HYDROLOGICAL RESPONSE OF AN EXPERIMENTAL WATERSHED OF LESSER HIMALAYA

Ph.D. THESIS

by

VIKRAM KUMAR

DEPARTMENT OF HYDROLOGY
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE - 247 667 (INDIA)
OCTOBER, 2018


भारतीय प्रौद्योगिकी संस्थान रुड़की
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE

HYDROLOGICAL RESPONSE OF AN EXPERIMENTAL WATERSHED OF LESSER HIMALAYA

A THESIS

***Submitted in partial fulfilment of the
requirements for the award of the degree***

of

DOCTOR OF PHILOSOPHY

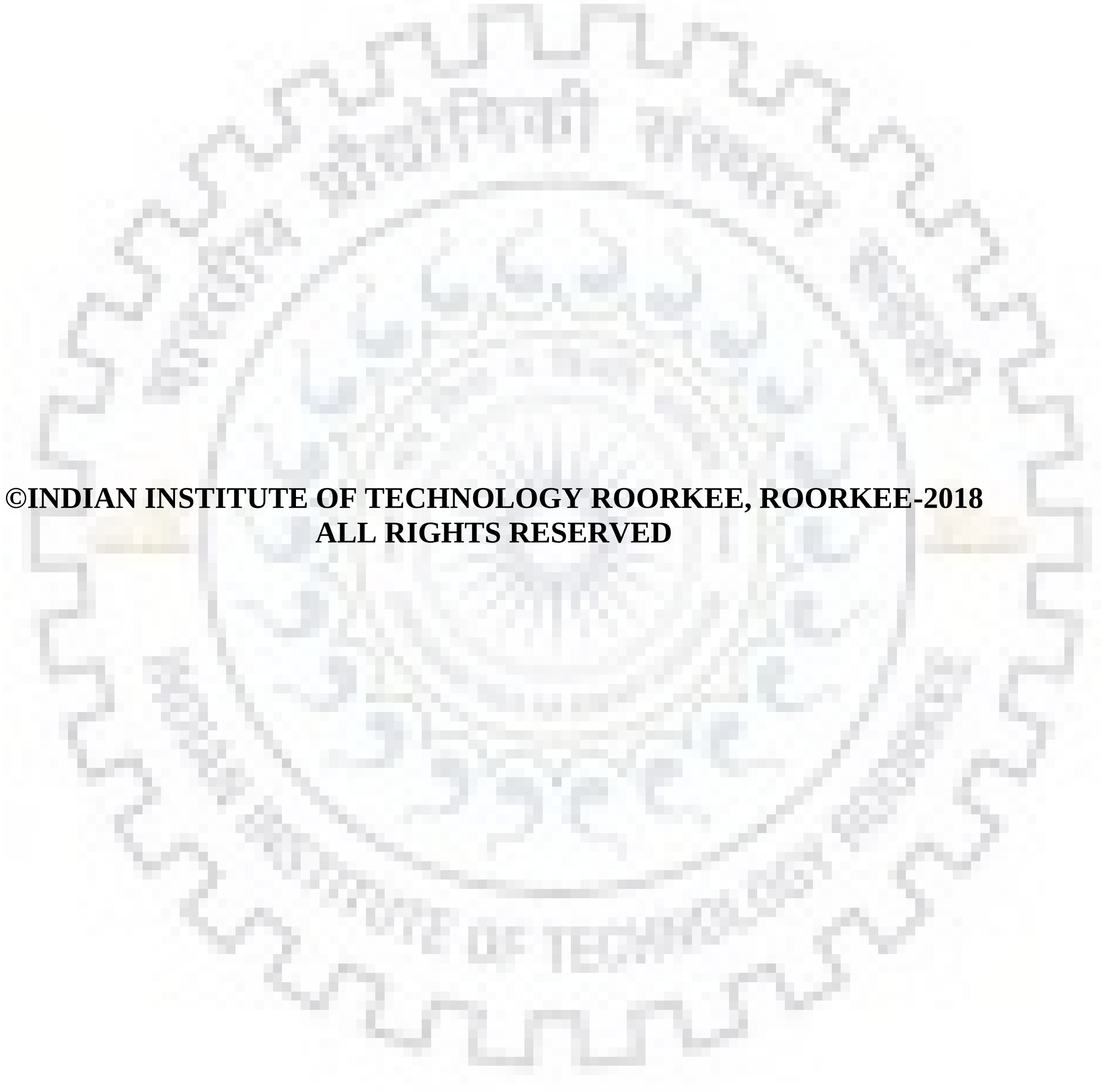
in

HYDROLOGY

by

VIKRAM KUMAR

**DEPARTMENT OF HYDROLOGY
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE – 247 667 (INDIA)
OCTOBER, 2018**



INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE

CANDIDATE’S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled “**HYDROLOGICAL RESPONSE OF AN EXPERIMENTAL WATERSHED OF LESSER HIMALAYA**” in partial fulfilment of the requirements for the award of the degree of **DOCTOR OF PHILOSOPHY** and submitted in the Department of Hydrology of the Indian Institute of Technology Roorkee, Roorkee, is an authentic record of my own work carried out during a period from January, 2013 to September, 2018 under the supervision of Dr. Sumit Sen, Assistant Professor, Department of Hydrology, Indian Institute of Technology Roorkee, Roorkee.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other institution.

(VIKRAM KUMAR)

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

(SUMIT SEN)
Supervisor

The Ph. D. Viva-Voce Examination of **Mr. Vikram Kumar**, Research Scholar, has been held on ………………, 2019.

Chairman, SRC

Signature of External Examiner

This is to certify that the student has made all the corrections in the thesis.

Signature of Supervisor

Head of the Department

ABSTRACT

Water availability over the earth surface as 97% in sea and 3% as fresh water, out of which very less amount is available for the utilization of mankind. Further climate change, growing population and poor management poses threat to meet the future water demand. This issue in Himalayan mountainous region on which 40% of the world's population depends face more challenges due to remoteness, susceptibility to natural disaster and restricted access for agriculture. Much of the water from the surface and sub-surface in mountains which keep the environment thriving and sustains increasing population have become under pressure. Water scarcity and other quality issues is consequences from unmanaged use and lack of hydro-meteorological data. Water quantification is of major concern in the India sub-continent especially in mountain region which required to cope up the issues of hydro-meteorological gauging locations and understanding of surface and sub-surface flow to meet the needs of water for domestic need and socio-economic development. The continuous monitoring of hydro-meteorological gauging data can support unfavorable influences of extreme conditions. Thus, an experimental watershed through intensive field instrumentation in Aglar watershed which comprised of different sub- watershed (Aglar, Paligaad, Balganga) located in Uttarakhand which has gained little attention in research is developed.

After the instrumentation, rating curves have been developed using power law at all the three sub watershed by means of installing water level recorder for stage and salt dilution for discharge measurement. Considering error as inherent, an attempt has taken to quantify uncertainty in rating curve which is not in practice using maximum likelihood method. The uncertainty estimated was 11.9%, 28% and 43% in Aglar, Balganga and Paligaad sub- watershed. Weighing factor concept has been introduced which correlate the degree of uncertainty with morphology of watershed. Detailed analysis of observed rainfall and surface flow were made to understand the hydrological responses of Aglar and Paligaad sub-watershed. Rainfall-runoff analysis revealed that in Paligaad, the rising and falling limb of the hydrograph are steeper with shorter time lag and respond to all rainfall events. But in Upper Aglar sub-watershed, during dry period it not respond to all the rainfall events, and flow only increases when there is enough antecedent soil moisture present. The quick response at Paligaad is because of the limited capacity to reserve the water as compared to Upper Aglar. The flow duration curve of a Paligaad tends to have higher “high flows”, than Aglar representing more frequent extreme conditions and slope of the lower end for both watershed shows the characteristics of the perennial storage.

Other than the surface flow, the subsurface flow (spring) is the main source of domestic water and there is growing concern about the drying of spring or becoming seasonal. Thus a fracture-and contact-type spring located in the same watershed has been instrumented to understand dynamic nature and model the recession behaviour of spring to gain information during lean period. Analysis of 10 rainfall and spring discharge events shows that, combined power law and exponential relationship fits the recession curve during the dry period whereas least square method fits recession curve during wet period. Relationship between (–dQ/dt) and (Q) for different recession events, characterizes the dynamic behavior of spring. Quantified spring volume force to develop water resource system for agriculture by evaluating the crop water requirement and possible better strategies to improve the water productivity of the region. The total water requirement for all their major crops is 6411.35mm and spring has potential to supplement the water requirement. Adopting the SRI practice, increases water productivity and sensitivity analysis of benefit to cost recommends that increase of crop yield by 30%, increase the revenue by 217%. It is thus essential to optimize the available water and area for irrigation for sustainable management of water resource development. To further increase the spring water, the springshed intervention practices were implemented to increase spring’s discharge. The measured average flow was 16.09lpm but soon after the intervention work the average flow increased by 2.6 times. Post-intervention work (2017) has increased the decay durations to 116 days for 142.98lpm (peak flow) to 12.69lpm (base flow) as compared to previous 100 days to recess from 30.3lpm to 3.93lpm in year 2014 and 98 days to recess from 80.07lpm to 16.4lpm in year 2016. The characteristic value from flow duration curve for the study location is increased to 95lpm after intervention from 30.6lpm. The above findings from the surface and subsurface can be considered as check for establishing benchmarks for sustainable development of watershed, climate change adaptation and development plans to cope up the water insecurity in rural Himalayas. Ability of the sub-surface flow for supplement agriculture water will help for better planning strategies which are resilient to face future challenges as well as advance the economic conditions of Himalayan rural farmers.

ACKNOWLEDGEMENT

I wish to acknowledge and express my sincere thanks to Dr. Sumit Sen, Department of Hydrology, Indian Institute of Technology Roorkee, who has kindly accepted to be my doctoral supervisor. I thank Dr. Sen for his excellent guidance, incessant encouragement, and immense support throughout my research. I am greatly indebted to Dr. Sen for his invaluable supervision, constructive criticism, and timely priceless practical advice with innovative ideas. I am very thankful to him for he has allowed me complete freedom in my work which helped me to be more independent, and helped me gain more confidence in myself that brought the best out of me. I express my heartfelt gratitude to him for guiding me through problematic times of the research. His constant motivation, patience to listen, and generous supervision proved to be pivotal in maintaining a morale of high value during challenging situations throughout my research.

I take this opportunity to thank Dr. M. K. Jain, Head of the Department of Hydrology, IIT Roorkee, for providing the necessary resources during the period of my research. I owe a great deal of gratitude to Prof. Dr. N.K. Goel, Chairman, SRC and to my esteemed committee members Dr. B.K. Yadav, Associate Professor, Department of Hydrology and Dr. Ashish Pandey, Associate Professor, Department of Water Resources Development and Management, IIT Roorkee for their valuable suggestions and moral support. My gratitude to Prof. Dr. M. Perumal for his scientific discussions and insightful suggestions which were the threads from which I could finally weave them into a finished product - my thesis. Special thanks to Prof. H. Joshi and Prof. D.S. Arya, Department of Hydrology, IIT Roorkee, for their encouragement and for providing access to the necessary instruments and other resources from the departmental laboratories during my research period. I am extremely indebted to other faculty members for being my mentors, helping resolve methodological issues and for carefully reviewing my thesis and providing feedback with many meaningful insights.

Water management greatly interests me, hence, driving me to do research in Lesser Himalaya. It was a great challenge to research in Thatyur, a remote Himalayan location as a stranger to the place. Staying and working in Thatyur for research was very difficult but it has become a very instructive experience. The first day, I arrived, the only thought that went through my mind was that “I have to quit and out of here”. But I am grateful to Dr. Sumit Sen and my parents for their encouragement who convinced me to continue with the same work. The fieldwork was very challenging with the day to day struggles of losing the data, loss of instruments, disappointments in getting the needed information on time, frustration with constant language barrier. But, I am thankful for these hurdles as I have greatly benefitted and learned from them. I have absolutely enjoyed my experience and have great memories.

I am grateful to my friends and colleagues, Ajay Vashista, Litten Ray, Rahul Singh, Vivek, Rajesh, Aliva, Vijaya, and several others for providing direct or indirect help during my research work and making my stay at I.I.T. Roorkee a very happy and memorable experience. Finally, I would like to thank all those that were not mentioned specifically by name that your contributions are not and will never be forgotten. I would like to express my special thanks to all of the staff members at the Department of Hydrology, IIT Roorkee, staff members of Central Himalayan Rural Action Group (CHIRAG) and People Science Institute (PSI) for their field support and other timely needed support. Thanks goes to Ministry of Human Resource and Development (MHRD), Government of India (GoI), for providing the financial assistance.

My family's unconditional love and support has played a very important role for me to complete my research work. There are no words to express my deep gratitude to my parents, Mr. Vijay Kumar and Mrs. Vimla Devi who are always a constant source of support, encouragement and inspiration to me. This achievement could not have been possible without the morale, support, encouragement and inspiration endowed to me by my mother-in-law, Dr. Sushama, brother Vikas, sister, Mrs. Vinita, brother-in-law, Avadh and loving niece Shivpriya. Last, but not least, I would like to thank my dear wife, Shaktibala and my dear daughter Tejaswani for their immense patience, unconditional love, understanding, accommodating, adjustment and support throughout the period of my study.

As I write these last words of acknowledgement of my thesis, I would like to thank everyone for their patience that was shown to me during the process of writing this thesis. Through personal struggles and circumstances, it has taken me a lot more time to finish this thesis work than was planned. Nevertheless, I am happy with the results of this long process of learning, writing, and reflection. As a last thought, even though it was hard to acknowledge during the process, I am convinced that the purpose of achieving something is embedded in the process involved in getting there and not in the end result itself. As I look back, I see a difficult but enriching and enlightening time of which all of the pleasant moments and memories will be remembered forever.

DEDICATION

I dedicate this dissertation to my most wonderful woman of my life Shaktibala. You have always inspired, supported and encouraged me during my long academic journey even though I believe that I do not deserve. I have experienced more of your love, friendship, sacrifice and patience during our journey together as a family. I have been truly blessed to be able to share the path that life has laid out for us as a family and as individuals, as each of us has grown and pursued our life’s joys, ambitions and academic pursuits. I love you and I am very proud of you for who you are and for all of your accomplishments and for helping me to accomplish my dream!

I would also like to dedicate this dissertation to the teachers and mentors who have helped and challenged me, and fed my hunger for learning throughout my life. Too often we fail to recognize the contributions of those special educators who help shape us to be successful in our personal, academic, and professional lives. There were many teachers and professors who contributed gladly and greatly in my pursuit of lifelong learning; however, my special thanks to Dr. Sumit Sen (IIT Roorkee), Prof. Dr. Rajesh Singhal and Dr. K.S. Grover (Rajasthan Technical University), Prof. Dr. Nicola Fohrer (Kiel University, Germany), and Prof. Dr. U. K. Choudhary (IIT BHU, Varanasi).

Last but not least, I would like to dedicate this dissertation with special heartfelt thanks to my parents - for you gave me my initial bearings and set high standards in front of me from my childhood, and at school and college levels, for continuing to teach, mentor, and inspire me throughout my life. You have truly made a difference in the path I took, my love of science and learning, and the level of success I have been able to achieve. I will always be deeply indebted to you!

LIST OF ACRONYMS

ANOVA	Analysis of variance
AWLS	Automatic water level sensor
CH	Central Himalaya
CV	Coefficient of variation
DEM	Digital elevation model
DMHS	Deterministic modelling hydrological system
DMS	Database management system
EC	Electrical conductivity
FDC	Flow duration curve
FRIS	Farm and ranch irrigation survey
GIS	Geographic information system
GRC	Generic rating curve
ICIMOD	International center for integrated mountain development
LH	Lesser Himalaya
LULC	Land use and land cover
MCT	Main central trust
MP	Microphysical parameterization
MRC	Master recession curve
MSL	Mean sea level
NACL	Sodium chloride
NGO	Non government organization

NSE	Nash satellite efficiency
PM	Penmann-Montieth
QPE	Quantitative precipitation estimation
RC	Rating curve
RCM	Regional climate model
RMSE	Root mean square error
SHG	Self help group
SRI	System for rice intensification
SUI	Survey of India
SW	South west
SWAT	Soil and water assessment tool
USGS	United State geophysical survey
WRF	Weather research and forecasting

TABLE OF CONTENTS

BIBLIOGRAPHY

LIST OF PUBLICATIONS

ANNEXURES

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 GENERAL

1.1.1. Increasing pressure on water resources at mountains

Mountains are significant sources of freshwater therefore they are also called the water towers of the world (Weingartner et al., 2003; Liniger et al., 1999). In the mountains, human kind not only use water for basic need (e.g., for drinking, cooking, and sanitation) but also for hydropower generation, agro business, industries, and recreation. Even though there are plenty of freshwater resources, the pressure or demand for water is increasing due to agribusiness and urbanization (Smil, 2001), along with the expansion of recreational activities, interest in hydropower, and climatic unpredictability (Schindler, 2001). Planning and managing the water resources at the mountains require a thorough understanding of the available sources of water like rainfall, streamflow, etc. in a watershed, the causes of water scarcity and the hydrological processes. Under water scarce situation, an improved understanding of watershed hydrology and water resource availability are very essential to inculcate in the sustainable water resources development and policy formulation. Presently, one billion individuals live in water scarce districts and it is expected that by the year 2025, this number will increase by 3.5 times (Wagener et al., 2008). The amount of water shortage, and its spatial and temporal variability are to a great extent obscure on account of the absence of the hydro-climatological information (Kipkemboi, 2005; Oyebande, 2001).

More water is used at the present time than ever before due to the increase in the population, but the total availability of the water remains same. Many studies have indicated that nearly 80% of the world’s population is exposed to significant fresh water insecurity due to urbanization, industrialization, misuse of water supplies, lack of watershed conservation practices, shortage of storage capacity and climate change (Vorosmarty et al., 2010). However, the two major issues are the increase in the population and the climate change. The per capita water availability in India dropped almost 15% over a decade from 1,816m^3 to 1,545m^3 in the year 2011 (Figure 1.1). The forecasts advocate that the water availability per capita will continue to decline further to 1,401m^{3}and 1,191m^3 by the years 2025 and 2050, respectively which can lead to water stress in India. Falkenmark (1986), defined the conditions of ‘‘water stress’’ as less than 1,700m^3 of available water per person per year and ‘‘severe water stress’’ as less than 1,000m^3 per person per year.

