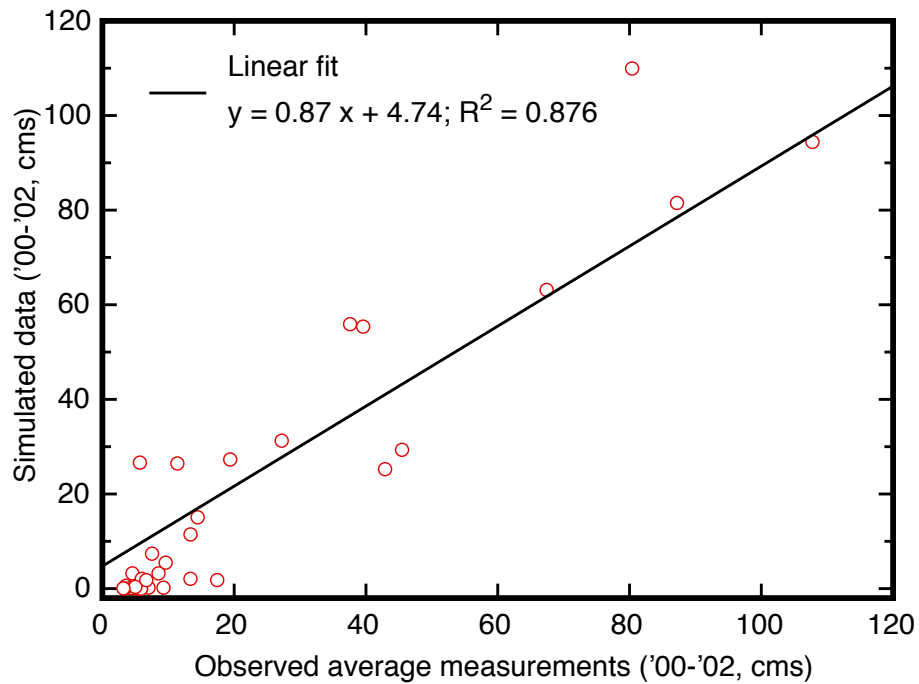


Figure 5.3: Correlation of observed vs simulated monthly discharge (2000-2002)

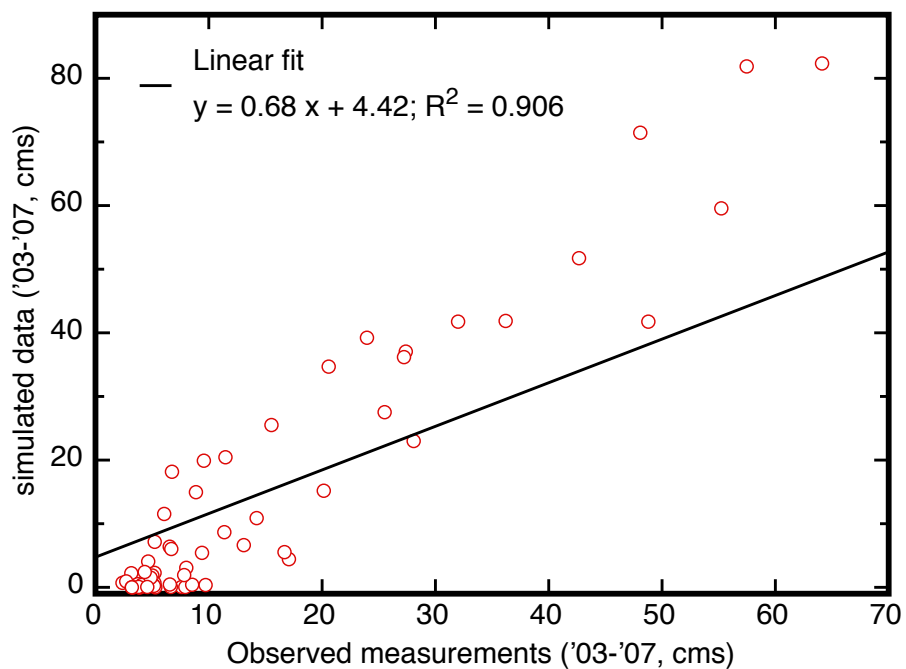


Figure 5.4: Correlation of observed vs simulated monthly discharge (2003-2007)

5.2 Rainwater harvesting potentiality

Rainwater harvesting potential of any given area may depend on various different factors. The factors may be physical as well as socio-economic ones. Due to the time constraint of this study, availability of reliable data, and the funding, the study only covered specific parameters, all being physical parameters. No socio-economic factors were accounted

for assessing the potential of Rainwater harvesting in KMc. The index is computed as the function of four basin characteristics—average basin slope, runoff coefficient, drainage density, and roof area. The four factors in this study are discussed in detail in the following sections.

5.2.1 Roof areas

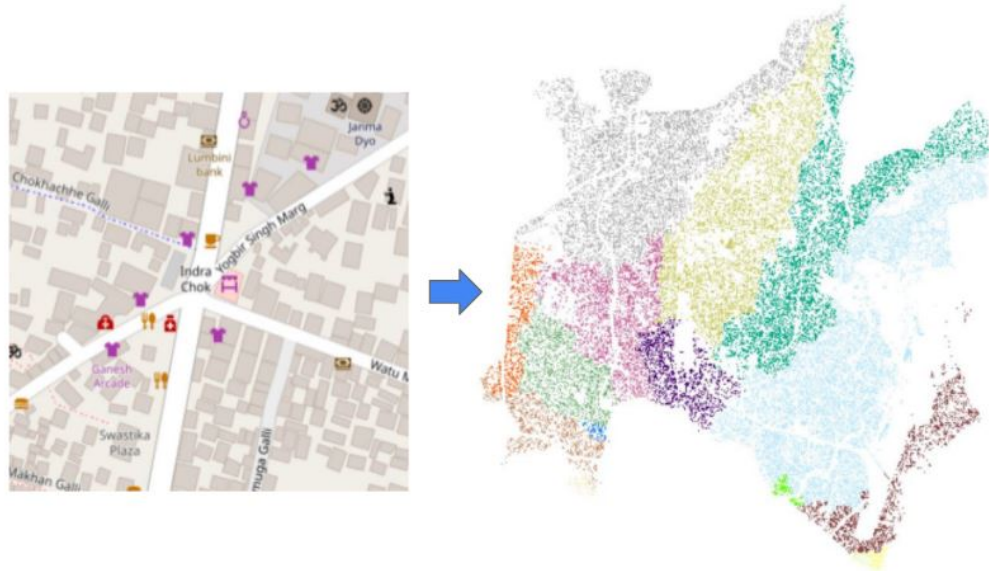


Figure 5.5: Computed roof areas using OSM for the study.

Open street map (OSM) was used to assess the roof area within the Kathmandu Metropolitan City. Initially, the buildings footprints were derived from OSM in the form of shape files. These shape files with geometric features were then loaded in GIS environment. In GIS one can assess the roof area of each footprint of buildings that were derived from OSM. Then the roof areas were segregated by the different sub-basins with color as shown in Fig. 5.6 with respect to the sub-basins within KMC. The total area of the roof falling under respective sub-basins is listed on the table 5.2. Further the roof area then was acquired in terms of the percentage of the sub-basins, and mapped within KMC. It is found that the about 30% of the total area of KMC falls under buildings only. The percentage of roof area within the sub-basins varied from 10% to 42%. The figure clearly shows the rivers that flow through the city.

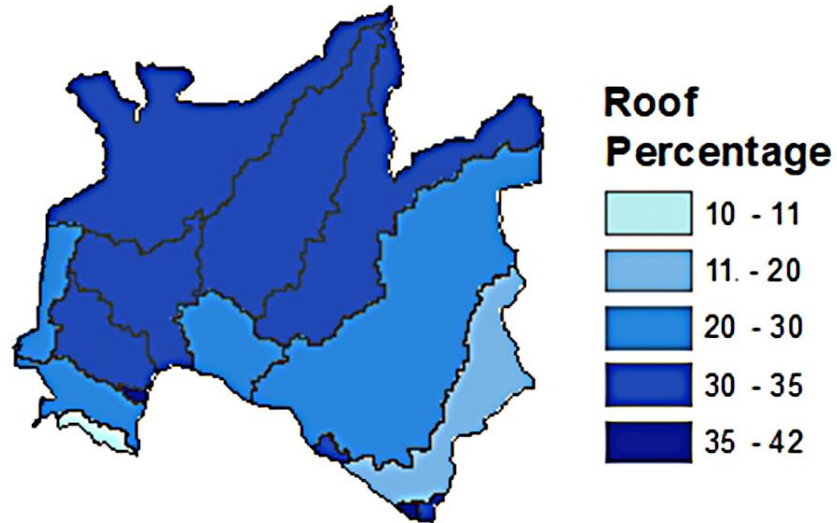


Figure 5.6: Sub-basin wise roof area percentage within KMC.

Table 5.2: Sub-basin wise roof area percentage within KMC.

Name	Sub-basin area	Roof area (m ²)	Roof-area
	<i>m²</i>	<i>m²</i>	%
W820	8600648	2684825	31.21654
W850	6915352	2406748	34.80297
W950	12166818	3594747	29.5455
W1010	3741211	738318.2	19.73474
W1050	6867857	2135854	31.09928
W1060	1166889	331857.7	28.43953
W1070	3478980	1143650	32.87314
W1090	2092015	673804.8	32.20841
W1120	2037217	559882.3	27.4827
W1140	106061	38174.27	35.99275
W1150	1515383	381815.8	25.196
W1190	173775	59867.36	34.45108
W1220	390200	42023.69	10.76978
W1260	123403	41183.12	33.37286
W1430	78087	33450.19	42.83707