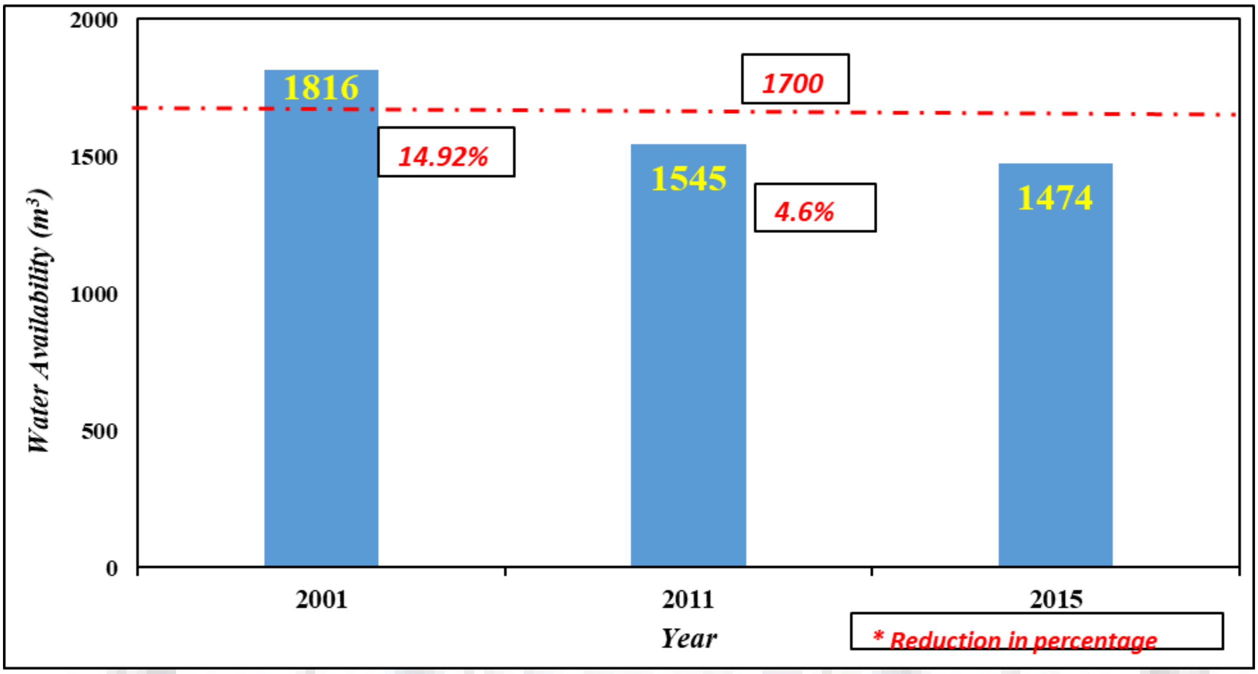


Figure 1.1: Per capita water availability in India (**Source**: *Ministry of statistics and programme implementation, 2015*)

The spatio-temporal distribution of water is very much non-uniform across the globe. Also the full amount of renewable water is not accessible to human uses due to different reasons such as the fact that a major part of the rainwater flows as surface runoff during short time period. Our understanding of these spatio-temporal distribution of rainfall and surface and sub-surface runoff is very little and even investigation is very restricted. Thus it is apparent that more research is needed to advance our understanding of water availability through (spring and stream) and its dynamic behaviour with how the land cover and other climatic variables influence surface and sub-surface flow and hydrological processes. Understanding of the hydrological processes in a watershed at mountains specially involves the knowledge of how rainfall spreads and reaches to a watershed outlet, what pathway of water flow is and its residence time (Wenninger et al., 2008). As we all know that change in the land use activities result in change in the soil physical and chemical properties. These changes alter the fluxes of water, sediments and contaminants within a watershed which in turn impact the hydrology and water quality that disturb the lives of the people living downstream of a watershed (Figure 1.2).

1.1.2 Managing water at mountainous watershed

The understanding and modeling of water distribution spatially and temporally much depends on watershed scale. The water distribution and flow issues and water management could be viewed in many different spatial scales such as global, national, river basin, catchment (sub basins), mountains, etc. The flow of the river from the upstream mountainous regions to the downstream (Ling et al., 2012) redirects the multifaceted exchanges between the meteorological and the environmental conditions. Thus, it is crucial to understand and quantify the stream flow/spring flow variation and the associated errors like systematic error in input variables, and errors due to non-optimal parameters values while developing the stage and discharge relationship with respect to time in order to assess the effects on hydrological responses and management practices.

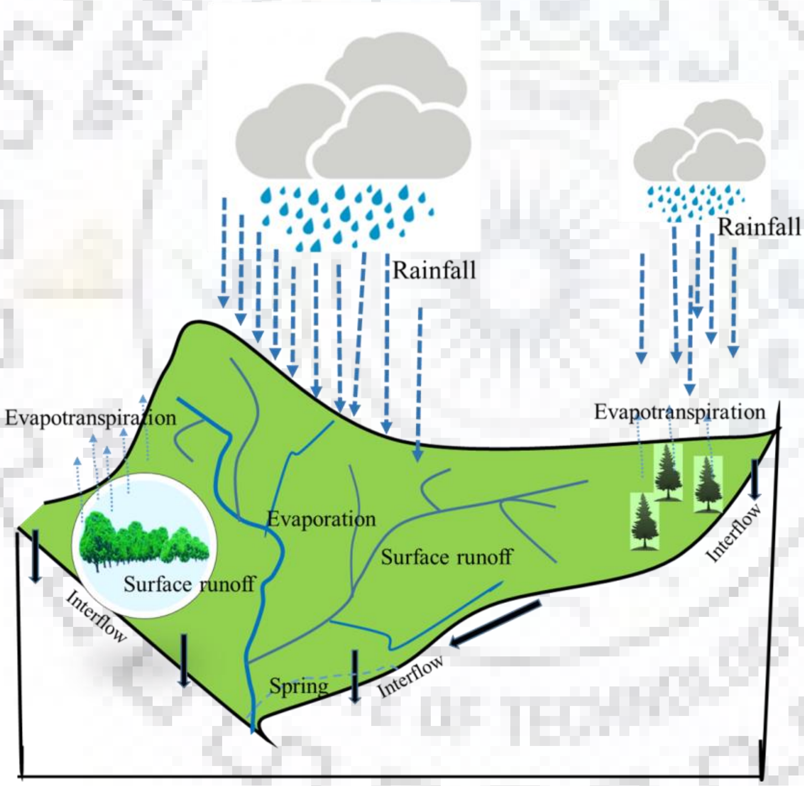


Figure 1.2 Sketch of water cycle (Representative of watershed)

In the field of hydrology and water resources, consistent prediction of rainfall and surface and sub-surface flow can provide information about unfavorable influences of high flow and low flow conditions which helps to escalate human readiness for future anomalous situations (Wedgbrow et al., 2002), and advises in the basic judgement making process for natural resource management (Kirono et al., 2010). Enhanced water management, thus, can possibly decrease monetary losses related to floods and low flow situations (Wood and

Lettenmaier, 2006). The analysis of variations in a hydrological process is significant because it will help to understand the effect of the availability of water at the downstream of a watershed. While approaching integrated watershed management, the main question that arises is of appropriate balancing of the available water to all consumers with an emphasis on irrigation for which water is a major requirement for crop production and to maintain a good balance in the ecosystem. Proper watershed planning at the upstream has to be done for land use and management or else it effects on the downstream with interactions of land use - land cover (LULC).

1.1.3. Need for LULC understanding

Land use and land cover alterations are the consequences of either anthropogenic intervention like agriculture intensification, deforestation and urbanization, or any erratic weather conditions. The significance of understanding interactions between LULC and flow behaviour is essential for noble and sustainable management (Jones et al., 2009). Recent research demonstrates that changes in LULC have an impact on the streamflow generation and flow behaviour. For example, research by Bradshaw et al. (2007) indicated that deforestation can intensify the chances of high flows (Figure 1.3). Presently, this LULC effect is even more relevant, as watersheds will be more impelled to encounter water shortage circumstances.

The differences in the discharge behaviour due to land cover have to be assessed to gain the understanding of the probable flow mechanism and dominating factor. Changes in the discharge behaviour is not only because of the alteration in the LULC but often depends on the precipitation (magnitude and amount) and soil conditions too. The forested watershed has capacity to hold the water for some time before it released from the storage on the other hand in the degraded land use system, the hydrograph is characterized by high and quick peak flow.

At the same time one cannot ignore the sub-surface flow (spring) which is a one of the component of hydrological cycle, as Dunne (1978) stated that sub-surface flow is one of the major components of a hydrograph. A large number of studies have focused on the identification of the mechanism responsible for sub-surface flow generation.

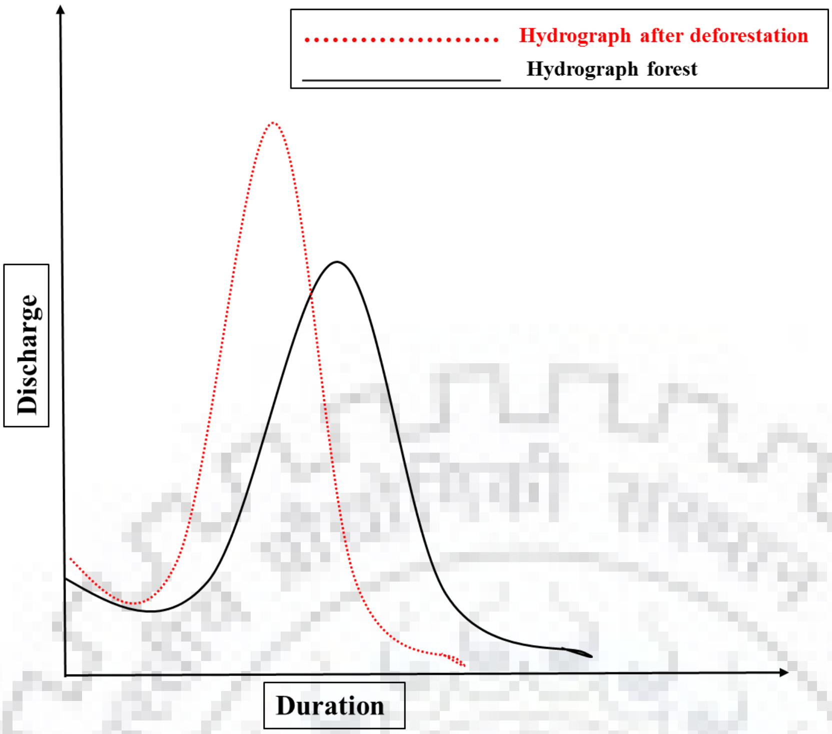


Figure 1.3 Conceptual hydrograph presentation for different land cover showing (a) reduced base flow and time of concentration, (b) enhanced peak discharge

Previously, the research of watershed management concentrated mostly on the management of natural assets such as soil, forest cover and water in medium and large watershed with the intention to slow down fast discharge and unrestrained soil erosion (Paul, 1997). In order to quantify the net water availability for different purpose and to understand discharge variability, continuous monitoring of hydrological and meteorological by setting up of hydro-meteorological gauging stations are equally important especially in the mountains where gauging networks are limited or often not available. Even the irrigation efficiency could be improved dramatically at some places, after understanding LULC which helps in meeting the water demands for irrigation, which is a big challenge in many parts of the world, especially in mountains.

1.2 BACKGROUND OF THE STUDY

The management of water resources is a major concern in Himalayan mountainous watershed, where agriculture is main user of water and plays a major role for sustainable development. Bartelmus (1997) defined sustainable development as “the set of improvement programs that meet the target of satisfying the human needs without violating long-term natural resource capacities and the standards of environmental quality and social equity”.

The management of mountainous watershed suggests judicious utilization of natural resources like water, soil, and biomass to acquire ideal generation with the least unsettling influence on the environment. The general goals of watershed management plans are to consider the watershed as a single hydrological unit, and intends to embrace reasonable measures for natural resources, provide water satisfactorily for agriculture, horticulture, and for household utilization, and to enhance the livelihood of the different small land holders and resident.

With the aim to better understand the hydrological response of surface flow in different land cover and dynamic behaviour of sub-surface flow in Himalayan mountainous watershed, this study has been carried out after data collection through intensive field instrumentation for Aglar watershed in Tehri-Garhwal district of Uttarakhand, India. There is inequality in the state of Uttarakhand amongst its districts in terms of development of various important infrastructure leading to inequality in living standards and income between the people living on the high hills, low hills and the plains. The area of this study is under continuous danger of natural hazards such as high flows, landslides and erosion which could have been be caused by deforestation, unscientific agricultural practices and other natural catastrophes. Even though the area that is being studied is relatively small (305 km^2), it is very well gifted with water resources; however, the spatial and temporal distribution of water resources are uneven. The Aglar watershed is lagging behind in its watershed management, agricultural yield through irrigation and utilization of natural resources which is necessary for sustainable development. Hence, there is an urgent need to offer a better understanding of hydrological processes and agriculture potential, which can improve the quality of life of the people living in the hilly areas and to the future coming generation which will further increase the force on available natural resources to sustain their survivals.

Further to the above said issues, the magnitude of productive land existing for the production of food is shrinking due to high intense rainfall and lack of adoption of soil and water conservation practices. Continuous, deprivation of the agricultural land is due to the removal of dense forested area and unmanaged use of the main renewable natural resources. Eventually, this leads to both non-justifiable productions of the agricultural yield and increase risk of natural disasters such as high flow, landslides and erosion. Therefore, management of these natural resources is vital to save and protect water resources which helps to enhance the living standards, and to improve the income of highland residents and residents of downstream. To provide sufficient water to the people for their needs in their required capacity at the required time, a better understanding and quantification of the discharge from both surface and sub-surface should be accomplished which is challenging. To increase the production of food and to sustain development in agricultural dominating areas, optimum use of land and water is required which is very essential for the prosperity, food security and progress of a rural mountainous people.

1.3 RESEARCH GAPS AND OBJECTIVES

In a rapid changing environment where degradation of soil and unpredicted change in climate is widespread, conservation of the natural resources is of great importance and involves a sound understanding of the numerous processes of hydrology. However, the field-based hydrological studies in the mountainous watershed is still poorly known; Klemes (1988) concluded his research outcome as “the blackest of the water cycle’s black boxes”. Hydrological extravagances such as low flow leading to droughts and high flow, have unfavorable socio-economic impact that challenges human life, causes property harm, interrupts agricultural productivity and water resources. These intermittent hydrological dangers influence both the developed and undeveloped regions and are characteristic of hydro-climatological instability. As these hydrological extreme events are projected to become more common in an unstable climate (Kundzewicz et al., 2007), thus, there is an urgent need to expand our knowledge of the hydrological processes.

In Aglar watershed, the challenge is to quantify water and natural resources, and to manage and allocate water to scarce water areas because of the harshness of the steep slope have varied greatly in this region. Many villagers of this area are challenged with an increased stress on the availability of their water resources together with a fluctuating climate. Hence, the focus of this study in this specific Aglar area is to proficiently quantify the surface and sub-surface flow corresponding to the rainfall and to improve understanding of hydrological responses. Furthermore, challenge is to understand, in what way hydrologic systems will behave with continuing changes in rainfall pattern (the distribution of the rainfall, the timing of its occurrence) and the influence of land cover pattern. Thus, there is need of hydrologic field instrumentation and collection of information across the watershed to improve the capability to respond to altering water availability and demands. In this context the following are the specific objectives of the present research study:

1. To develop an Aglar experimental watershed with intensive instrumentation and data collection to understand the hydrological response.

2. To develop rating curve and assessment of associated uncertainty and correlate it with morphometry of watershed.
3. To investigate the sub-surface flow dynamic behavior and modeling of recession curve.
4. To quantify the crop water requirement and develop micro watershed irrigation using spring system.
5. To understand the impact of spring intervention on spring yield.

In summary, the wide-spread issues of circulation and delivery of water at the Aglar watershed is likely to intensify the competition of water for human domestic use and their irrigation water requirement. Many other prevailing aspects ranging from natural and anthropogenic climate changes to the complex socioeconomic, and hydrological factors are important for understanding watershed hydrology and water availability at Aglar watershed. Further studies on field instrumentation and data collection for understanding the rainfall-runoff distribution and spring (sub-surface) flow dynamics are also prerequisite to achieve the sustainable development at sub-watershed level. Therefore, there is an urgent need to increase an understanding of the hydrology and water resources systems that can help to address the water and related issues. The methodological framework used in this study was strengthened by the combined use of rigorous field investigation, continuous data monitoring and rainfall-runoff analysis along with the understanding of spring discharge dynamics. The spatial investigations were carried out at the sub-watershed level and the used temporal resolutions were daily, monthly, and annually in the monitored time series.

1.4 ORGANIZATION OF THESIS

The thesis consists of nine chapters, covering the following aspects of the research study:

Chapter One introduces the importance of hydrology study, present the research gaps and outlines the research objectives.

Chapter Two briefly reviews the importance and problems related to water resources in the Himalayas, the present state-of-the-art knowledge, and outlines the need of field instrumentation.

Chapter Three describes the Aglar watershed area characteristics and the morphometric analysis.

Chapter Four explains the instrumentation and the data analysis that were used, along with the analysis of the streamflow behaviour of two different streams located in different land cover to understand the hydrological responses.

Chapter Five presents the development of rating curve and the quantification of associated uncertainty in the developed rating curves. Chapter also describes in brief as to how the uncertainty is related to morphological parameters of the watershed through a newly developed weighing factor concept.

Chapter Six discusses the quantification of the sub-surface flow that is the only domestic source of water and its temporal behaviour. It also expands on the modeling of the recession behaviour of a spring. Furthermore, the chapter also shares the results of the developed model, its validation and the criteria for the evaluation of the model.

Chapter Seven presents the detailed procedure used for the estimation of crop water requirement in the watershed. The chapter also presents the analysis of the monthly requirement of water through the spring to demonstrate that the spring as a supplement for irrigation in the mountainous watershed. Furthermore, optimization, and adaptation of system rice intensification are discussed.

Chapter Eight presents the spring intervention work that was done to enhance the storage of the aquifer to increase the outflow from the spring. To test the suitability of the different master recession curve representations with different decay functions. The results obtained through the master recession curve can be used to predict the water availability during the lean period.

Chapter Nine discusses the synthesis of the results of the research study. It also summarizes the findings of the study, and provides the concluding remarks, recommendations, and directions for further studies in the Aglar watershed.

CHAPTER 2

REVIEW OF LITERATURE

Review of literature on important aspects of the present study is discussed in the present chapter. The literature review is covered in four sections in the light of the main objectives of the present study. The first section presents the review of literature on the importance of field instrumentation and hydrological studies. The second section includes hydrological studies in the Himalayas, especially Tehri-Garhwal region of the Uttarakhand state. The third section review the different data issues and its concern. The fourth and the last section incorporates the importance of sub-surface flow (spring) and its impact on the requirement of water for irrigation purpose.

2.1 GENERAL

Water is one of the prime elements responsible for life on the Earth, without which one cannot survive. In spite of the fact that there is a lot of water on the Earth, it is not easily available in terms of quantity and quality, particularly in the mountainous regions. In order to comprehend the complex water systems in the mountains, understanding mountain hydrology is integral. It is very important to study the Indian Himalayan region (Figure 2.1), due to the enormous nature of the area it occupies which is 5 lakh km^2 but also due to the fact that the Himalayas act as a barrier for the south-west (SW) monsoon winds that lead to the abundant rainfall in different regions.