5.2.2 Drainage density

Drainage density is defined as the total length of rivers or drainage in the given area or a catchment. It describes the spacing and distribution of drainage system of the catchment. Drainage density of any given sub-basin is derived using the equation,

$$D_d = \frac{L_r}{A_b} \quad (5.1)$$

where,

D_d = Drainage density

L_r = Total length of river within sub-basin

A_b = Total area of the sub-basin

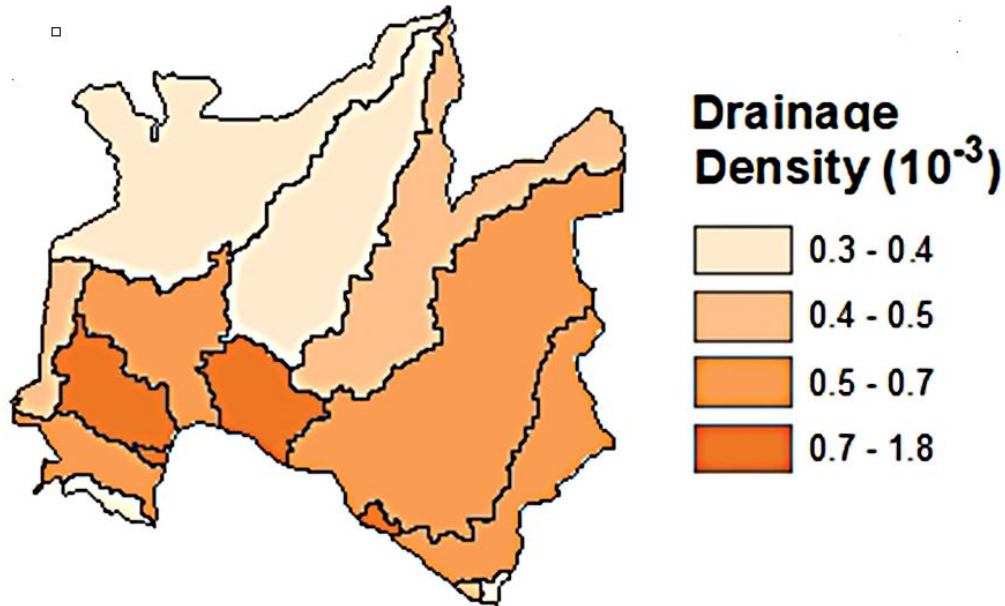


Figure 5.7: Sub-basin wise drainage density within KMC

The total length of drainage of the sub-basin is derived from the basin properties of the hydrological model prepared in HEC-geoHMS. Also, the area of the sub-basin is also derived in GIS. Then using equation 5.1, the drainage density is computed. It was found that the value of drainage density for the sub-basins of our study area varied from 0.0003 m/m^2 to 0.0018 m/m^2 . The sub-basins with higher drainage density were found around the Bagmati river, which is quite obvious to get.

5.2.3 Runoff coefficient

Runoff coefficient one of the most important parameter of this study in assessing rainwater harvesting potentiality of KMC. Runoff coefficient is obtained as the ratio of the total runoff to the total precipitation received by that area. Hydrological modelling of the Bagmati basin. The sub-basin wise precipitation is derived from the Thiessen polygon method accounting the precipitation from the 21 different rainfall stations distributed around the study basin as described in table 4.1. Use of Thiessen polygon gives the better spatial distribution of rainfall across the study area by the area weightage given to each station for

respective sub-basins. The sub-basin wise precipitation was thus obtained by the Thiessen polygon method by using the formula 4.1. The runoff from each sub basins is then derived from the output of the modelled basin in HEC-HMS. To get the estimate of runoff coefficient of each sub-basin the received precipitation was taken as the average of the period of 7 years (2000-2007). The figure 5.8 maps the sub-basin wise runoff coefficient

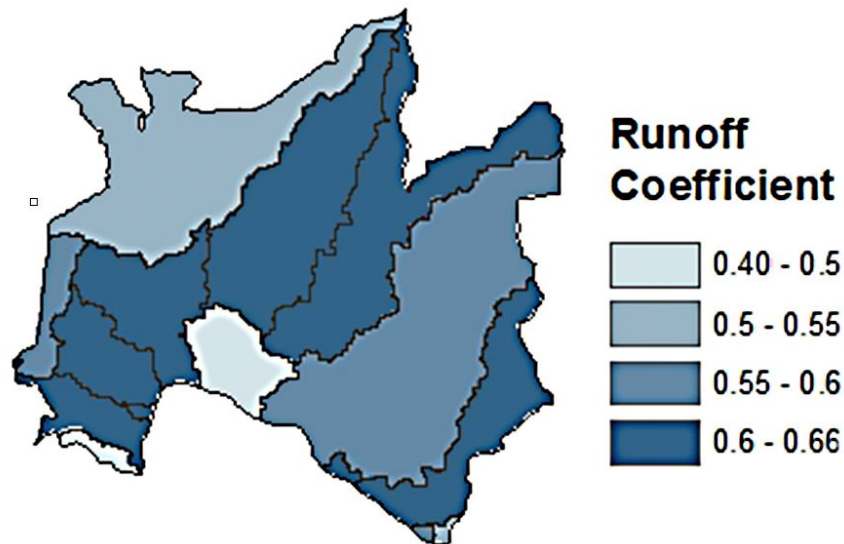


Figure 5.8: Sub-basin wise runoff coefficients within KMC

of the sub-basins within KMC. The obtained runoff coefficients varied from 40% to 66%. Higher number of sub-basins had high runoff coefficient above 60% i.e 7 of of 15. Fewer sub-basins had relatively low runoff coefficients.

5.2.4 Basin slope

Basin slope is obtained from the Digital Elevation Model of the study area. In GIS, the sub-basin wise average basin slope is computed in terms of percentage rise. Thus obtained slope was then categorized using natural jenks method in GIS and mapped as shown in the figure 5.9. It can be seen that the average basin slope of the sub-basis varied from 5% to 33%. The slopes are milder in the central part of valley and around the Bagmati river of KMC. This only makes those areas more suitable for human settlement and also for rainwater harvesting.

5.2.5 Rainwater harvesting potentiality index

After the considered four factors characteristics of the basins were computed individually, the rainwater harvesting potentiality index was then computed as the function of the those factors. Multi criteria decision based Analytical Hierarchy Process was carried out as described in the section 4.4. Based on the literature and opinions from the expert, weights were assigned for four criteria and their associated features in the scale of 1–9 as suggested

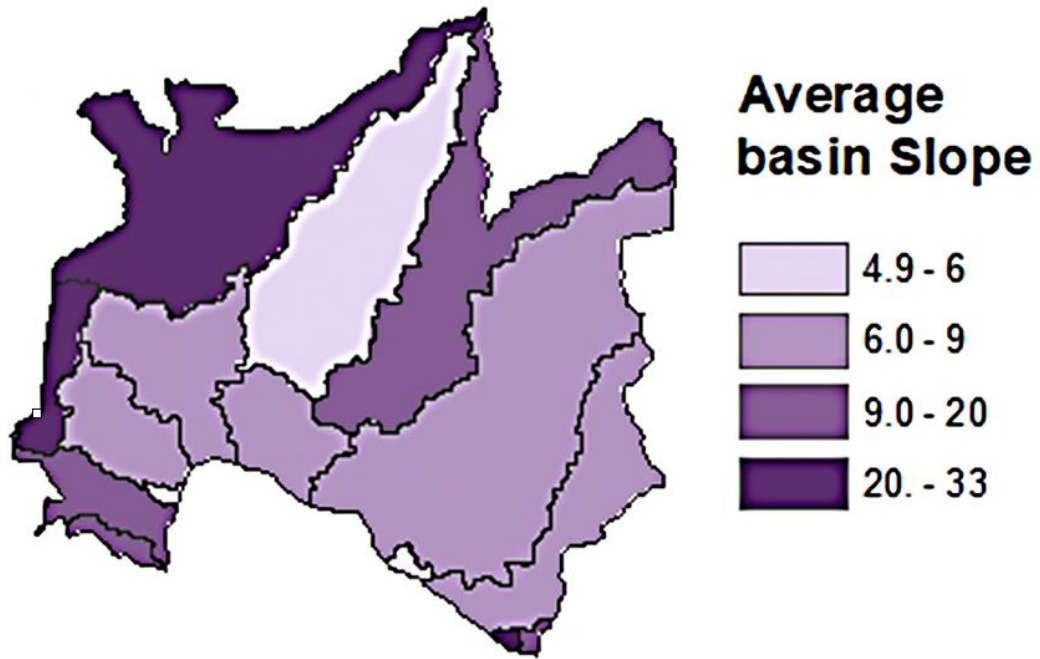


Figure 5.9: Sub-basin wise average basin slope

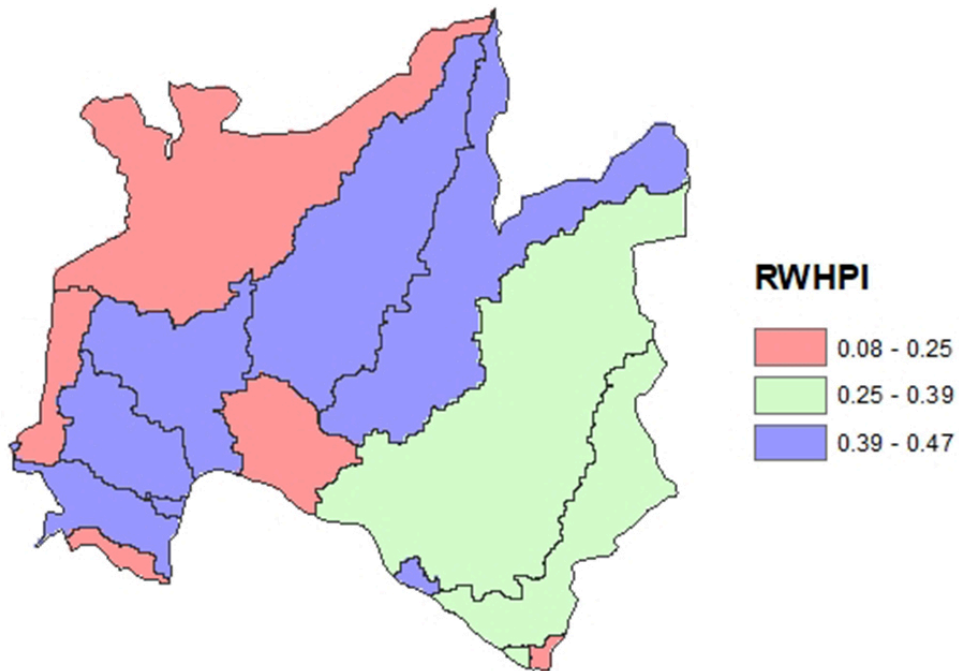


Figure 5.10: Computed rain water harvesting potential.

by Saaty (1980). Thus, RWH potentiality in the study resonates on assigned weights and pair-wise comparison of the factors in the form of matrices of the weight assigned. The assigned weights to these factors were normalized by the technique - eigen vector technique and also examined for consistency by calculated consistency ratio using equation 4.9. Depending upon these factors and the provided normalized weights to their their features as per Wind and Saaty (1980), Rainwater Harvesting Potential Index was calculated using

Eq. 4.10. The summary of the criteria and normalized weights are tabulated in Table 5.3. Thus computed RWHPI of the present study area ranged from 0.086 to 0.470. It was further broadly classified into three classes by in ArcGIS[®], categorizing the value ranges 0.086-0.250 as low; 0.250-0.390 as moderate; and 0.390-0.470 as good potential index. From Fig. 5.10, it is clearly seen that vast majority of the basin is well suited for rainwater harvesting, as most of the region has either moderate, or good potential index for RWHPI. Six out of 15 basins comprising of 28% of the total basin area, i.e 14.23 km², was found to have good RWHPI. Moderate RWHPI with 4 sub basins having 46.30% of the total basin area, while 24.90% of the KMC has low RWHPI.