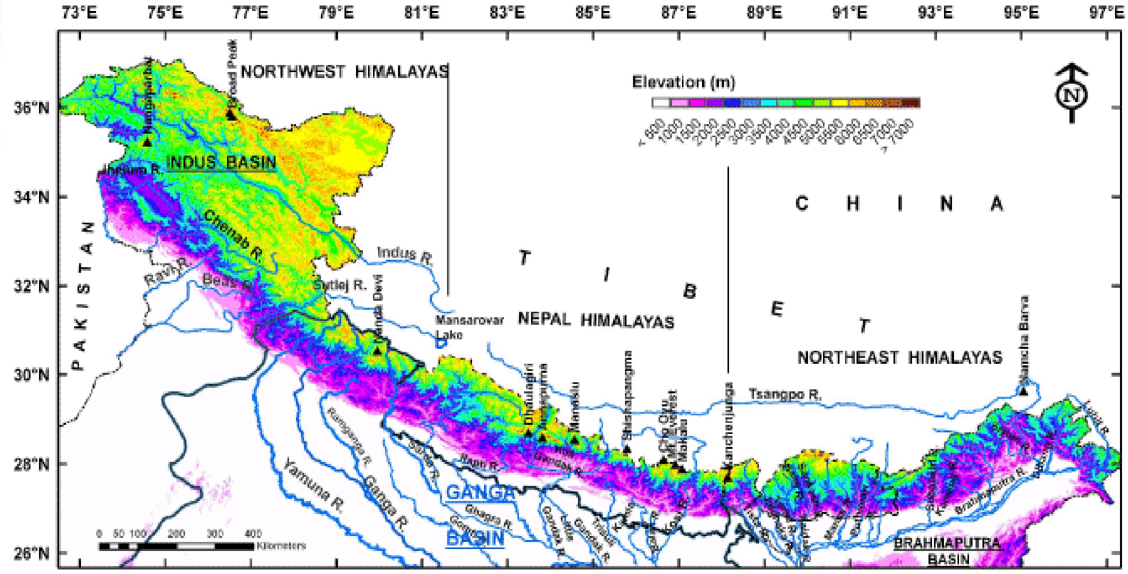


Figure 2.1: Map showing Indian Himalayan region (Source: *Nandargi and Dhar, 2015*)

The role of a water resource planner is to apply technical understanding with a hydrological modeling approach supported by good quality of hydrological data to resolve water issues for the people living in remote locations on the mountains. Some of the water issues are the quality, lack of availability, low flow and high flow conditions of water, etc. The extreme variability in climatic conditions and retreat of glaciers determine the availability of water in the region which contribute to the region’s poverty and harsh living conditions. Therefore, much devotion and care should be taken to design a data collection of hydrological measurements in order to understand the hydrology of mountainous watershed and streamflow analysis.

2.2 STUDIES ON HIMALAYAN REGION

Earlier studies on the Himalayan region indicated an important characteristic in the information and dissemination of water resources. The Himalayan region mainly enclose the headwaters of the rivers - Ganges, Brahmaputra, Yellow, Indus, Mekong, Salween, Amu Darya, Yangtze, and Tarim which provide water to the 130 crores of population who are living downstream of the rivers (Eriksson et al., 2009). The presence and melting of glaciers and snow in the head catchment of the Himalayan major rivers withstands the seasonal requirement of water in the downstream areas. Lately, the current research has concentrated on the influence of climate variability on the forthcoming hydrological processes at a micro level by adopting the regional climate model (RCM) data as there were not very many investigations at small area in the Himalayan watershed.

Nepal (2015) studied the likely influence of climate variability and change on the hydrological processes in the northern portion of the Koshi river basin of the Himalayas. The region of the study was characterized by steep topography and peaks with an altitude in between 140m to 8848m covering a total area of 57,000km^2. The past data of temperature and precipitation was analyzed for the trend using 36 precipitation stations data and five temperature stations data. Analyzed weather data for the past 40 years indicated a significant rise in the average temperature of 0.058 °C per year for maximum temperature and it is 0.014 °C per year for minimum temperature. It was found out that the deviations in the precipitation over different stations were spatially less consistent and more flexible than the variation in data of temperature. About 24 precipitation stations’ analysis indicated an increase in the trend, and the remaining 12 stations indicated a decreasing trend. The RCM data advocated that the average yearly temperature would rise by 4 °C and the precipitation by 14% by the end of the 100 year periods.

Agarwal et al. (2016) suggested in their study that the ecological communities of the mountain are changing and augmenting the scope of advancement and the challenges faced by the people living in the mountain. Hence, there is a critical need to consider the adaptation of climate change into planning for improvement and for policy development approach. However, the incorporation of adjustment approaches into the national and the subnational development planning remains profoundly insufficient and is a basic challenge in the large-scale execution of the methodologies. One of the significant difficulties is that of time scale: climate science discusses long-term data, though policy leaders and government officials require short-term data. Hence, the study concluded that robust knowledge creation at the regional levels is a necessary first step for informed decision making.

Schreier (2005) addressed the issues in the Himalayas due to the variability in the climate. The study indicated that it is not easy to confirm that the changes in the land use pattern, changes the percentage of surface flow. The Himalayas complexity and the danger enforced by climate change suggest to adopt innovative approaches rather than the traditional approaches as summarized in Table 2.1.

Table 2.1: Summary of Watershed management approaches

Traditional Approach	**Innovative Approach**
Building flood protection structures	Design flood concepts
Creating impervious surfaces	Reducing impervious surfaces
Attention on point source pollution	Focus on non-point source pollution
Draining wetlands	Creating wetlands
Sectoral water management	Integrated watershed method for several uses
End of pipe treatment	Source control
Compacting soils	Minimizing and remediating soil compaction

Further to the above listed traditional approaches, the study presented other major concerns such as (a) poor understanding of mountainous regions (b) impacts on the rainfall infiltration and runoff generation due to changes in the land pattern (c) scaling problems and (d) segregating influences brought by climate unpredictability in the Himalayas.

Rawat et al. (2011) evaluated the influence of climate alteration on hydrological threats through integrated Database Management System (DMS) in Dabka watershed of the Kosi located in the part of lesser Himalayan mountains. The results of climate informatics advocated that the moist temperate zones and sub-tropical temperate zones are changing in the direction of upper altitudes upsetting the favorable circumstances of the present land use pattern. Outcomes from the study found that, if the degradation of land use continues at a faster rate then several natural and hydro-geological hazards, for example soil erosion, peak discharge, flash floods, and non-seismic landslides will occur during the monsoon season and drought during the non-monsoon seasons.

Eriksson (2009) tried to fill the gap of study of climate change on higher Himalayan regions. It was found out that the temperature in the greater Himalayas has considerably changed and is more noteworthy than the worldwide normal: for instance, 0.6°C per ten years in Nepal as compared with the worldwide normal temperature of 0.74°C during last 100 years. Variations in rainfall amount and intensity are vague with expanding and diminishing patterns in various parts of the region. The most genuine alterations were identified with the recurrence and the extent of extraordinary climate incidents, for instance, rainfall with very great intensity that leads to landslides and floods. The study recommended to build up the local understanding, advances and practices within the community along with the ecological systems to support the organizations working for adaptation and sustainability of the watershed. Scientific knowledge together with valid, remarkable, and authentic information is critical to improve the formation of comprehensive policies and to strictly adhere the guidelines mentioned in the policies. Suggestions that can be opted for policy and adaptation is summarized in Table 2.2.

Table 2.2: Recommended polices to cope the problems in Himalayan Region

	Scientific Uncertainty	***Adaptation***	***Mitigation***	***Public engagement***
Local or regional public	Local or small scale monitoring, local information, inventions and practices	Better land resources management, preparedness for surprises	Renewable energy, alternative livelihoods, and mitigation	Representation in dialogues and decision making
Civil society	Participatory vulnerability analysis, linking local to global, facilitating knowledge learning	Community preparedness, facilitating local learning and adaption	Social auditing, green watch and monitoring	Access to information, awareness campaigns, social inclusion, intercultural dialogues
Market	Partnership in research, new hardware and software for monitoring	New technology, support for community development and local education	Self-regulating and reducing greenhouse gas emissions	Green certification, support for civil society
State	Regional cooperation, support long term research, engage in research process	Inter sectoral collaboration, support for poverty alleviation and environmental conservation	Commitment to international treaties, developing good policies	Transparency in information and support for public debates

Rai and Sharma (1998) studied the sedimentation issues in the Himalayas. The study attempted to focus on the impact of land cover on sediment in the rivers of the Sikkim region through remote sensing and GIS. The analysis of the study found out that the land use has changed by 11% in three years from forest and agroforestry to open agriculture and significant areas of diversified forests have changed to open mixed forests. The total sediment and nutrient loss in the watersheds was assessed. It ranged from 4.18 t/ha/year to 8.82 t/ha/year during the duration of the study. The findings from the present study suggested that the highland watersheds can be hydro ecologically feasible with agroforestry such as dense forest covered with substantial cardamom plantations.

Hasan and Pradhanang (2017) understood the importance of climate change and hydrologic modeling for the socio-economy and the livelihood of the people living in the Himalayan mountain region. In this study, the authors applied an upgraded multi-variable and multi-site methodology for adjustment of the model parameters of the Soil Water Assessment Tool (SWAT) to define its capacity and mimic the flow system of the watershed. Grouping of dissimilar model outcome metrics pointed out that the upgraded technique of SWAT increased the effectiveness of the daily forecast discharge from the Karnali River. The developed SWAT model predicted the daily discharge and measured the low flow (Q_{25}) and the high flow (Q_{75}) matrices reasonably well. Hence, the study recommended to implement a multivariable and multi-site approach to ascertain the forthcoming flow condition in the mountainous watershed.

Li et al. (2017) used a combined application of the Weather Research and Forecasting (WRF) model and the WRF-Hydro hydrological modeling extension package (WRF/WRF-Hydro) over a period of ten years to the Himalayan mountainous river catchment for their study. The study quantitatively evaluated two microphysical parameterization (MP) patterns to make known how in a different way these two MP impact the orographic precipitation and how it controls the hydrological responses of a watershed. The implemented technique, WRF-Hydro modeling displayed judicious performance in arresting the spatial and temporal high resolution precipitation. The subsequent streamflow hydrographs revealed a worthy correspondence with an observation at monthly timescales, even though the model have a tendency to underestimate the total streamflow volumes. Finally, the study concluded that the hydrological modelling through WRF-Hydro modelling displays a potential for unambiguously forecasting variations in the hydrology cycle of partially gauged or ungauged basins.

Andermann et al. (2012) studied the influence of transient groundwater storage from a river discharge taking into consideration the general perception that the water budget was primarily controlled by the rainfall during the monsoon season, snow and glacier melt and secondarily by evapotranspiration. In their study, the daily river discharge and rainfall in 12 different watersheds in Nepal from the records for the past 30 years, were investigated. The study noticed yearly hysteresis loops which means, a lag time between the river discharge and the rainfall in unglaciated and glaciated watershed and that the lag times were free of the geological setting. Hence, the study deduced that the water that was stored provisionally in a basin or a reservoir with a response time between the rainfall and the discharge for about 45 days, significantly showed a diffusivity in its flow which is typical of a fractured aquifer.

Prabhakar and Somanathan (2006) analysed the magnitude by which the mid Himalayan Kumaoun and Garhwal of Uttarakhand, and lesser extent to western Nepal forests have degraded using the multispectral satellite image. The precision in their study was assessed by the section extracted from an Ikonos 1-meter resolution image. The study has concluded that around 61% of the forested area has less than 40% top cover.

Naudiyal and Schmerbeck (2017) summed up the present condition of information on pine and oak forest progression in the mid montane central Himalayan forest. The biological ecological management related to these vegetation assumes a crucial part in the livelihood of the people. The research highlighted that the anthropogenic disorders frequently performed as the prime catalyst for deviations in the eco-system amenities. Suitable forestry managing strategies could be established when there is a comprehensive understanding about the changing aspects of a forest and the knowledge of the driving factors. There is ample scope for more research in understanding the issues that are driving the forests to change rapidly. Furthermore, there is a serious requirement to apprehend the role of well-ordered fires to assist the ecosystem i.e. fodder availability which are vital for the pastoral communities.

Rasul (2010) inspected a part of the Himalayan mountain frameworks in sustenance generation to take care of the demand of the growing population. The developing concern of water is increasing as sustainability of rice and wheat in South Asian nations is emerging as a challenge postured by the expanding water pressure and climate change. The investigation advised that the availability of irrigation water is one of the critical factors to increase production of food and for agricultural sustainability in the entire South Asia. The influence of change in climatic conditions on rice, wheat and other cereal products in South Asia will possibly be negative and might be as great as 18.2–22.1 %. Further, the study indicated that the three major rivers which are tributaries of the Indus, the Ganga and the Brahmaputra are the most important sources of surface water for rice and wheat production in South Asia. Moreover, the surface water and the influence of discharge to groundwater in the mountains were similarly substantial, making it a supplemental resource for farming and food production as well as for food security in South Asia.

Immerzeel et al. (2013) and Lutz et al. (2014) studied the Himalayan watersheds and sub-watersheds. The study directed that the general yearly total runoff resultant from the rainfall will increase with the climate change and also will contribute from the glacier melt.

The Indian Himalayan watershed extends around 600kms along the southwest slope in the three states (Himachal Pradesh, Uttar Pradesh and Uttarakhand) with elevations varies between 300 to 3000m above mean sea level. Much of the area is classified as forest and the area is very fragile ecosystem having highly erodible soils and steep slopes. The rainfed farming and rangelands are mainly scattered throughout the Himalayan mountainous region with changing amount of coverage area. The degradation of rangelands is increasing due to overgrazing and anthropogenic land use changes along with natural factors (low forest canopy covers and high erosion rates) which adds to the complexity in understanding the Himalayan hydrology and water resources potential of the watershed considered in the wider spatio-temporal perspective.

2.3 STUDIES ON UTTARAKHAND MOUNTAINS

The state of Uttarakhand is one of the most susceptible states for climate change related risks in India. The state contains about 4.53% of India’s total forest area and about 3.1% of India’s agricultural land. It contains both plain and mountainous regions. The mountainous regions are frequently susceptible to climate change and have been exposed to “above average warming” in the 20th century. The natural resources such as soil and water of the mountainous region offer life supporting and cultural ‘ecosystem’ services to the people living upstream as well as to people living downstream. Some of the recent published articles on Uttarakhand Himalayas are included as part of the literature review.

Tamchos and Kaul (2015) raised concerns over the rapid expanding rate of water-related issues such as flood, landslides, etc. in the state of Uttarakhand. These issues create distress to the public and a challenge to the active water resource professionals and the Government. The main reasons for these exceptional issues are unpreparedness, deforestation, poor knowledge of the geo-environment, unaware occupation of hazardous areas, and inadequate future projecting experiences. These reasons unfavorably influence the dynamic geo-environment of the topography, social mind and financially burden the public and the Government in rescue, re-establishment and relief operations. The study also claimed that the past and the recent devastation caused due to floods in Uttarakhand were the direct result of unscientific planning in the use of land and ignorance of geomorphology of watersheds. It is a well-known fact that major effort should be placed in addressing the real and scientific origin of the problem by being pro-active instead of being reactive and working hard after the fact in handling the effects of flooding. The development has to be advanced in a scientific way by incorporating geoscientific strategies such as architectural and engineering inputs, town-planning etc., so as to address and stop the magnitude of destruction or loss and to escape the unintentional loss of people.

Gupta et al. (2016) studied the extreme climatic conditions during 15–17 June, 2013. The incessant rainfall generated numerous primary as well as secondary landslide hazards in the Garhwal Himalayas. The study documented the occurrence of landslides spatially and its significance in the lower regions between the Bhatwari and the Uttarkashi regions of Uttarakhand. It has been evaluated that there was a normal aggradation of about 0.5 m/year in the Bhagirathi River posing a genuine risk to the incline land stability on either sides of the river. The study further suggested that there was an urgent need for the formulation of policies pressing the requirement for digging from the riverbed so as to keep up with the persistent and continuous stream of water during the high flow.

Aryal et al. (2017) suggested active participation of local communities both women and men; rich and poor to collaborate with the relevant stakeholders in different phases of analysis, planning, implementation, monitoring and evaluation for sustainable natural resource management in the mountains (Figure 2.2). The study could be used as a participatory tool relying mostly on oral and visual techniques such as focus group discussions, resource mapping, institutional diagrams, and transect walk. For sustainable management of natural resources there should be a two-way processes of interaction, exploration, questioning, and analysis, rather than just collection of extensive data. The study concluded that the more attention is focused on the former, the higher quality data could be generated.

Figure 2.2: Cycle for sustainable development (adopted from Aryal et al. (2017))

Tiwari and Joshi (2012) studied the rainfall inconsistency in its amount and intensity and their negative influences on water resources and health of the rural people. The continuous growing variability in the rainfall pattern due to natural and anthropogenic changes has reduced the total number of rainy days in addition to the total cumulative rainfall amount steadily but significantly, and amplified the occurrences and magnitude of extreme weather conditions such as cloud bursts, droughts, flash floods, dry spells etc. Decrease in rainfall and an increase in erratic rainfall has reduced the recharge of groundwater as an end result. Around 36 % of naturally occurring springs in the mountains and 3.2 km of stream-length has dried up completely in the head catchment of the Kosi River. The findings of the study suggested that the efficiency from agriculture production has dropped by 25 %, and incessantly decreased the trend in per capita food production over the previous 30 years. The upper catchment is presently confronting yearly normal sustenance deficiency of 65 % and almost 69 % of the aggregate populace is influenced by different types of water-borne sicknesses.

Buechler et al. (2016) investigated the logical natural inconsistencies in hydropower administration in view of the interest of the neighborhood occupants and different partners including hydropower engineers, urban and other provincial power clients, and state-level policymakers. The research concentrated on the Bhilangana watershed, where water subordinate employments separated by gender orientation incorporate cultivating, fishing, livestock rearing and fodder accumulation. In the study, social equity approach was connected to hydropower activities in order to inspect a portion of the negative effects to distinguish procedures that can defend or improve employment of women, youth, and men in the territories with hydropower ventures, while keeping up with the basic balanced environment conditions. Embracing the above techniques would convert into a superior harmony between addressing the requirements of rural and urban people.

Maikhuri et al. (2017) concentrated their study on documentation of probable parameters for socio-economic, social susceptibility and disaster risk valuation of mountainous rural people who are struggling to handle the surprises of disaster and the managing strategies to alleviate the influence of such major tragedy that took place in Kedarnath valley of Uttarakhand in the year of 2013. The study prescribed a portion of the major interventions and scientific innovations for quick implementation and to additionally limit them to be economically sustainable and be prepared to react quickly towards any such calamity with more positive effect in the future.

Chauhan (2010) discussed the evolution of watershed development, its implementation and highlighted some of the issues that could be managed. The study revealed that success of watershed management projects was isolated and were commonly found in micro watersheds. The overall impact of the watershed projects was immensely unbalanced financially in general as the development and benefits were moderate as well as unevenly shared. The review indicated the gap in understanding the technical aspects of hydrogeology, change in livelihood patterns and land use patterns.