Table 5.3: Weights of selected criteria and their features

Criteria	Features	Normalized weight
Runoff coefficient		0.70
	0.40-0.50	0.07
	0.50-0.55	0.15
	0.55-0.60	0.30
	0.60-0.66	0.48
Drainage Density (m/m ² 10 ⁻³)		0.13
	0.30-0.40	0.08
	0.40-0.50	0.15
	0.50-0.70	0.31
	0.70-1.88	0.46
Slope (%)		0.04
	4.9-6.0	0.42
	6.0-10.0	0.33
	10.0-20.0	0.02
	>20.0	0.08
Roof density (%)		0.13
	<11	0.06
	11-20	0.13
	20-30	0.19
	30-35	0.25
	35-43	0.38

Table 5.4: Runoff volume from buildings roof of KMC

Sub-basins	Total roof area (m^2)	Average annual ppt (mm)	Runoff Volume (MLD)
W820	2684824.85	1797	10745384
W850	2406748.12	1677	8989930
W950	3594747.08	1505	12053353
W1010	738318.17	1627	2675117
W1050	2135854.34	1465	6969439
W1060	331857.71	1526	1127823
W1070	1143650.11	1264	3220817
W1090	673804.76	1340	2010964
W1120	559882.34	1193	1488293
W1140	38174.27	1193	101475
W1150	381815.84	1422	1209598
W1190	59867.36	1193	159141
W1220	42023.69	1285	120278
W1260	41183.12	1503	137882
W1430	33450.19	1565	116574
Total			51,126,067

5.3 Potential quantity rainfall for harvesting and meeting city demands

5.3.1 Quantity rainwater harvest from roof catchments

Roof areas are one of the major catchments for RWH in urban context or cities. On average buildings alone covered 30% of the total area of KMC. This section discuss the potential of rainwater harvest from the KMC considering roof of the buildings as catchment. Roof area are one of the most important factor for roof rainwater harvest specially for domestic use. The factor becomes more important in study area like this i.e urban settings where considerable amount of the area of the KMC is covered with buildings, thus providing catchment for rainwater harvesting. Where there is not only existing water crisis due to its high population growth and urbanization, but the place also receives good amount of rainfall R-RWH is a serious solution to the problem. The quantity runoff from roof catchment is calculated using formula 4.11. The required precipitation is received from the DHM and after processing using Thiessen polygon, area here is the roof catchment and runoff coefficient of the roof is adopted depending on the literature (Gautam, 2017). The average runoff coefficient of the roof catchment was obtained as 0.813 as discussed in section 4.5. The calculated average runoff volume via roof catchment within KMC resulted in 51 MLD. The basin wise detail is shown in table.5.4.