Mittal et al. (2008) highlighted that Uttarakhand has certain key features that differentiate it from the rest of the other states in India. The study portrayed its prospective for improvement in terms of development. Nevertheless, improvement primarily has been in the plains as compared to hilly regions, and thus the hilly regions were left behind. The study claimed that being a small state, it faces the challenge of elevating the occupation of people, to limit migration through locally focused businesses as sources of income generation and to help improve the personal life and satisfaction among individuals living in the rural areas. Hence, there is a dire need to revamp the sustainable plans that are in place to address the problems for people living in the hilly areas of the state with the available resources.

Kumar (2005) has analyzed the capability of smaller and medium scale hydropower in Uttarakhand. Aside from its large and medium hydropower potential, which was evaluated to be 20,000 megawatts, Uttarakhand additionally has a tremendous potential for small and micro-scale hydropower generation in the mountainous region. The general hydropower generation capability of the state was evaluated as 40,000 megawatts, which is a large portion of the extra power anticipated to be acknowledged for the entire nation during the next two decades. The hydropower capability of Uttarakhand could be a great resource to improve the quality of life of the rural people.

The ongoing water resources development strategies in the Himalayan mountains have impacted the local rainfall distribution within a watershed which in turn has an impact on surface runoff, sub-surface flows and stream flows of a watershed. The earlier studies attempted to provide issues and limited understanding of water resources availability and their development potential. However, the implications of water resources development strategies on the watershed hydrology including different users across the watershed are not properly investigated. The need for restoring water for irrigation uses have not been adequately assessed in the previous studies. Also the linkages of the rainfall with the LULC are not evaluated properly to assess the implications of LULC.

2.4 HYDROLOGICAL DATA ISSUES

As more frequent problems due to climate changes and other issues such as floods and landslides occur, there is a need to strengthen the early warning systems and flood forecasting systems. One significant reason which can mitigate in flood forecasting is the collection of hydrological data and data sharing. Therefore, the monitoring of long-term streamflow, rainfall and other meteorological variables like temperature, humidity, wind speed etc. and archiving of the subsequent monitored data are some of the actions to be taken that are important for water resources research, for policy formulation by the Government, for crucial understanding of hydrological and other processes and, in most cases, provide the basis for predictive modeling. Research on the issues concerning the hydrological data is provided as a review.

Houghton-Carr et al. (2006) studied the achievements of two regional initiatives to address the “data problem” and discussed how to use the experience gained for the benefit of future projects. The study emphasized that the water resources were to be developed in an equitable, integrated and sustainable manner, to support enhanced socio-economic development. However, the hydrological systems are complex with many uncertainties. It is essential that the methods and tools needed to be developed have to be based on consistent, good quality, and readily available data from sites of key importance throughout the region and represent the complete range of probable flow conditions. The study resolved that the data might not be ideal for every application. However, it can at least provide a starting point for the initial assessments, particularly, to support investments in major water resource projects like irrigation schemes, and to serve as a foundation from which to respond to new challenges.

Wijesekera and Perera (2012) showed in their study that the statistical tests and the rational judgements would enable suitable corrections even though it is common to find that most of the hydrological and meteorological data are either flagged for quality or poorly documented. The statistical tests that were carried out using the SPELL-Stat software on the rainfall data of Attanagalu Oya catchment in Sri Lanka consisted of six rain gauge stations having daily rainfall data for 30 years. The water resources development and management is heavily dependent on the hydrological and meteorological data. In order to make sure that the results obtained from these data were reliable for practical applications, such data should be, homogeneous and consistent either to carryout frequency analyses or to simulate a hydrological system. The study suggested that in the absence of meta data, water resource professionals prerequisite to consider regional and global changes to rainfall. However, it is difficult to address the micro climatic changes in the absence of meta data.

Vinogradov et al. (2011) resolved the issue of poor data and non availability of data in the remote locations around the mountains and other regions by proposing the Deterministic Modelling Hydrological System (DMHS) ‘Runoff –Erosion–Pollution’. The ability to transfer the model parameters from small to large basins without calibration, low requirements of input meteorological data, and the model performance has validated the model as a viable alternative to traditional ‘physically based’ models. The objective for developing the model was to use it as a universal scale irrespective of the catchment size so that it can be applied in the mountainous regions, in the flat terrains, and in the basins with different natural climatic zones.

Gampe and Ludwig (2017) studied the uncertainty of eight gridded precipitation data sets of the Adige in Northern Italy, covering an area of 12,100km^2 from various sources over an alpine catchment to bridge the gaps in data scarce regions and to overcome the issues with observational data set. The results of the study demonstrated that, all data sets captured the monthly precipitation reasonably well, with the correlation coefficients between 0.8 and 0.95. As expected, the daily correlations were considerably lower, with no data set showing correlation greater than 0.8. Overall the lower correlations for the annual precipitation data sets reasonably captured an inter-annual variability, and indicated large seasonal differences. The higher resolution data sets, independent of their source, showed a better agreement with and the coarser data sets showed a great potential, especially in the representation of the overall climatology. Additionally, the study recommended the requirement of a more dense station network also in the higher elevations, to reduce the uncertainties in the observational data sets.

Yoon and Lee (2017) have completed a study in the urban areas where proper flood management was problematic due to the rare availability of sparse gauge data and radar data of high accuracy. To overcome the problems, the researchers have established three types of quantitative precipitation estimation (QPE) products using the rainfall data that was derived from 190 gauges and the automated weather stations. The accuracy of QPE approach was assessed in terms of the amount and spatial distribution of rainfall in an urban area. The results included highly accurate peak discharge and overflow phenomena in simulations. Hence, the study suggested that a radar will generally provide better quantitative precipitation estimates with a higher resolution, especially at the considered basin (30~50 km).

Nepal et al. (2017) developed a spatial transferability of the model parameters of the process-oriented J2000 hydrological model. It is required because of ungauged catchments in the Himalayan region. They have carried out study in two glaciated subcatchments of the Koshi river basin in the eastern Nepal. The model represented an overall hydrograph well in both subcatchments, including the baseflow, rising and falling limbs; however, the peak flows were underestimated. The efficiency results according to both the Nash–Sutcliffe (NSE) and the coefficient of determination (R^2) were above 0.84. The results from the study indicated that the transfer of the J2000 parameters to a neighbouring catchment in the Himalayan region with similar watershed characteristics is viable.

Singh and Thadani (2015) focused on the constraints associated with research in the Himalayas and the limitations of the output based on fragmented and incomplete data. Intensive review suggested that understanding the impact of climate change is vital to consider the larger picture in Himalyas, to be able to focus on issues on downstream flow. There is a need to estimate future flow patterns and hydrological regimes however, good long-term data sets were needed. The study appreciated the open-access Regional Database Initiative of the International Centre for Integrated Mountain Development (ICIMOD) that had put in the efforts at long-term monitoring in transboundary landscapes. Better monitoring and understanding of the Himalayan glaciers were initiated in the past few years as a result of climate change but the stream flow and spring hydrogeology remain poorly understood so far despite the increase in dependency on the springs in Himalayas.

Rijsberman (2006) reviewed water scarcity indicators and global assessments based on Falkenmark indicator which is popular because it is easy to apply and understand. However, it failed to explain the true nature of water scarcity. The more complex indicators were not applied widely due to lack of data and the definitions were not intuitive. The study concluded that, water will be a major constraint for agriculture in the coming decades, particularly in Asia and Africa which require major institutional adjustments.

Olen and Wu (2015) used the most comprehensive data of irrigated agricultural production in the United States. The Farm and Ranch Irrigation Survey (FRIS) of the United States Department of Agriculture (USDA) was utilized to assess the effects of water scarcity and climate on land use by the decisions made by the farmers to grow specially crops, wheat, and forage crops. The analysis found out that the farmers’ response was driven by a reduction in the land allocated to pasture. The farmers who used only surface water had lower average water costs and were able to allocate more land to pasture than other crops. The farmers response to drought was by increasing the land allocation to orchards and vineyards while reducing the allocation of land for crops like alfalfa and hay.

Shiklomanov et al. (2002) found out that the operational river discharge monitoring was declining both in North America and Eurasia. The problem was severe especially in the Far East of Siberia and the province of Ontario, where 73% and 67 % of river gauges were closed between the years 1986 and 1999 respectively. It was concluded that these reductions will greatly affect the ability to study the variations and alterations to the pan-Arctic hydrological cycle. Widespread loss of hydrological monitoring networks over the last 10-15 years in both the developed and the developing countries is of a great concern to the scientific community as it seeks to manage water resources and detect the impact of global change on the hydrological cycle. The problem of hydrographic monitoring loss across the pan-Arctic is particularly acute and may interfere with the understanding of high-latitude and global environmental change.

Chini and Stillwell (2016) have sent open-record requests to over 200 water and wastewater utilities in 112 cities representing all of the 50 States and the District of Columbia in the United States of America. The open-records were the only means of utility-level data available for researchers and the public. Utilizing the open-records data, the temporal resolution of energy and water data which varies widely between the utilities were plotted. At the end of the study, it was found out that the discrepancy in time scales between the water and the energy data impedes informed decision-making opportunities in the energy-water nexus. The study finally, concluded to recommend that, it is necessary for future research to create and maintain a comprehensive water resources database at the local scale for comparision which alternatively provides an opportunity to understand the differences.

There is a significant lack of watershed hydrological data in this mountainous region and its understanding will help in development of optimal watershed monitoring network. With such information gaps, a sound knowledge of basin hydrology is essential for effective water development policies and sustainable development so that their negative impacts on different uses and users can be avoided, minimized or mitigated. Therefore, there is a dire need for increasing instrumentation to collect the hydrological data and understanding of watershed hydrology in view of the changing phases of water management in the Aglar watershed. A sound knowledge of spatio-temporal hydrology is also imperative for addressing the pressing water management issues revealed by close consultations with key stakeholders in the Aglar watershed located in the Lesser Himalaya.

2.5 IMPORTANCE OF SPRING FLOW

Springs are predominantly originating in mountainous or hilly region. Spring is defined as a place where water flows from an aquifer to the Earth's surface (Figure 2.3). These naturally occurring springs in the Himalaya and other hilly region plays an important role in domestic water supply and compensate the other needs. Increased population, varying rainfall magnitude and reduced per capita water availability have gained attention on sustainability of spring flow.

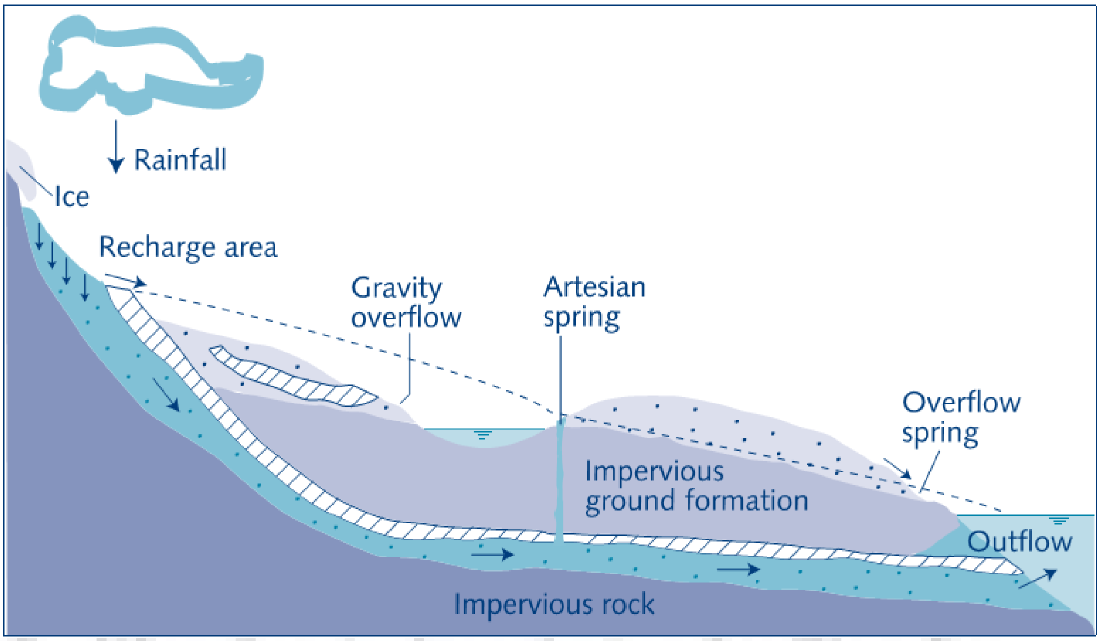


Figure 2.3: Typical figure showing occurrence of natural spring (Source: *Kresic, 1997*)

Agarwal et al. (2015) concentrated their study on the springs of Chandrabhaga and Danda watersheds in the Garhwal district of Uttarakhand. The study analyzed the rainfall and the spring flow pattern. It was found out that the second order polynomial relationship was the best fit between the annual rainfall and the annual average spring flow. During the low flow condition, the aquifer retains water for a much longer period of time with less fluctuation in the spring hydrograph. The average water availability from all of the springs was greater than the required demand of water for domestic purposes. On the other hand, the minimum water availability was less than the required demand of water for domestic purposes but was greater than the actual use of water for domestic purposes. Hence, the study concluded that the availability of water is the limiting factor for the use of water and that there is a need to increase the minimum water availability through the springs.

Fiorillo (2009) analysed the discharge from spring of Southern Italy to establish the relationship between the rainfall and area recharge of a large karst system. The study is focused in an area which is characterized by dry summers and a wet period during autumn and winter. Analysis of the spring discharge revels that because of less rainfall there was less recharge in the area and results flat shape with no peak in spring hydrographs which indicating constantly decreasing discharge from the spring which is also a signature of drought. Study have also shown that discharge from spring have dependency on past records of the previous years as average seasonal and annual rainfall do not have any specific pattern and have a memory effect. Understanding of this memory effect between spring discharge and rainfall can help to mitigate the effect of drought and better planning of water resources.

Vashisht (2016) studied the springs of the greater Himalayan Sikkim region and observed that either the springs have turned out to be seasonal or their discharge rates -especially during recession periods have lessened to a noteworthy level. The researcher proposed a function to describe the flow behaviour during the recession period. Prior to the study, the common theory was that the decay of spring during the rainless period was well fitted with only two mathematical components. But the study resolved that it was not correct. It could exclusively be governed by a number of permeable (porous) mediums having different developments inside the spring catchment. To express the decay of the discharge function of a spring, it is a prerequisite to understand the characteristics of the hydrograph and its variation from time to time, especially the exponential coefficients which are the major constraints. The difference in the exponential coefficients of the recession curve at different times could be computed by assessing the factor i.e. the ratios of its maximum to minimum value-from all the data that was monitored.

Kreye et al. (1996) emphasized on defining source area for development of recharge in the springshed area, factors affecting spring discharge and found that, spring discharge contributing a major portion (15%) of central water supply in British Columbia. Study also shows the application of spring discharge such as in waterworks and how the water supply can be done to provide water at lowest cost.

Vaidya (2015) has proposed strategies to increase the domestic supply of water through tapping the spring and the river flows by constructing ponds or tanks for use by the community of a village at an assessable location, and if possible, reservoirs for collecting the rain water which flows directly into the rivers in the Himalayas. The major findings of the study suggested that there were numerous biophysical and institutional requirements that should be overcome for effective execution of the proposed strategies which are (a) dynamic cooperation of nearby residents at all phases to accomplish local water management (b) ensure that the involvement of the State or the Central government administration does not hinder the prevailing tradeoff mechanisms (c) create self-help groups (SHG) and motivate the public with the collaboration of local non-governmental organizations (NGO), empower women and underprivileged or poor to contribute vigorously and (d) legitimize watershed management and consider linkages between upstream and downstream that are fundamental for successful water storage initiatives.

Valdiya and Bartarya (1991) studied the hydrological behaviour of the mountainous watershed of Lesser Himalayan located in Kumaun district which is extremely affected by the deforestation. Result found the drying up of few springs and reduction in the outflow from the spring discharge because of deforestation and other associated caused such as increased erosion, reduction on canopy cover and alterations in the land cover. Study concluded that the reduced springs discharge may also be because of less rainfall received (9.7% to 76%) during studied duration in some watersheds. Their study recommended the use of the watershed as follows: one third from top for forest, middle one third for pastures and left fortion for agriculture. Discharge from spring demonstrates an episodic annual rhythm which denotes the recharges of the aquifer that withstands discharge of springs yearly.

Negi and Joshi (2002) studied the drinking water issues in the Indian Himalaya and shows the concern to promote the development of spring sanctuaries in the recharge zones in the mountainous watershed to increase the discharge. Spring sanctuaries was developed through trenching (15–30 cm deep and 1–20 m long), planting of Alnus nepalensis, Prunus cerasoides (deciduous), and Quercus leucotrichophora. Average water discharge from the spring was increased from 1055 to 2153 l/d during 1995 to 2000.

Mahamuni and Upasani (2009) studied the springs of the lower and middle Himalayan in the Tehri Garhwal district and found that the socio-economic development of these regions directly or indirectly dependent on springs. It was observed during investigation that the other sources of water can be used by some centralized scheme to supply water for agricultural and infrastructural developments for semi urban areas and adjacent villages only. The quality of spring water remains almost constant whereas the qualities of streams in the area largely affected by sedimentation due to steeper slopes during rainy season.

Cynthia et al. (2004) assess the dependability on the springs as a sustainable source of domestic water. Quantification was done by measuring the seasonal and annual rainfall and discharge from total seven springs (5 small and 2 large). In this study, recession behaviour of spring was also analyzed. Analyses of monthly rainfall and spring discharge shows that spring discharge follows an analogous pattern to that of the rainfall. In order to understand the spring flow behavior during the dry season, they analyzed the behaviour of spring discharge using a mechanistic recession flow model. Analyzed result from the recession flow model pronounces that the aquifer obeys the rules of a linear reservoir during the dry season of spring flow. Study also showed that the ‘‘half-life’’ of the springs was around 30 days.

Amit (2002) stands for the recession curve analysis of spring discharge which contains the information of the storage-discharge and temporal decay relation for different types of aquifers. He has analyzed the perennial spring discharge from Galilee and Judean Mountains in Israel. He has showed that the recession behaviour from any spring can be well predicted using exponential decay function comprising of two exponential coefficients (α_1 and α_2). Studied result shows that, coefficients α_1 and α_2 were constant for some specific type of spring representing the hydraulic conductivity property of an aquifer. Comparative value of different α_1 and α_2 for different type of springs and different years shows that lithology and geometry of water conduits are main responsible factors which governs discharge from spring.

Agarwal et al. (2014) studied the spring discharge in Danda watersheds in the middle Devprayag having an area of 3 km^2 by collecting other continuous automated hydro-meteorological data collection. Study hypothesized that the rapid response of spring discharge due to rainfall because of location of spring is with in close vicinity of the watershed and rainfall is only factor influencing spring discharge behaviour. Study after detailed analysis concluded that water is enough available but storage tanks are necessary to store excess spring discharge and proper planning and decision support system is required to distribute the stored water. They also suggest to use drip irrigation method to get the most out of the use of limited available spring water.