5.3.2 Quantity rainwater harvest from KMC - catchment

Basin wise daily precipitation (derived using Thiessen polygon) of 8 years was used as rainfall input. HEC-HMS gives the basin-wise total runoff volume and total rainfall is obtained by multiplying the basin area with the precipitation on the respective basin. The sub-basin wise runoff coefficient is obtained as discussed in section 5.2.3. The summary of total annual rainfall of the respective sub-basins within the Kathmandu Metropolitan City is summarized in Table 5.5. The study showed that the total annual runoff volume from KMC is 44 MCM (Million Cubic Meter) which is equivalent to 121 MLD (million liters per day).

Table 5.5: Basin wise annual runoff within KMC

Name	Area within KMC m ²	Runoff coefficient	Annual ppt mm	Annual runoff m ³
W850	6915352	0.606	1677	7031773
W950	12166818	0.567	1505	10398651
W820	8600648	0.514	1797	7957229
W1010	3741211	0.600	1627	3651534
W1050	6867857	0.638	1465	6421189
W1060	1166889	0.580	1526	1034122
W1070	3478980	0.674	1264	2967659
W1090	2092015	0.604	1340	1694281
W1120	2037217	0.395	1193	962181.1
W1150	1515383	0.602	1422	1299092
W1180	106061	0.658	1193	83295.39
W1190	173775	0.509	1193	105584.9
W1220	390200	0.475	1285	238601.3
W1260	123403	0.540	1503	100342.8
W1430	78087	0.567	1565	69342.89
Total	49453895			44,014,878

5.3.3 City water demand management

The Kathmandu valley currently is in 80% water deficit. The study looked after the potential the city has in rainwater harvesting and also the potential quantity that can be harvested in a year from - roof of the buildings and also from the Kathmandu Metropolitan City. This quantity is compared with respect to the existing water demand. In the figure 5.11, first stacked bar graph shows the current status of water demand and supply. Later one is the probable future in the optimistic scenario for water demand and supply status of the valley which was deduced from the study. The scenario includes the successful implementation of Melamchi water supply project. The current gap is so huge that the Melamchi alone would not be enough in addressing the supply deficit by meeting the demand only through

the mid-way. While on discussing the most optimistic of Rainwater harvesting from KMC, the study showed that RWH from KMC alone could yield the water of 121 MLD. With the addition of this water in the water supply system of the Kathmandu valley, it is seen that that water supply deficit will drop as low as 18% from the existing huge deficit of 10%. This leap in the supply here while considering RWH is only from KMC while demand for whole Kathmandu valley is considered. Thus, it becomes more clear regarding the potential of RWH in addressing the domestic demand. With all these positives of RWH, the economic constraints and physical limitation in the storage tank sizing and, quality of water remain there.