Above literature review reveled that, alterations in LULC settings have carried significant impact on water flows and threat to eco-hydrology of the Himalayan area. The rapid growth in urbanization has increased the demand for land for development purposes consequently forest and water resources are coming under enormous pressure. The general trends of landuse change are gradual decline in coverage of scrub and coniferous forest, increase in urban development and somewhere in agriculture area. The increase in built-up land in the valleys has reduced the recharge source of groundwater which needs to be protected through controlling unplanned growth of urbanization. The rise in global warming accompanied with high variability in precipitation projects extreme changes in water balance and ultimately deterioration of the land quality. An integrated adaptation strategy needs to be developed at watershed levels to cope with future implications of hydrological changes through focusing on key hydrological areas and improving adaptive capacities of the communities at risk. Existing knowledge and data gaps need to be filled by instrumentation, systematic data collection and enhanced capacities for research since these will be fundamental for developing climate change adaptation and mitigation programmes for the Aglar watershed and other

Himalayan region in future. Review further revels an instant prerequisite for collective research of surface and sub-surface flow which reduces ambiguity in the hydrological processes occurring in the Himalayas and other mountainous watershed. Based on the literature review, background and objectives for the present research work have been articulated as given in chapter 1. The next chapter describe in detail about the characteristics of the study area and morphometric analysis.

This study contributes directly to improve understanding of the Aglar watershed hydrology and water availability. In general, this research contributes in improving understanding of micro scale hydrological processes exhibited in Himalayan watershed which is quite diverse in hydroclimatic features and is subjected to data scarcity. The knowledge generated by this study is helpful to improve understanding of spatio-temporal variability of the watershed hydrology and its use in the sustainable management of water resources, and similar regions of lesser Himalaya and elsewhere.

CHAPTER 3

PRESENTATION OF THE AGLAR WATERSHED

Chapter three introduces the area of the study and presents its main physical characteristics such as geographical location, extent of the basin, geology, morphology, pedology, climatology and land use. The location of the study is Aglar watershed in Tehri-Garhwal district of Uttarakhand state which is considered as a hilly state. The northern part of the hills around the Aglar watershed is well recognized for its snow/ice shielded summits, perennial streams and valleys, different environment conditions and undulated geography with fewer vegetation to no vegetation in the southern part. The mountainous region of the state is blessed with good water resources and 60% of forest cover (Chauhan 2010) but the problem lies in the utilization of these resources as they are used in an unscientific way making it difficult to sustain the resources.

3.1 AREA OF THE STUDY

3.1.1 Location and Extent of the Watershed

The Aglar watershed is a mountainous watershed of 30,500 hectares located within 30.49° N to 30.52° N and 78.14° E to 78.16° E in Tehri-Garhwal district of Uttarakhand, India (Figure 3.1). It is located behind the Mussoorie ridge which is known as the “Hill Queen” in the Lesser Himalayas. The watershed is characterized by undulating topography that ranges in altitude approximately from 450m to 3022m above the mean sea level (msl) and drains into the Yamuna River near the Yamuna Bridge. The micro watershed region includes the three sub adjoining watersheds the Upper Aglar, the Paligaad and the Balganga commonly referred to as the Aglar watershed, located on the Survey of India (SoI) Topo sheet Nos. 53J and 53N.

3.1.2 Physical characteristics of the Aglar Watershed

The hydrological response from the Aglar watershed depends on multiple interactions that took place over a long period of time between the internal geological and external climatology and meteorology. The interactions occur at the interface between the lithosphere and the atmosphere which determine the characteristics of, the terrestrial morphology, the watershed hydrology, the soils and the type of land use (Figure 3.2). The tributaries of the Aglar River flows with a decreased flow by the end of the winter season subjecting to water crunch during the summer season due to erratic and skewed nature of the rainfall. The multipurpose demand for water has also changed with time as there was an increase in the population, the pattern of water availability and the utilization of water. Hence, sustainability has become a challenging issue for water resources development and management.

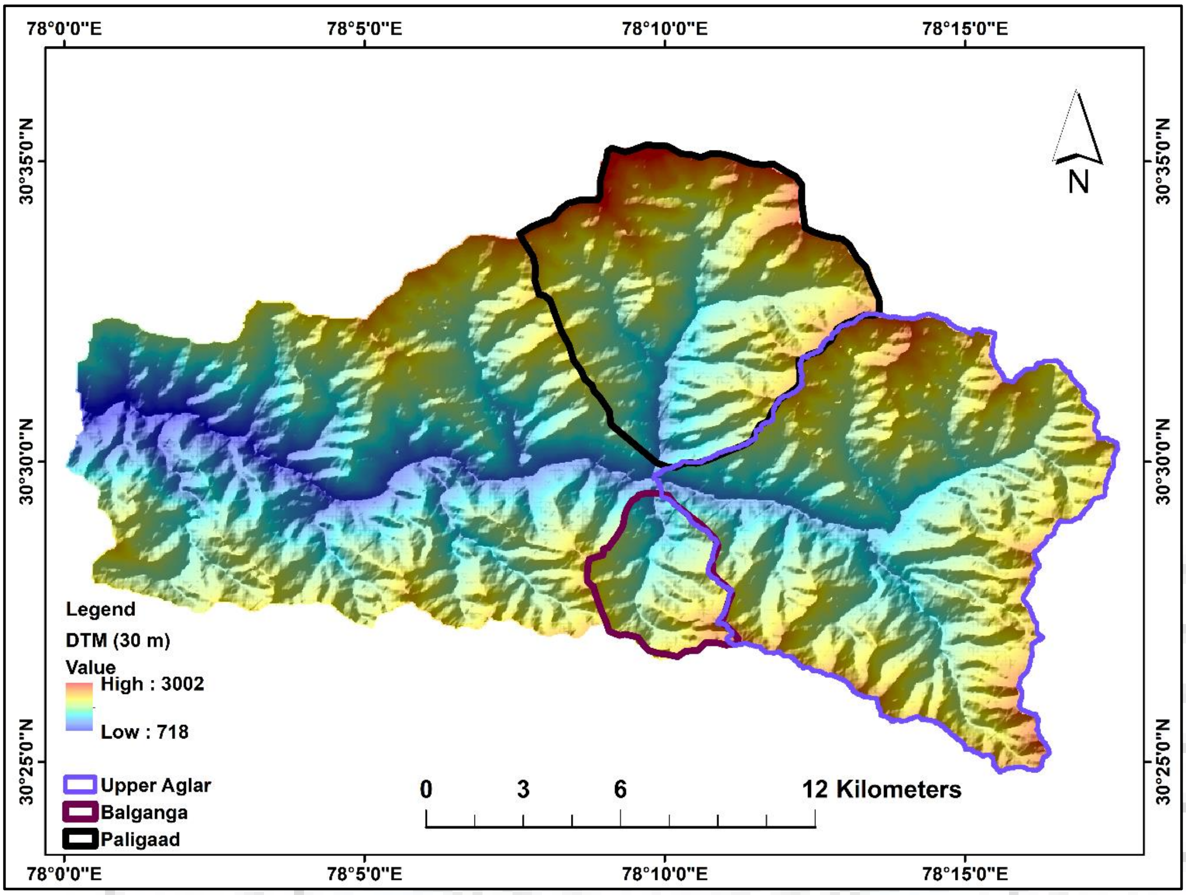


Figure 3.1: Index map of Aglar watershed (area of the study)

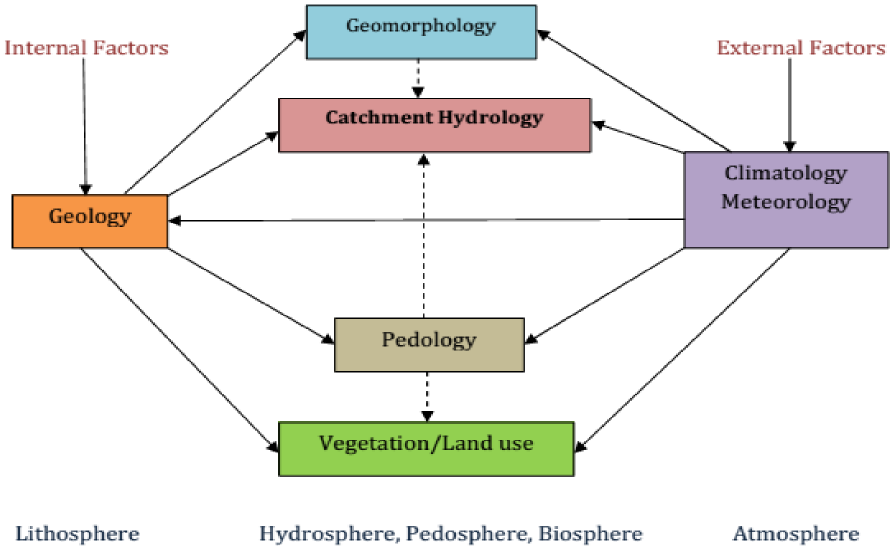


Figure 3.2: Factors that determine watershed hydrological processes

3.1.3 Geology

Repeated tectonic instabilities caused by different orogenic cycles makes the geological setup of Aglar watershed complex. The location of the study is characterized by rocks of Lesser Himalaya (LH) and Central Himalaya (CH). Extensive geographical and geological mapping in the lesser Himalaya done in the year 1980 by Valdiya (1980) (Figure 3.3).

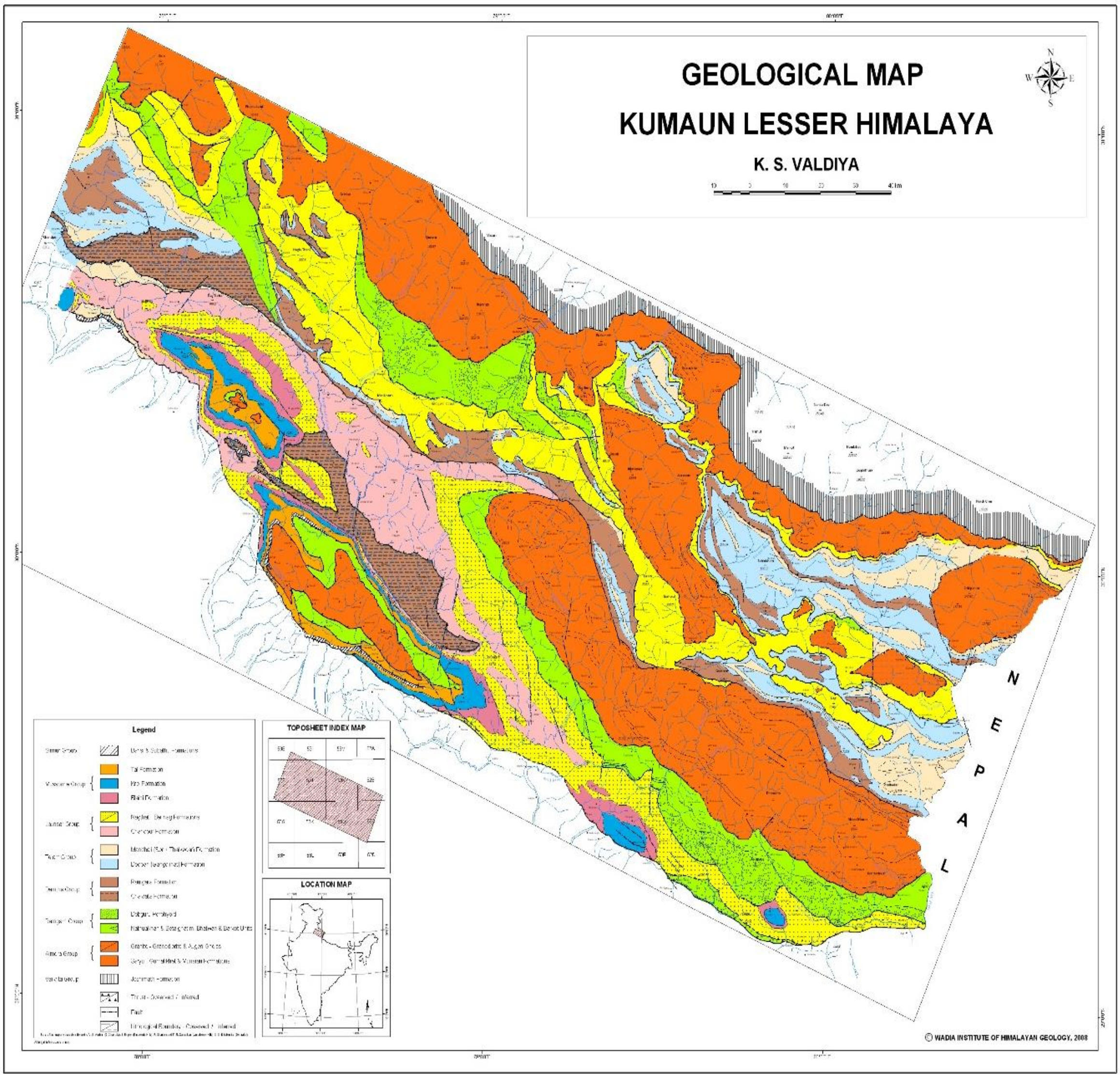


Figure 3.3: Lesser Himalaya geological map **(**Valdiya, 1980**)**

The Lesser Himalaya portion of the Tehri Garhwal district encompasses different geological groups such as Tal Group, Blaini-Krol Group and Jaunsar Group. The area of the study is located in the southern direction of the Main Central Thrust (MCT). The Major rock types occur are psammitic and mica gneiss, quartzite, mica schist and amphibolite as plunge sheets above the sedimentary rocks of Lesser Himalaya in diverse tectonic situations.

3.1.4 Morphology

Study of morphometric parameters of the watershed provide information about the water storage capacity of the rocks, permeability of the rocks and the yield capacity of the watershed. To study the morphometric characteristics, maps were prepared using the Geo referencing in ArcGIS 10.2.2 and ortho rectification in addition to digitization using ERDAS software. The filtered and corrected digital elevation model (DEM) was introduced in ArcGIS 10.2.2 package for basic hydrological steps like basin delineation and further morphometric parameters measurement and calculation. The qualitative analysis of different morphometric parameters (Table 3.1) of the Aglar watershed were estimated from a digitized map. A flow chart of the methodologies is presented in Figure 3.4.

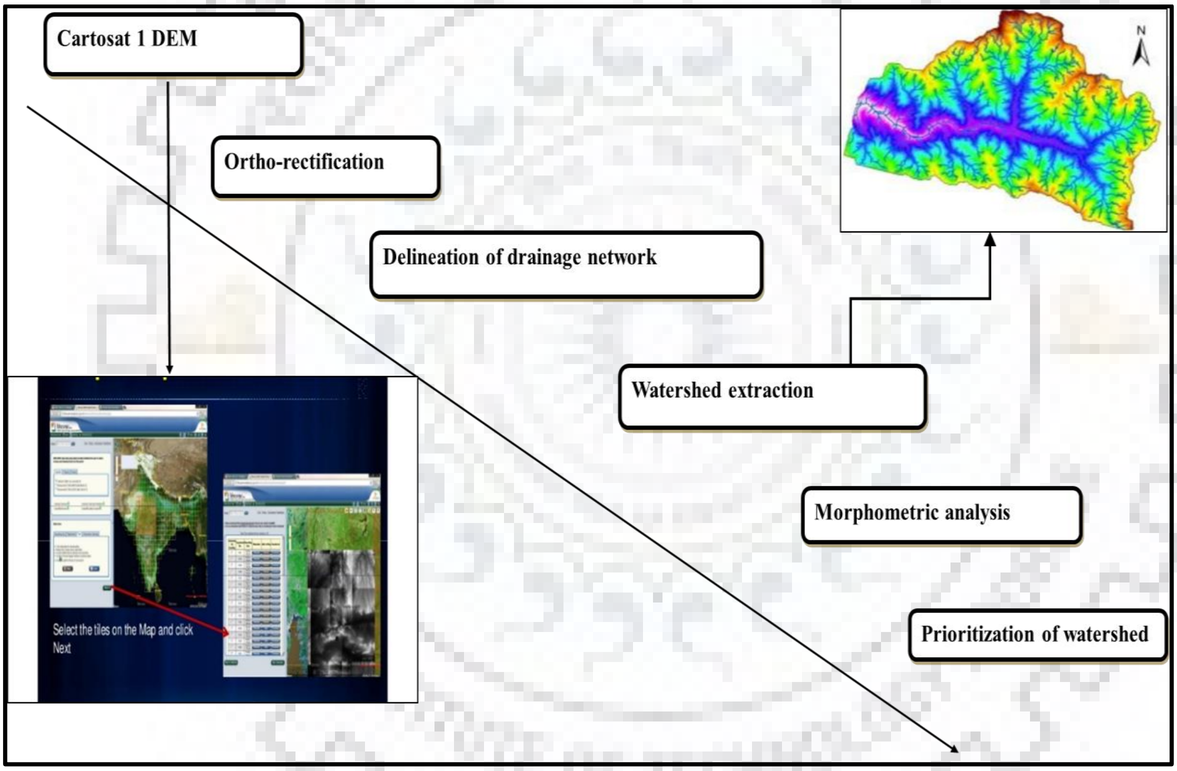


Figure 3.4. Methodology adopted for morphometric analysis using RS and GIS

Using the inbuilt hydrology tool DEM in ArcGIS 10.2.2, different maps were prepared for the fill, flow direction, flow accumulation, and stream order. All of the maps were produced in an order, where the preceding map turns out to be the base map to produce a subsequent map. The morphometric characteristic of the Aglar watershed was examined in three different classifications i.e. linear aspect, aerial aspect and relief aspect using the procedures and formulae enumerated in Table 3.1.

Table 3.1: Computation of different morphometric parameters using formulae

Sr No.	*Morphometric Parameter*	*Formula*	*Reference*
1	Stream order (u)	-	Strahler (1964)
2	Stream length (Lu)	-	Horton (1945)
3	Mean stream length (L_{sm})	$L_{sm} = L_u / N_u$ Where, L_u = Total stream length of order 'u' N_u = Total no. of stream segments of order 'u'	Strahler (1964)
4	Stream length ratio (R_L)	$R_L = L_u / L_u - 1$ Where, L_u = Total stream length of the order 'u' $L_u - 1$ = Total stream length of next lower order	Horton (1945)
5	Bifurcation ratio (R_b)	$R_b = N_u / N_{u+1}$ Where, N_u = Total no. of stream segments of order 'u' N_{u+1} = No. of segments of the next higher order	Schumn (1956)
6	Mean bifurcation ratio (R_{bm})	R_{bm} = Average of (R_b)of all orders	Strahler (1957)
7	Relief ratio (R_h)	$R_h = H / L_b$ Where, H = Total relief (Relative relief) of the watershed (km) L_b = Watershed length	Schumm (1956)
8	Drainage density (D_d)	$D_d = L_u / A$ Where, L_u = Total stream length of all orders A = Area of the watershed (km^2)	Horton (1932)
9	Stream frequency (F_s)	$F_s = N_u / A$ Where, N_u = Total no. of streams of all orders A = Area of the watershed (km^2)	Horton (1932)
10	Drainage texture (R_t)	$R_t = N_u / P$ Where, N_u = Total no. of streams of all orders P = Perimeter (km)	Horton (1945)
11	Form factor (R_f)	$R_f = A / L_b^2$ Where, A = Area of the watershed (km^2) L_b = Square of watershed length	Horton (1932)
12	Circularity ratio (R_c)	$R_c = 4 * pi * A / P^2$ Where, Pi = 'Pi' value i.e., 3.14 A = Area of the watershed (km^2) P = Perimeter (km)	Miller (1953)
13	Elongation ratio (R_e)	$R_e = 2 / L_b * (A/ Pi)^{0.5}$ Where, A = Area of the watershed (km^2) Pi = 'Pi' value i.e., 3.14 L_b = Basin length	Schumn (1956)
14	Length of overland flow (Lo)	$L_g = 1 / D_d * 2$ Where, D_d = Drainage density	Horton (1945)

3.1.4.1 Linear Aspect

The linear aspects of the any watershed are stream order (U), stream length (L_u) and stream frequency (F_s).

Stream order (U): On the basis of the calculation, it was inferred that the Aglar watershed is a 3rd order stream that covers approximately an area of 305 km^2. The linear morphological parameters of the watershed is summarized in Table 3.2. The variation in stream order and the size of the watershed was mainly due to the physiographic and the geological conditions of the region (Zende et al, 2013). A total number of 29 streams were identified of which twenty were 1st order streams, eight were 2nd order and one was of the 3rd order. Observation of the drainage patterns of the stream network from the watershed revealed mainly as parallel type indicating a hilly watershed.

Table 3.2: Linear aspect of Aglar watershed

Linear Aspect of drainage network					
Stream Order	**No. of streams**	**Total length of stream (km)**	**Mean stream length (km)**	**Bifurcation ratio**	**Stream length ratio**
1	20	58.51	2.92		
2	8	15.30	1.90	2.5	0.261
3	1	2.52	2.52	8	0.165
Total	29	76.33	7.34		0.426

Stream length (L_u): The stream length of a watershed is the aerial distance between the watershed outlet and the farthest point on the perimeter of the watershed (Gregory and Walling, 1973). In general, the total length of the stream segments decreases as the stream order increases. It is one of the most significant variables in characterizing a watershed runoff and watershed features. It is common that shorter streams are prominent in hilly regions with larger slopes whereas longer streams are generally indicative of flat regions with lesser slope.

Mean stream length (L_{sm}): According to Strahler (1964), the stream length is a characteristic property related to the drainage network components and its associated watershed. The mean stream length reveals the characteristic size of the components of a drainage network and its contributing surface. In a watershed, the mean stream length of a given order is higher than that of the lower order and less than that of its next higher order. The mean stream length of the area is presented in Table 3.2. It is noticed that the mean stream length of the area of the study varied from 1.9 km to 2.92 km with a cumulative mean stream length of 7.34 km.

Stream Length ratio (R_l): The stream length ratio was derived after the Horton's law of stream length which states that the mean stream length segment of each of the successive orders of a basin tends to approximate a direct geometric series with the stream length increasing towards higher order of streams.

3.1.4.2 Areal Aspect

Drainage density (D_d): The drainage density of the area of the study is estimated to figure out the closeness of the spacing of the channels (Horton, 1932). A low drainage density (0.25) of Aglar watershed indicated that it has highly resistant, impermeable subsoil material with dense vegetative cover (Nayar and Kavitha, 2013).

Stream frequency (F_s): The stream frequency of the watershed is provided in Table 3.3. Generally, a watershed with a large area under dense forest has low drainage frequency and the area with more agricultural land has a high drainage frequency.

Table 3.3: Relief and areal aspect of Aglar watershed

Morphometric characteristics	**Estimated value**
Area (km^2)	305.86
Perimeter (km)	118
Length of basin (km)	255.72
Drainage texture	0.25
Texture ratio	0.25
Drainage density	0.25
Stream Frequency (per km)	0.09
Form factor	1.21
Circulatory ratio	0.28
Elongation ratio	0.08
Length of overland flow (m)	0.12
Shape Index	0.83
Relief (km)	2.31
Relief ratio	0.01
Ruggedness number	0.58

Texture ratio (R_T): Texture ratio or drainage texture indicates the relative spacing of the drainage lines. It is defined as the number of stream segments of all of the orders per perimeter of that area (Horton, 1945). Smith (1950) has classified drainage density into five different textures. The drainage density less than 2 indicates very coarse, between 2 and 4 is coarse, between 4 and 6 is moderate, between 6 and 8 is fine and greater than 8 is very fine drainage texture. For the Aglar watershed, the drainage density is of very coarse drainage texture with a texture ratio of 0.25.

Watershed Perimeter: A watershed perimeter is the length of the watershed boundary that encloses the catchment area. It is used in conjunction with the basin area to provide a measure of the departure of the basin from a true circle and in conjunction with the relief to provide a measure of the general steepness of a watershed. For the Aglar watershed, the watershed perimeter is 118km.

Form factor (R_f): The form factor for the watershed of the study area is 1.21 (Table 3.3). The observation revealed that the watershed is more or less elongated in shape. The elongated watershed with a low value of R_f indicated that the watershed will have a flatter peak flow for longer duration. The flood flows of such elongated watershed are easier to manage than the flood flows from circular watershed (Zende et al, 2013).

Elongation Ratio (R_e): Schumm (1956) defined the elongation ratio as the ratio between the diameter of the circle of the same area as of the drainage watershed and the maximum length of the watershed. The elongation ratio of 0.08 for the Aglar watershed indicated a normal relief and a gentle ground slope.

Circularity Ratio (R_c): Miller (1953) defined circulatory ratio as the ratio of the area of the watershed to the area of the circle having the same perimeter as the watershed. It depends on the length and frequency of the streams, the geological structures, the land use/ land cover, climate, the relief and slope of the watershed (Zende et al, 2013). In the present case (Table 3.3), the R_c value of the Aglar watershed is 0.28 which depicted that the watershed is almost elongated in shape.

Length of overland flow (L_o): The length of overland flow is the length of water over the ground before it concentrates into definite stream channels (Horton, 1945). The length of the overland flow approximately equals to the reciprocal of the drainage density (Figure 3.5). Table 3.3 displays the L_o values. The Lo value of 2 m of the area of the study indicated a comparatively low relief of the area.

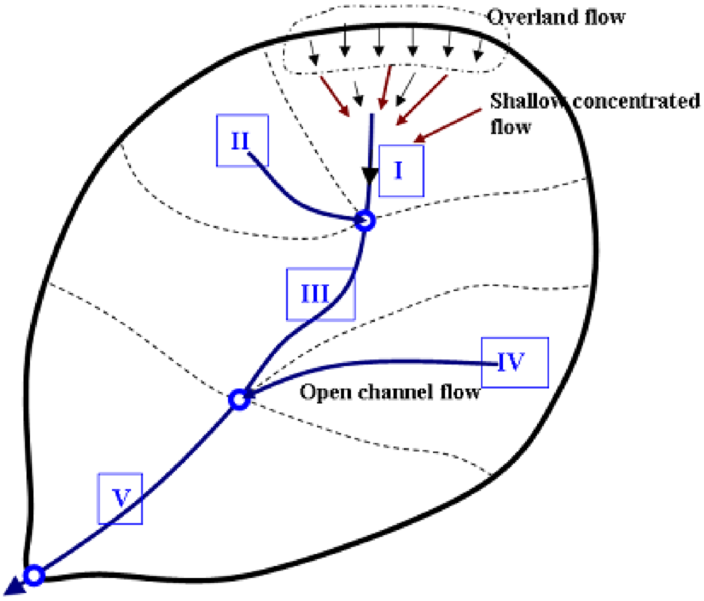


Figure 3.5. Representation of overland flow in watershed

3.1.4.3 Relief aspects

Relief ratio: The elevation difference between the highest and lowest points on the valley floor of a watershed is known as the total relief of that watershed. The maximum relief to the horizontal distance along the watershed parallel to the principal drainage line is termed as the relief ratio (Schumm, 1956). The relief ratio has a direct relationship with the relief and the channel gradient. In the area of the study, the value of the relief ratio is 0.001 indicating a low relief.

Ruggedness number (R_n): Ruggedness number is the product of the maximum watershed relief (H) and the drainage density (D_d), where both the parameters are in the same unit. An extreme high value of ruggedness number occurs when both the variables are large and the slope is steep (Strahler, 1956). The value of ruggedness number in the Aglar watershed is 0.58. (Schumm, 1956).

Major emphasis for morphometric analysis has been given because of its importance in development of quantitative physiographic procedures to pronounce the development and behavior of watershed drainage networks. Above analysis of the Aglar watershed will prove useful and beneficial and used in further chapters to link the uncertainty in discharge measurement and understanding of hydrological responses. This will also provide the key information to the planners and decision makers for proper natural resource management at micro-level.

3.1.5 Climate

The climate in Aglar watershed varies between subtropical to temperate humid climates with an average annual temperature approximately between 6ºC to 19.8ºC. The geographical factors such as the distance from the sea and the altitude, influence the climate (rainfall and temperature) of a watershed. The main rainy period is the southwest monsoon with an annual average of 1092mm but just adjacent to this watershed there was annual average rainfall of about 2223mm recorded at Mussoorie (Pant and Roy, 1990).

The major part of the rainfall occurs only within three monsoon months from July to September. The number of rainy days varies from 70 to 80 days in a year. Earlier observations revealed January as the coldest month with a mean maximum temperature of 19.6°C and the mean minimum temperature of 4.6°C. The Relative humidity in the watershed increases rapidly with the onset of monsoon and reaches its maximum of 85% in the morning and 84% in the evening during the month of August, when the peak monsoon period sets in. Relative humidity is the minimum during the summer months from April to June with the month of May being the driest month at 47% in the morning and 25% in the evening. The average wind speed is a minimum of 0.8 km/hr in December and a maximum in July with 4.1 km/hr whereas the average annual wind speed is 2.3 km/hr.

3.1.6 Agriculture and Land use

Agriculture is the main occupation of the people in this watershed with about 22% of the watershed region under irrigation. However, intensive cultivation is not possible as the major part of the region is mountainous. Rice, wheat, mandua, barley, maize and sawan are the principal crops generally grown in the region. Rice is the major crop during the monsoon season in the Aglar watershed (Figure 3.6 (a)). Vegetable cultivation is restricted to homestead level and confined mainly to French bean, potato, pea, capsicum, cucumber, radish, etc. The farmer’s agricultural fields are mainly surrounded by Himalayan subtropical pine and oak forests (Figure 3.6 (b, c) which has some influence in streamflow generations (Sun and Liu, 2013). The predominant agroforestry species in these sites are Grewia optiva, Melia azedarach and Quercus leucotrichophora.

Figure 3.6 (a) Rice cultivation in terrace field, (b) medium dense pine forest (c) dense mixed oak forest.

The Aglar watershed is divided into six major Land-Use/ Land-Cover (LULC) classes such as forests, shrubs, pastures, bare, agriculture, build-up, and water body (Figure 3.7).

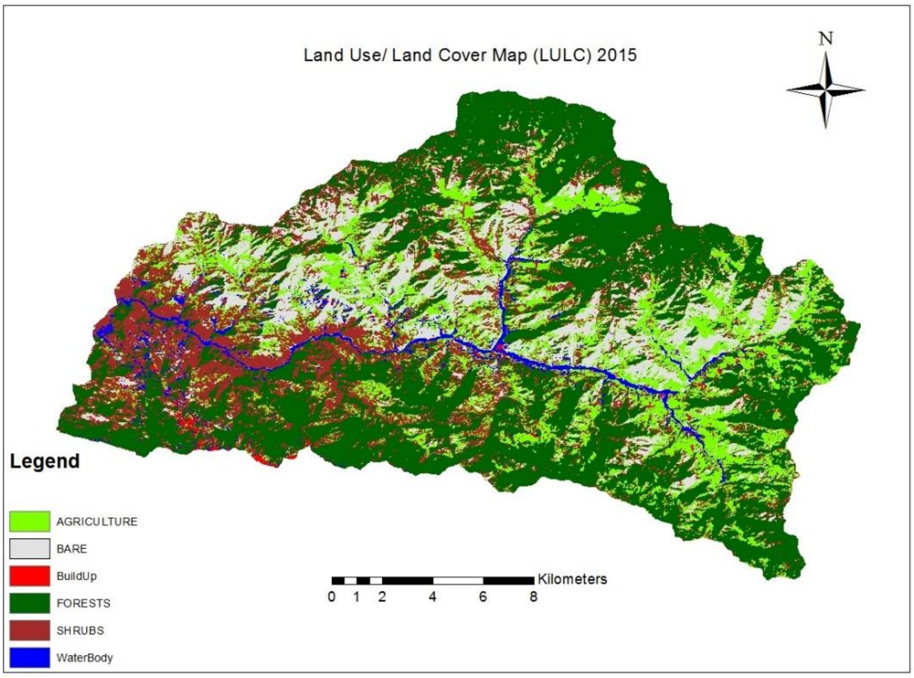


Figure 3.7: Land Use Land Cover of Aglar watershed

From LULC classification, it is observed that the forests form a major part on the northern side of the watershed. On the southern side of the watershed, a very small area is inhabited. Agriculture is mainly practiced on the slopes where the land is divided into terraces. Shrubs and agriculture are a prominent Land-Cover especially in the north and southwest direction of the watershed.

3.1.7 Soil Type

The main soil types found in the catchment are loamy, silty loam, sandy loam, clay and loamy clay consisting of hydrologic soil groups B, D and others (rock type). Hydrologic soil groups are classified on the basis of the runoff potential. Group B soils have a moderate infiltration rate when thoroughly wet and consist primarily of moderately deep and moderately well drained soils that have moderately fine texture to moderately coarse texture. Group D soils have a very slow infiltration rate with a high runoff potential when thoroughly wet and consist chiefly of clays that have a high shrink-swell potential, have a high water table, have a clay layer at or near the surface, and that are shallow over nearly impervious material.

This chapter described the study area which plays a very important role because it illustrates the watershed characteristics, land cover and soil variability of the watershed. Increase in population by 28.61% between 2001-2011 and urbanization (4.1%) has leads to understand the area resources distribution (land cover and soil). The morphometry parameter analyzed will further used to develop the concept of weighing factor in subsequent chapter. The distribution of land cover will help to understand the hydrological processes in different sub-watersheds of the study location.

CHAPTER 4

RAINFALL DISCHARGE DATA ANALYSIS

Chapter four discusses the analysis of the monitored data of rainfall and river flow of mountainous system to advance the understanding of the hydrological response. Worthiness in monitored river flow data in two different sub-watersheds i.e. Upper Aglar and Paligaad was studied and presented in this chapter.

4.1 INTRODUCTION

In the Aglar sub-watershed as described in the last chapter (Figure 3.1), demands for water are increasing and sustainable management of water resources has become an important issue. The main challenges were lack of hydro-meteorological data, low water and land productivity, spring depletion and growing competition for water among upstream and downstream areas and among different sectors of water use such as irrigation and domestic. In Aglar watershed, substantial irrigation development is on the way, but the knowledge and understanding of watershed hydrology (including the spatio-temporal water balance variations) and impacts of these developments on other users and water uses across the basin are patchy. The non-availability of substantial water, anguishes the natural practice such as the soil water retention ability, occurrence and percentage of recharge, water quality etc. which eventually alter the hydrological cycle (Figure 1.2) and the growth of the local vegetation. Observational systems to quantify various hydrological processes and assess water quality has also declined in the last few years due to financial and political unsteadiness (e.g. NRC, 1991; Entekhabi et al., 1999).

Quantitative and holistic understanding of Aglar watershed located in steep slope becomes complex in the absence of hydro-meteorological data. As we know that, with the increase in water demands as discussed in chapter 1, the management of water resources becomes increasingly complex due to the huge number of interacting factors such as upstream-downstream impacts, increasing impacts on the irrigation. Providing food security and guaranteeing the right to safe drinking water to all in the present time remains a key challenge for sustainable development of watersheds. This challenge is even more in the rural Himalayan regions where the maximum are poor people (having very less money or other resources of survival).

Thus, there is an urgent need to take suitable actions like establishing monitoring stations, quantifying the water resources and forecasting for future availability to safeguard and for sustainable management of the Himalayan Mountains to confirm food and water security. The natural resources data like the rainfall and the river flow, especially in the mountainous regions is very important for water resource management and for related scientific researches. However, insufficient data or the lack of information renders many hydrological understanding difficult (Seibert, 2009). It can be argued that under such conditions, increasing the knowledge of the watershed hydrology by setting up the instrument to collect the right information at sub-watershed level at desired time interval plays a key role for constructing a sound and sustainable water management. Further, data analysis provide sound understanding of watershed hydrology which is essential for effective water allocation and policies developments so that negative impacts can be avoided, minimized or mitigated.

Hydrological analysis provides the basis for detailed accounting of water use for different user and water productivity. It is a basic requirement for water resources development and management evaluations and decision making related to a) assessing water availability, b) understanding the balance between the actual use resource availability, c) improving water allocation decisions, d) monitoring the performance of water use, and e) formulating environmental flow requirements and working out ecosystem restoration strategies. This chapter provides a comprehensive analysis of spatio-temporal variability of the rainfall and streamflow over the monitored period in the Upper Aglar and Paligaad sub-watershed. Additionally, water availability and seasonal variations are evaluated for the year different years and analysis for different sub-watershed for sustainable management of water resources are highlighted.

4.2 DATA COLLECTION AND MONITORING

The continuous long term monitoring of the hydrologic data, storing and sharing of the monitored data are inseparable from hydrology and research of water resources. There is considerable vagueness in the spatio-temporal trends of rainfall, temperature and discharge because of enormous regional changes and restrictions on the monitoring systems (Bates et al. 2008). In the developed countries such as the United States of America, the discharge in the rivers, which is the foremost important component of the water cycle that is constantly being monitored since the late 19th century for improved water resources management and its distribution (Barrows 1998).

However, in India and other developing countries, monitoring of the river flow and other hydro meteorological parameters are not well established till date which could have been used potentially to study the influence of climate change on water resources and to deliver the baseline evidence about water availability and its temporal variation.

An important aspect for strengthening the meteorological and hydrologic monitoring data collection is to evaluate and consider the vulnerabilities related to the methodology of the data collection and the site selection. The two aspects that play a vital role are the enquiry of how long to continue to monitor a gauging station for data collection. Hydrologic estimation depends vigorously on the estimations of low frequency data monitored over a long time, because the low-frequency but high-magnitude events could have close irreversible consequences for water supply. The river discharge and the measurement of the rainfall with extended duration are of great importance for prediction and modeling of high flows, allocation of water and for development of strategies for better water resources planning. The government and different stake holders need to take a different approach toward hydrological monitoring and collection of data. A better resolution to outbreak the 21st century water issues (number of monitoring stations), could be achieved by integrating the monitored data into strategic planning. There is furthermore a strong requirement of teamwork and collaboration between organizations involved in collecting and handling the hydrologic data, mainly from the experimental watersheds and from the legacy monitoring systems. In view of the above issues, the Aglar watershed of 305 km^2 was instrumented with five river gauges, four rain gauges, one spring gauge and one automatic weather station (AWS) to assess the spatial and temporal distribution of hydro-meteorological parameters. Overall aim for developing the experimental watershed is to generate the high frequency hydrological data which were not present to answer the research question related to hydrological responses of different watershed having different watershed classification.