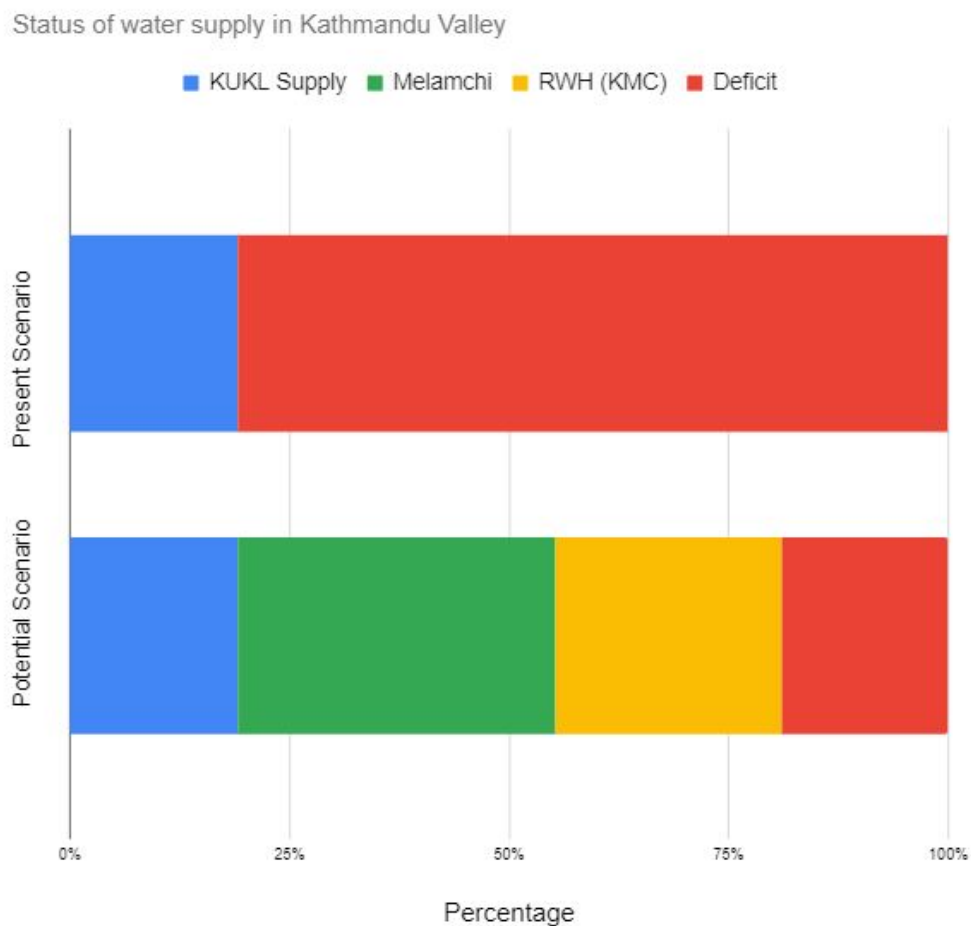


Figure 5.11: Status of supply-demand in Kathmandu Valley

Proper harvesting of water means better utilization of rainwater. Rainwater can be used for meeting the domestic as well as for recharging ground water through shallow wells. What this directly leads to is less runoff of rainwater into the streets. This would ultimately result in less urban flooding as well.

Chapter 6: Conclusions and Recommendation

6.1 Conclusions

Kathmandu Metropolitan city is already under stress of huge water demand deficit. The water supply from KUKL is below 20% of the demand. Even if Melamchi Drinking water project is implemented successfully in future it will not be able to fulfill the gap and still leave a huge space to be filled. Residents of KMC rely on alternative sources of water, the major one being ground water. The extraction amount of groundwater is very high, which is accompanied by lower recharge due to growing urbanization. The situation is only growing worse. In addition to this, KMC is also facing increased monsoon flooding both in terms of frequency and magnitude, further enhanced due to urbanization and climate change.

In this study, the potentiality of rainwater harvesting was studied as a solution to solving both the problems. ArcGIS[®], Open Street Map, and HEC-HMS were major tools used in this study. Ultimately, the potential was assessed with Rainwater Harvesting Potential Index (RWHPI). Kathmandu Metropolitan City was divided into various zones, derived as sub-basins of the Bagmati basin. The conclusions derived from this research are listed as follows:

1. It was found that the majority of area, 75.1%, in KMC has moderate to good potential index for rainwater harvesting. Only a small area of KMC from this study 24.9%, has low RWHPI.
2. Upon considering the roof area for RWH, it showed that it could supply 51 MLD domestic water to supplement the lacking supply of 91 MLD from the municipal source, which goes a long way to meet the total demand of 218 MLD within KMC.
3. The total annual runoff volume for KMC from the estimates of runoff coefficient from the model was found as 44,014,878 m^3 i.e 121 MLD (Million liters per day).
4. In the most optimistic scenario, where Melamchi Water Supply Project is successfully implemented along with the rainwater harvesting from KMC, the supply deficit of the entire Kathmandu Valley will drop to 18% from massive 80% of the current scenario.
5. The rainwater when harvested would prevent it from being drained into the streets, which would help reduce the intensity of urban flooding to some extent in the city.

6.2 Recommendations

The specific recommendations from the study are listed as follows:

1. In order to combat economic challenges, government subsidies may go a long way in encouraging rainwater harvesting.
2. For a more accurate data source, first hand survey and municipal drawings may be considered instead of open street map, which would result in higher accuracy results.
3. Extensive research with taking an account on other different parameters (both physical as well as socio-economic) would return a more complete model for assessing the potential of rainwater harvesting.

References

- Akter, A. and Ahmed, S. (2015). Potentiality of rainwater harvesting for an urban community in Bangladesh. *Journal of Hydrology*, 528:84–93.
- Bajracharya, A. R., Rai, R. R., and Rana, S. (2015). Effects of urbanization on storm water run-off: a case study of Kathmandu metropolitan city, Nepal. *Journal of the Institute of Engineering*, 11(1):36–49.
- Borah, D. K. (1993). Soil and water conservation engineering.
- Central Bureau of Statistics (2019). Environment of statistic of Nepal 2019. Technical report, National Planning Commission, Government of Nepal, Kathmandu, Nepal.
- Dahal, V., Shakya, N. M., and Bhattarai, R. (2016). Estimating the impact of climate change on water availability in Bagmati basin, Nepal. *Environmental Processes*, 3(1):1–17.
- Devkota, N. and Shrestha, N. M. (2021). Development of rainfall–runoff model for extreme storm events in the Bagmati river basin, Nepal. *Journal of Engineering Issues and Solutions*, 1(1):158–173.
- Dixit, A. and Upadhyay, M. (2005). Augmenting groundwater in Kathmandu valley: challenges and possibilities. Technical Report 13, Nepal Water Conservation Foundation, Kathmandu, Nepal.
- Duwal, S., Thapa, A. B., Upadhyay, S., Prajapati, R., and Silwal, P. (2019). Shallow groundwater level variation in the Kathmandu valley: A gis-based study. *KEC conference 2019*.
- Gado, T. A. and El-Agha, D. E. (2020). Feasibility of rainwater harvesting for sustainable water management in urban areas of Egypt. *Environmental Science and Pollution Research*, 27(26):32304–32317.
- Ganesh, R., Koju, R., and Prajapati, R. R. (2018). Assessment of groundwater quality and water table mapping of Bhaktapur municipality. *Journal of Science and Engineering*, 5:43–50.
- Gautam, D. and N Prajapati, R. (2014). Drawdown and dynamics of groundwater table in Kathmandu valley, Nepal. *The Open Hydrology Journal*, 8(1).
- Gautam, R. (2017). Potential of rainwater harvesting in Nepal: A case study of Kathmandu. Master's thesis, Norwegian University of Life Sciences, Ås.
- ICIMOD (2010). Regional database system.