The first instrumentation were two rain gauges and a river flow gauges in the year 2013. Later with the availability of funds other rain gauges and river gauges along with the AWS were installed to generate the temperature and evaporation data. Appendix-I, summarized the hydro-meteorological parameters that were monitored with the measurement duration, location and ongoing monitoring status until the month of May, 2018. Monitoring at two gauging stations i.e.

Mathamali and Shivalaya has been stopped after monitoring of few months due to site specific issues.

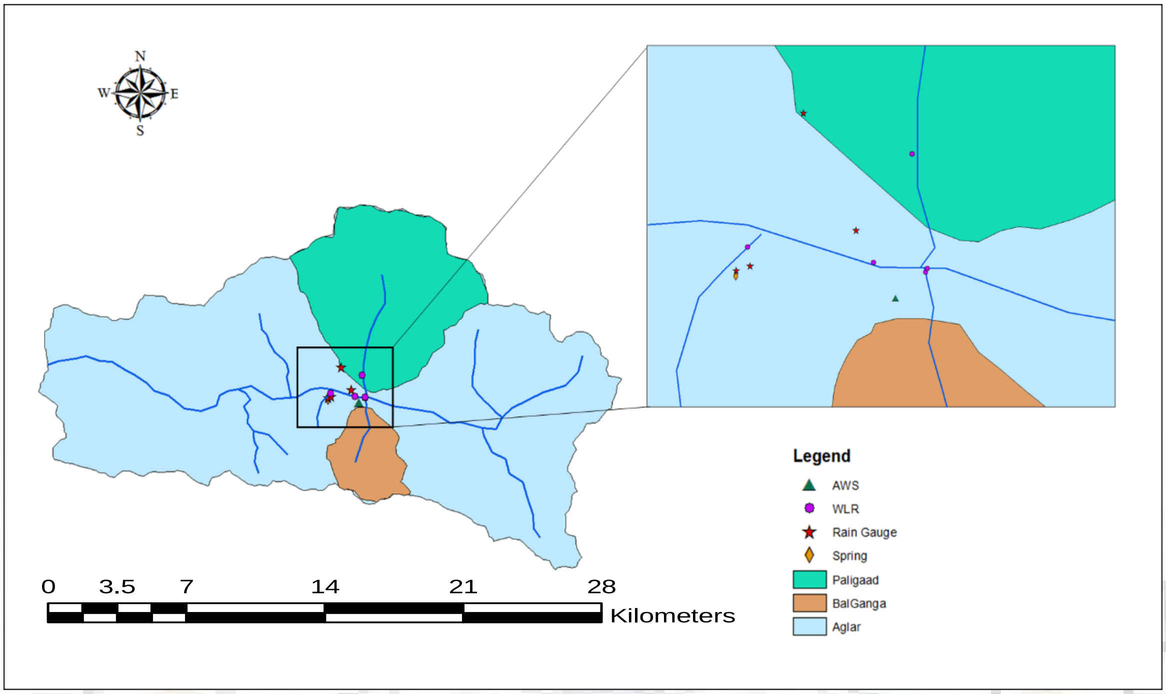


Figure 4.1: Monitoring location in Aglar watershed

4.3 DATA ANALYSIS

Data collection and analysis was poorly carried out in the Aglar watershed due to lack of financial support, limited standardized and training opportunities due to poor recognition of the importance of hydrological information and data, and inadequate policies and systems. The analysis of the hydrological data can help to prepare and plan for extreme events to identify where the risks were the highest and to better manage the water resources in ways that suits the economic and environmental needs.

4.3.1 Rainfall analysis

Understanding the amount of rainfall and the intensity along with which it falls in the Aglar watershed, its spatial and temporal variations is essential to every farmer for irrigation which includes the cropping pattern and the schedule. An Odyssey tipping bucket rain gauge logger (Figure 4.2) and a rain wise logger were used to measure the rainfall accurately, which archives the time of each individual bucket tip representing the intensity of the rainfall. The rain gauge which was used to measure the rainfall was calibrated at the workshop which normally does not require any attention except that it should be kept clean. However, for safety purposes, it was calibrated again in the Department of Hydrology (Watershed Hydrology Laboratory) before being installed at the rain gauge sites in the Aglar watershed.

Calibration of rain gauge: The following method of calibration is used:

A plastic container big enough to hold one litre of water is required to carry out a calibration. The container should have a 1mm hole drilled in the bottom of the container at the lowest point, if the base of the container is not flat. A site file (calibration file name) must be set up before the calibration starts. Unplug the serial cable from the logger and screw the cap back on. Place the rain gauge onto an area where the water that drains from the gauge will not cause a problem. Place the water container into the cone and tip 1 litre of water into the container. The bucket should start tipping within a few seconds. The tip rate should be approximately one tip every five seconds. The calculation to determine the number of tips is as follows:

Radius = 8.25 cm; Area of rain gauge orifice = Pi * 8.25^ 2 = 214.08 square cm,

1 mm of rain = 21.41 cc of water;

The number of bucket tips per 1 cm of rain = 10 mm/0.2 mm = 50

The number of bucket tips for 1 litre of water, if the rains gauge calibration is perfect, should be:

(1000/214.1) x 50 = 233.

Thus each tip should be 0.2 mm of rain so that the calibration value is 233 x 0.2 = 46.6 mm.

When all the water from the container has emptied into the rain gauge, the recorder must be down loaded into your computer. Plug the serial cable into the Odyssey recorder and click on ‘Stop Logger and Save Data’. Then select the site that was used to set up the recorder for the calibration.

Four rain gauges (2 each) on different land cover located in Mathamali and Mundani were installed at different locations to capture the spatial behaviour of the rainfall for every 15-minute time resolution. The investigation of the daily rainfall took place for four years from the year 2014 to the year 2017 in the Aglar watershed. The amount of daily rainfall from both the aspects (land cover) indicated almost the same amount of rainfall irrespective of the season (Figure 4.3).

The month of July was the wettest month as it received the maximum occurrences of rain spells and the lowest number of rainless (no rain) days.

Figure 4.2: a) Tipping bucket b) Data downloading from tipping bucket

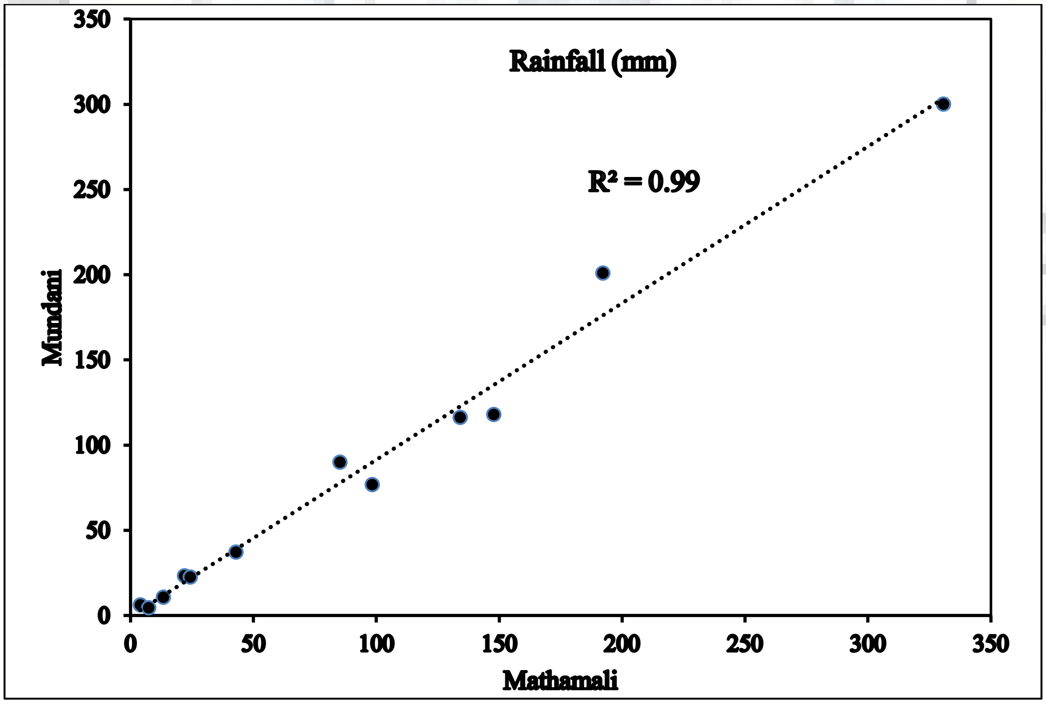


Figure 4.3: Monthly average rainfall at Mathamali and Mundani

The observed records of the average daily rainfall for four years from the year 2014 to the year 2017 were investigated to provide the probable rainfall volume of annual, seasonal, and monthly rainfall. The annual rainfall data was distinguished into four different periods as Summer for the months of March, April and May, Monsoon for the months of June, July, August and September, Post-Monsoon for the months of October and November and Winter for the months of December, January and February.

Table 4.1: Mean seasonal rainfall at Aglar watershed

	Rainfall							
	Amount (mm)	Contribution (%)	Amount (mm)	Contribution (%)	Amount (mm)	Contribution (%)	Amount (mm)	Contribution (%)
Period	***2014***		***2015***		***2016***		***2017***	
Summer	221.3	24.8	272.9	27.2	152.6	13.9	246.3	19.4
Monsson	530.9	59.5	627.1	62.6	829.8	75.4	919.0	72.6
Post Monsson	0.0	0.0	11.2	1.1	1.4	0.1	0.8	0.1
Winter	139.5	15.6	90.6	9.0	117.2	10.6	100.4	7.9
Total	891.8	100.0	1001.8	100.0	1101.0	100.0	1266.5	100.0

4.3.1.1 Seasonal, Monthly and Annual Rainfall Analysis

The analysis of the mean seasonal rainfall (Table 4.1) revealed that an average of 726.7mm of rainfall occurred during the Monsoon period. The average rainfall amount was found to be 223.3mm and 111.9mm in summer and winter respectively. In the post-monsoon period, the rainfall was found to be at the lowest with an average of 3.4mm. The percentage of the seasonal rainfall to the total rainfall was 67.5% in the monsoon, 21.3% in the summer, 10.8% in the winter and 0.3% in the post-monsoon periods. During the monsoon period the average rainfall contribution in July was the highest at 350.57mm followed by August at 197.25mm, June at 127.8mmand September at 51.01mm. The highest percentage of the total rainy days that were observed was in the month of July with 36.4% followed by August with 32.4%, June with 18.8% and September with 12.4%.

The average annual rainfall of the Tehri region was found to be 1028.6mm with an average of 62 rainy days (GWR, 2011). Careful analysis of the annual rainfall data of the four years for the region revealed that in the years 2016 and 2017, the annual rainfall was more than the average rainfall of Tehri district, whereas in the years 2014 and 2015 the annual rainfall was less than the average rainfall of Tehri district. The highest of 71 rainy days occurred in the year 2017 followed by 62 rainy days in the year 2015, and 60 rainy days in the year 2014 with the lowest of 57 rainy days in the year 2016.

The monthly rainfall differed from month to month, with the maximum rainfall occurring in the month of July followed by August. It was noticed that most of the time the month that received the maximum rainfall had the lowest coefficient of variation (CV). It was observed that the monthly rainfall during the four years of 2014-2017 as shown in Figure 4.4, did not indicate any definite rainfall pattern and the monthly rainfall variations were randomly distributed around the normal rainfall.

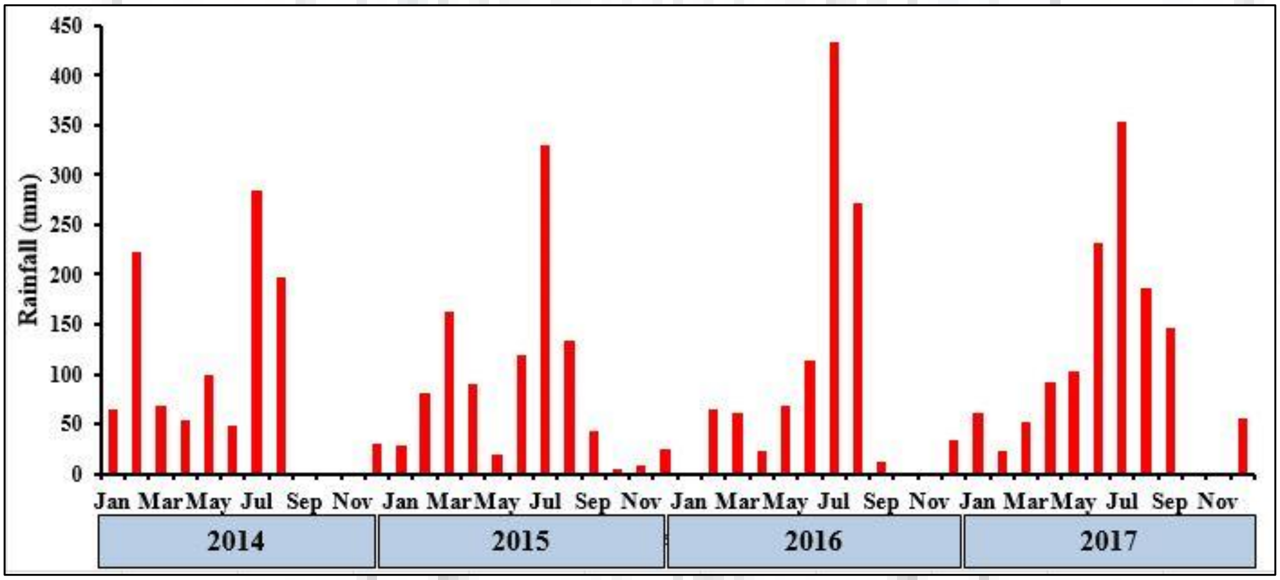


Figure 4.4: Monthly rainfall in the Aglar watershed (2014-2017)

4.3.1.2 Dry spells

The investigation of dry spells in the water scarce region is a valuable parameter for agricultural engineers and planners to make informed decisions about the best and suitable crops and to suggest the cropping patterns and practices. To evaluate the threat of dry spells in the region of the study, the days without rain during the seasonal rainfall period for different years have been derived and presented in Table 4.2. It was revealed that on an average, early September remains dry with 1st to the 20th, and the probability of rain is very less as compared to mid-July with 11th to the 20th as there was excess rainfall during July which could be stored for later use.

Table 4.2: Probability of dry spell during seasonal rainfall

(Date) Month begins with	**2014**	**2015**	**2016**	**2017**	**Average**
(1-10) June	0.9	0.9	0.8	0.7	0.8
(11-20) June	1.0	0.8	0.5	0.6	0.7
(21-30) June	0.6	0.5	0.7	0.5	0.6
(1-10) July	0.8	0.6	0.7	0.4	0.6
(11-20) July	0.1	0.6	0.6	0.6	0.5
(21-31) July	0.4	0.5	0.4	0.3	0.4
(1-10) August	0.4	0.4	0.6	0.6	0.5
(11-20) August	0.8	0.7	0.2	0.9	0.7
(21-31) August	0.8	0.8	0.5	0.5	0.7
(1-10) September	1.0	1.0	1.0	1.0	1.0
(11-20) September	1.0	0.8	1.0	1.0	1.0
(21-30) September	1.0	0.8	0.9	0.7	0.9

In order to validate how and if the daily rainfall amount has changed over time in terms of the intensity of rainfall in mm/d, Alpert et al. (2002) rainfall intensity based categorization has been adopted . Table 4.3 displays the six major classifications of rainfall that comprised of light, light–moderate, moderate–heavy, heavy, heavy–torrential and torrential rainfall.

Table 4.3: Daily rainfall class and description at Aglar watershed

Class	Intensity (I) (mm/d)	Description	No. of events
1	$0.1 <= I < 4$	Light	220
2	$4 <= I < 16$	Light Moderate	131
3	$16 <= I < 32$	Moderate heavy	48
4	$32 <= I < 64$	Heavy	22
5	$64 <= I < 128$	Heavy torrential	12
6	$I >=128$	Torrential	0

The daily rainfall data at the Aglar watershed indicated that there was no occurrence of torrential rainfall. The maximum occurrences were either of Class 1 - Light rain and Class 2 -Light moderate rain. The above analysis suggested to revisit the classification and develop a new classification based on the parameters for a lesser Himalayan mountainous watershed by calculating the intensity of rainfall on the basis of 15-min duration. The new classification comprises of only three types light ($0 < I > 16$), moderate ($16.1 < I > 32$) and heavy ($I > 32$) which further need to be explored based on long term regional rainfall intensity data. The study by Pumo et al. (2010) revealed that the amount of the rainfall diminished and one of the causes might be an increase in the evapotranspiration. The rainfall in the period of the study was said to be normal because the rainfall received during the period has exceeded in one out of the two years with the probability of exceedance equal to 50% (Smith, 1992).

4.3.2 Discharge analysis

4.3.2.1 *Methodology and Data*

The three sub watersheds or rivers in the Lesser Himalaya - the Aglar, the Paligaad and the Balganga were instrumented from April 2014 to collect continuous rainfall and stage measurement. The discharge of the river was measured time to time to develop a rating curve. The basic statistical discharge parameters such as the minimum, the maximum etc. for these three rivers is displayed in Table 4.4. A detailed description of the methodology involved in this chapter is described subsequently below.

Table 4.4 Daily discharge (m^3/s) statistical parameters for three rivers in the study area

		Statistical Parameters (m^3/s)			
Station	**Area (km^2)**	**Minimum**	**Maximum**	**Average**	**Standard Deviation**
Aglar	99.65	0.220	2.460	0.580	0.281
Paligaad	59.78	0.120	9.030	0.980	1.331
Balganga	13.12	0.004	0.520	0.079	0.058

Measurement of stage and discharge

The stage measurement of the rivers was monitored with an automatic water level sensor (AWLS) placed in a stilling well made up of perforated pipes (Figure 4.5). The AWLS is a capacitance-based water level recorder with a data logger (Odyssey, Data flow system ltd). The detailed operational principle and calibration of AWLS are as follow:

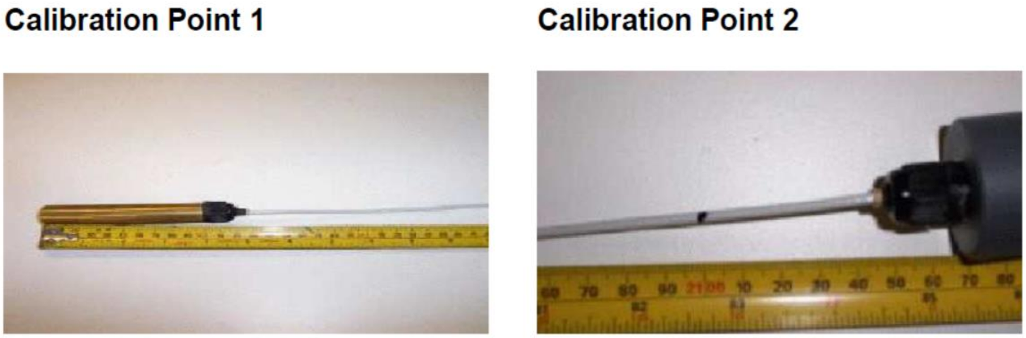
Figure 4.5 a) Medium flow condition and AWLS in PVC pipe b) Data downloading from Odyssey data logger

(a) Principal of Operation:

A capacitor consists of two conducting plates or cylinders separated by a non-conducting insulating material. This insulator is called a dielectric. The value of the capacitor (if the distance between the plates is fixed) is directly proportional to the area of the two plates in the capacitor. The stability of the dielectric material governs the stability or quality of the capacitor. Teflon is used as the dielectric in water level probes, as it is one of the best dielectric materials available and also has good long-term stability. Teflon has zero moisture absorption; its characteristics are therefore not altered by water immersion. The Teflon-covered measuring element forms one plate of the capacitor and the Teflon is the insulator or dielectric. The second plate is the water in which the probe is immersed. As the water level varies, the area of water that is in contact with the Teflon surface also varies. The water is like a cylinder that is moving up and down the cylindrical Teflon-lined element. Hence the variation in capacitance is directly proportional to the height variation of the water in contact with the Teflon. The brass counterweight at the base of the sensor element is also used to make electrical contact with the water. The capacitance value is measured by the electronic module that is mounted at the top of the probe and recorded by the Odyssey recorder that is also included in the electronic module. This module converts the value of the capacitance into a digital signal so that the Odyssey data recorder measures it.