- Jalsrot Vikas Sanstha (2018). Water Nepal: A historic perspective. *Jalsrot Vikas Sanstha*.
- JICA (1990). Groundwater management project in Kathmandu valley. *JICA Final Report, Executive Summary*, page 2.
- Khatakho, R., Gautam, D., Aryal, K. R., Pandey, V. P., Rupakhety, R., Lamichhane, S., Liu, Y.-C., Abdouli, K., Talchabhadel, R., Thapa, B. R., et al. (2021). Multi-hazard risk assessment of Kathmandu valley, Nepal. *Sustainability*, 13(10):5369.
- KUKL (2021). Kathmandu Upatyaka Khanepani Limited annual report. Technical Report 13, Kathmandu Upatyaka Khanepani Limited, Kathmandu, Nepal.
- Macrotrends (2021). Kathmandu, Nepal metro area population 1950-2021. <https://www.macrotrends.net/cities/21928/Kathmandu/population>. Accessed: 2021-08-13.
- Mahmoud, W. H., Elagib, N. A., Gaese, H., and Heinrich, J. (2014). Rainfall conditions and rainwater harvesting potential in the urban area of Khartoum. *Resources, Conservation and Recycling*, 91:89–99.
- Mahnot, S., Sharma, D., Mishra, A., Singh, P., and Roy, K. (2003). ‘water harvesting management’ in kaul v (ed) practical guide series 6. *Jaipur: SDC Intercooperation Coordination Unit*.
- Maliene, V., Grigonis, V., Palevicius, V., and Griffiths, S. (2011). Geographic information system: Old principles with new capabilities. *Urban Design International*, 16(1):1–6.
- Ministry of Physical Planning and Works (2002). Optimising water use in Kathmandu valley. Technical report, Ministry of Physical Planning and Works.
- Mohanty, A. (2011). State of environment in Kathmandu valley, Nepal: a special review. *Journal of the Institute of Engineering*, 8(1-2):126–137.
- Moriasi, D. N., Gitau, M. W., Pai, N., and Daggupati, P. (2015). Hydrologic and water quality models: Performance measures and evaluation criteria. *Transactions of the ASABE*, 58(6):1763–1785.
- Nyachhyon, B. L. (2006). Service enhancement and development of sanitary sewerage system in urban and semi-urban setting in Nepal. *Policy paper*, 23:86–94.
- Pandey, P. and Dugar, S. (2019). Flood hazard mapping in an urban context: A case study of hanumante stream, Bhaktapur (Nepal). In *Proceedings of IOE Graduate Conference*.
- Pandey, V. P., Chapagain, S. K., and Kazama, F. (2010). Evaluation of groundwater environment of Kathmandu valley. *Environmental Earth Sciences*, 60(6):1329–1342.

- Pradhan-Salike, I. and Pokharel, J. R. (2017). Impact of urbanization and climate change on urban flooding: a case of the Kathmandu valley. *JNRD-Journal of Natural Resources and Development*, 7:56–66.
- Saurav, K., Shrestha, S., Ninsawat, S., and Chonwattana, S. (2021). Predicting flood events in Kathmandu metropolitan city under climate change and urbanisation. *Journal of Environmental Management*, 281:111894.
- Shakya, B. and Thanju, J. P. (2013). Technical guidelines for installation of rainwater harvesting system and its operation. *Hydro Nepal: Journal of Water, Energy and Environment*, 12:45–51.
- Shrestha, R. R. et al. (2009). Rainwater harvesting and groundwater recharge for water storage in the Kathmandu valley. *ICIMOD Newsletter*, 56:27–30.
- Shrestha, S., Rajbhandari, K., Singtan, D., and Mishra, S. (2011). Rainwater harvesting for recharging shallow groundwater. *A WaterAid Nepal*, 41.
- Suwal, B. R. (2014). Internal migration in Nepal. *Central Bureau of Statistics*.
- Timsina, N. P., Poudel, D. P., Upadhyaya, R., and Shrestha, A. (2020). Trend of urban growth in Nepal with a focus in Kathmandu valley: A review of processes and drivers of change. *Tomorrow's Cities*.
- Van Liew, M., Arnold, J., and Garbrecht, J. (2003). Hydrologic simulation on agricultural watersheds: Choosing between two models. *Transactions of the ASAE*, 46(6):1539.
- Wind, Y. and Saaty, T. L. (1980). Marketing applications of the analytic hierarchy process. *Management science*, 26(7):641–658.