(b) Calibration

Mark two points on the Teflon element (Figure 4.6) with a waterproof marker pen, both measured from the bottom of the counterweight - one at 200mm and the other equal to the specified length of the probe i.e. 0.5m, 1.5m, 1m, 2m, 3m or 5m. These two points will be used to obtain your calibration values.


Calibration Point 1

Calibration Point 2

Figure 4.6 Calibration of water level logger

For probes up to 2 metres the calibration can be carried out in a PVC pipe stopped at one end and filled with water. The following procedure is to be adopted to achieve the maximum accuracy. Either the trace mode on a PC may be used or the recorder can be set to a 10 second log interval. To obtain comparative data, always use the same heights on the probe for the two calibration values.

1) After the probe has been cleaned, immerse it in a water filled calibration tube to the bottom mark on the probe. If the logging mode is being used hold it at this level for about one minute. If the trace mode is being used wait until the reading is stable, then note the value that is displayed on the computer screen.

2) Lower the probe to the second point. Hold it at this level for approximately one minute. If the trace mode is being used wait until the reading is stable, then note the value that is displayed on the computer screen. Remove the probe from the calibration tube.

3) If the trace mode was used, abort the trace mode by clicking on the button. EXIT PROBE TRACE If the recording mode was used, download the data to your PC and then view the data by entering EDIT SITE DATA. Pick out two values that correspond to the two water levels that were used to generate the calibration data. The values that are obtained should be compared with

the previous calibration. If there is a large discrepancy, then the calibration should be repeated. The value for the offset, assuming that the same calibration points were used, should be within 10 to 20 counts of the previous value.

AWLS has recorded the depth of water in the river from the river bed at 15 minute intervals from April, 2014 at the Aglar and the Paligaad and from June, 2014 at the Balganga river. The recorded river depth from the sensors was downloaded once or twice in a month to avoid any loss of data. On the day the data was downloaded, the recorded data was verified with visual measurements. With the increase in the river discharge, the surplus water in the river lead the river to expand laterally and increased the depth of river. The discharge in all of the rivers was measured by the well-known salt dilution technique for mountainous catchment where current metering may be inaccurate.

The salt dilution method is an easy-to-use technique for measuring discharge in the small turbulent streams that are typically found in mountain areas. The equipment is light and suitable for use in the field, thus the method is ideal for use in remote high altitude regions. The method has been used successfully in small turbulent mountain streams in many places worldwide. It is being used by the Swiss Hydrological Survey in Switzerland; the People and Resource Dynamics Project in Mountain Watersheds of the Hindu Kush-Himalayas (PARDYP) in China, India, Nepal, and Pakistan; in Nepal to assess small hydropower potential; and in the Wang Watershed Management Project (WWMP) in Bhutan. The technique is based on the principle that a given amount of salt is diluted more by a large amount of water than by a small amount. This means that the higher the discharge the more diluted will be salt that is placed in the water upstream. The salt dilution method involves injecting (inserting) a known amount of salt into a stream. This process is technically known as slug injection. The salt acts as a tracer to measure the discharge. The concentration of dissolved salt is measured downstream at a point where it has fully mixed with the stream water.

The following conditions are needed for the salt dilution method to be used accurately:

- stream discharge is constant during the measurement period;
- all the injected salt passes the measurement point without any of it being absorbed or lost in any way;

- there are no ponds or calm zones or other conditions that prevent the salt from being evenly dispersed in the stream; and
- there are no livestock bathing in the stream whose urine and other body fluids (sweat) could cause fluctuations in the conductivity of the water which is used to measure the discharge.

In the salt dilution technique, a known amount of sodium chloride solution (NaCl) is injected into the river and concurrently measuring the electrical conductivity (EC) at regular intervals at downstream. Using the concept of mass conservation, the discharge of the river Q (m^3/s) was calculated using the 4.1 equation

$$Q = \frac{M_S}{\int_0^T (C_t - C_o)dt} \tag{4.1}$$

where M_s is the weight of the sodium chloride injected in kilograms (kgs), T is the time of the passage of the salt slug per second, C_o and C_t are the initial and the concentration of sodium chloride at time t in (kg/m^3). NaCl was selected as a tracer as it is low in cost, is non-toxic, is easily available at the site and aids to precisely measure using the electrical conductivity (EC) meter. In the mountainous region, the discharge measurement using the slug injection can be precise within about ±5 %. The use of salt dilution technique to measure the discharge was restricted up to 15 m^3/s due to environmental considerations (Church, 1973). However, the plausibility check can be made in the field and if the result seems to be incorrect another measurement can be made immediately. A disadvantage of this method is that only a runoff less than 4 m^3/s can be made easily, because the amount of salt to be dissolved is difficult to handle.

The flow in the river is the combined effect of different watershed characteristics, geographical and climatological influences. The changes in land use and variations in precipitation patterns evidently alter the mountain hydrology. Monitoring and analysing the river flow data in the mountainous catchment is the key but an expensive one among the different hydrological cycle processes. However, the data have widespread applications in the management of water resources, design of reservoirs, flood banks, sewage treatment works, and flood forecasting and warning. Other than the listed applications, the discharge data are also equally important for water policy formulations, to evaluate hydro-power potential, to improve services and recreational value of the ecology and the wetlands. However, we often need to deal with many ungauged or poorly gauged basins without adequate and accurate river flow observations (Sivapalan et al., 2003). These data-sparse basins often exist in the mountainous regions (Castellarin et al., 2007), unregulated regions (Stainton and Metcalfe, 2007), and rural or remote areas (Makungo et al., 2010). To reduce errors in the river flow data collection process, a clear procedure must be set up to communicate to the data collectors for suitable site selection, observation time, measurement intervals, and dates of records also ensure that gauges must be maintained in good condition. The site selection criteria should include:

a) the river has to be fairly straight and stable with uniform cross-section of river banks,

b) the flow in the river channel has to be free from back-water effect,

c) the flow in the river channel has to be limited within the banks for all of the stages during the data collection,

d) the site selected has to be easily reachable at all times,

e) if possible, the river has to be converging rather than diverging.

For off-site data quality control, a careful check for data errors has to be made before transmission, for example, to check for consistency in recorded time-series and to check for extreme values. Outliers in discharge value have to be investigated and corrected or omitted from the record if needed. The river discharge was measured by different methods in which some were measured directly, while other methods were used measure the velocity using specific equations. To measure the low flow and the high flow of the rivers different approaches were used. The choice of the approach or the method to monitor the river flow depended upon multiple factors such as the type of the flow, the flow rate range, the site configuration, the expected accuracy, and the cost (Appendix - II). It was convenient to consider the river flow data to be one of the three types – Monthly river flows, Daily river flows and Peak and annual river flows. Some of the uses of river flow analysis include, 1) comparison of differences in the river flows between time periods in the measured record such as comparing the river flow situation prior to and after a major construction, 2) comparison of river flow conditions determined by simulation of alternative water management activities, 3) comparison of river flow conditions resulted from alternative states of the watershed such as urban versus rural as an example, and 4) comparison of the river flows at different locations along a river or between rivers.

The mean of daily recorded river flow of 0.98 m^3/s for Paligaad and 0.58 m^3/s for Upper Aglar indicated that the Upper Aglar River was comparatively small River in terms of the total volume yield. Table 4.5 displays the discharge characteristics for the years 2014-2015 and the years 2015-2016 of both the gauging stations.

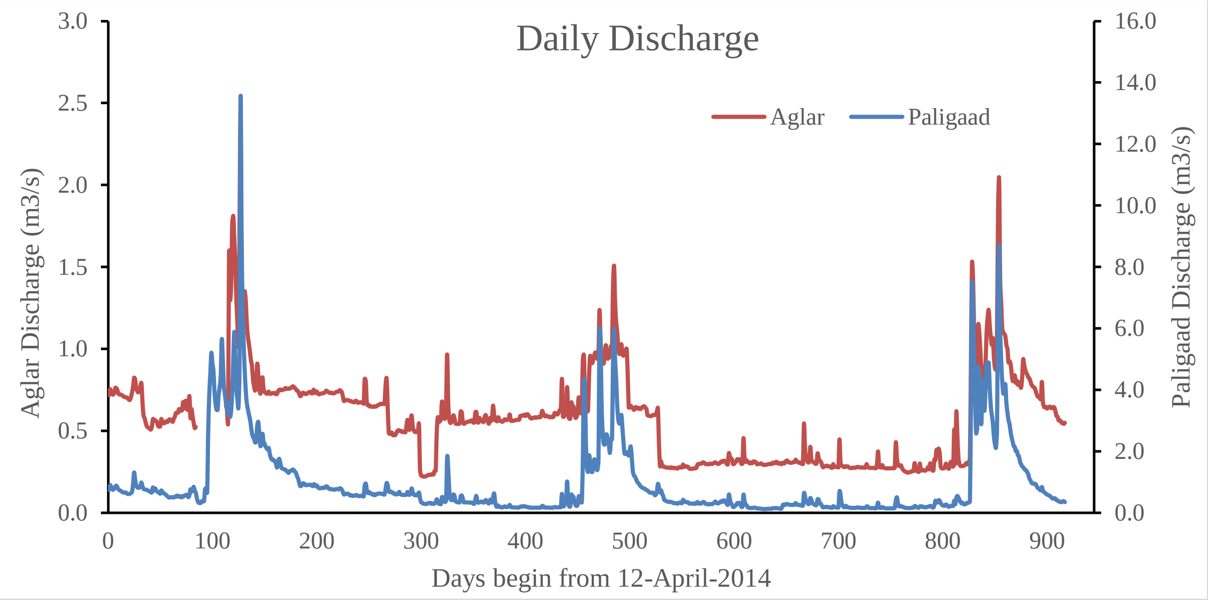


Figure 4.7: Daily flow behaviour of Upper Aglar and Paligaad

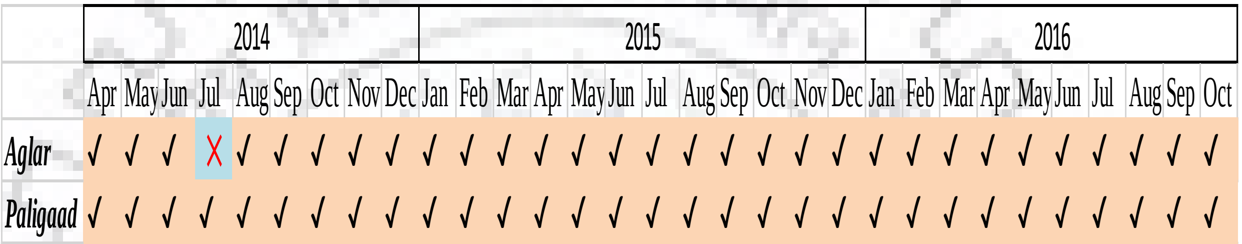
Table 4.5: Main characteristics of discharges, Q (m^3/s), measured at two analysed hydrological stations

***Q* (m^3/s)**	**Paligaad**		**Upper Aglar**	
	2014–2015	**2015-16**	**2014–2015**	**2015-16**
Q_{min}	0.28	0.12	0.22	0.24
Q_{max}	13.48	8.69	2.46	2.04
Q_{avg}	1.23	0.82	0.68	0.51
Std Dev.	1.41	1.25	0.25	0.28

The annual (2014-2016) river discharge data were analyzed to determine the conclusions. The year-wise and seasonal discharge behaviour is given as below:

4.3.2.2 *Flow records and investigation of doubtful flow values*

The flow gauges' data collected daily in the Upper Aglar and Paligaad rivers was for 31 months. However, no more than 5% of the data for Upper Aglar river were missing. The maximum percentage of the missing data was 3% at the Upper Aglar as shown in Figure 4.8. Automatic recording water level sensor were used as equipment to measure water levels which then were converted to flow using rating curves developed for these gaging sites.



	2014									2015												2016									
	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Aglar	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Paligaad	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Figure 4.8: Length and missing data of the flow time-series plotted on monthly time scale

All of the monitored flow values were used to develop a box plot excluding the zero flow as it did not affect the appearance of the box plot significantly (Figure 4.9). Nine suspicious daily flow values -3 in the water year for 2014-15 and 6 for 2015-16 for Paligaad river and 1 suspicious daily flow value for the Upper Aglar river as shown were removed (Figure 4.9). All of these values were more than the acceptable limit (judged on basis of experience) at the same gauge. The suspicious value of the flow at 13.48 m^3/s recorded on the 16th of August, 2014 at Paligaad was removed as there was no evidence of such a high rainfall that could support the occurrence of this high flow and it could be because of faulty measure by sensor. The analysis of the seasonal variability suggested that this unexpected high flow value could probably be the reason that the flow in August 2014 was higher than that has averaged over the rest of the record.

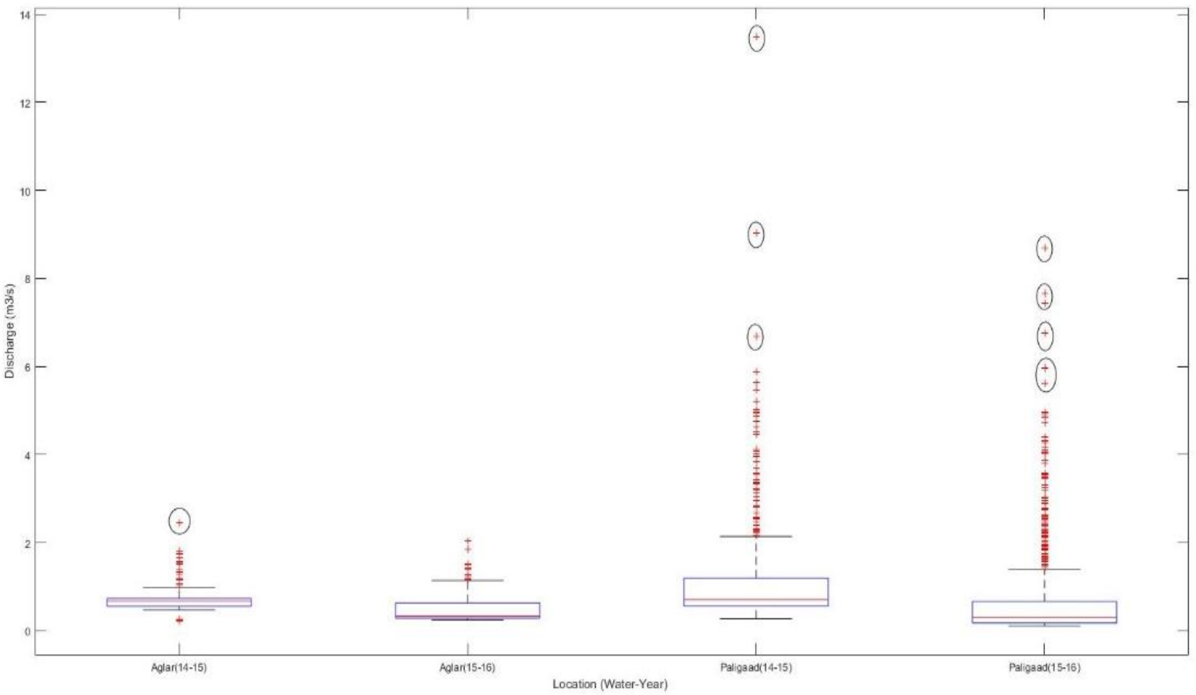


Figure 4.9: Boxplot of Upper Aglar and Paligaad for year (2014-15) and (2015-16)

4.3.2.3 Annual discharge variation

The first year's (2014) annual average flow of the discharge recorded was at 1.4m^3/s for Paligaad river and 0.75 m^3/s for Upper Aglar river. The highest discharge of water recorded was in the month of August at 4.23m^3/s for Paligaad river, 1.2 m^3/s for Upper Aglar river followed by the month of September at 1.89m^3/s for Paliagad river and 0.75 m^3/s for Aglar river. The lowest water discharge was recorded in the month of June at 0.56m^3/s for Paligaad river and 0.6 m^3/s for Upper Aglar River followed by the month of December at 0.61m^3/s for Paligaad river and 0.67 m^3/s for Upper Aglar river. The first year hydrograph was closely related to the rainfall. The highest rainfall of 41.2% was recorded in July and the second highest rainfall of 29.5% was recorded in August which indicated that the rainfall in July was higher than that of August, whereas the water discharge was higher in the month of August rather than in the month of July. This may be ascribed due to the less surface runoff of rainwater and higher infiltration. The average water discharge rate was 62.56 and 210 mm/km^2/yr. in the first year for the Paligaad and Upper Aglar rivers respectively. The second year's (2015) annual average river discharge recorded was at 0.67 m^3/s for Paligaad river and 0.53 m^3/s for Upper Aglar river. It was noted that there was an important variability in the mean monthly water discharge as compared to the first year, 2014.

The minimum monthly discharge, was obtained in the month of May with 0.18 m^3/s for Paligaad river and in the months of November and December with 0.31 m^3/s for Upper Aglar river when compared with the other months. The maximum discharge recorded was in the months of August and July with 2.53 m^3/s, 0.93 m^3/s and 1.81 m^3/s, 0.82 m^3/s respectively. The minimum discharge recorded was greater than 0.18 m^3/s and 0.28 m^3/s in the second year (2015). The ranges of the variation were high at 2.35 m^3/s for the Paligaad river when compared to the Upper Aglar river at 1.53 m^3/s which indicated a sharper increase in the discharge for the Paligaad river. 61.7% and 35% of the total discharge was monitored in the months of July, August and September whereas the other months from November to June generated only 34% and 60% of the total water discharge. The third year’s (2016) annual average river discharge of the year was at 0.89 m^3/s for Paligaad river and 0.48 m^3/s for Upper Aglar river which were lower than that were recorded during the first year (2014). The main reason was due to less intensity rainfall, no high intensity discharge and no consumption of the river water for irrigation. The hydrological graph indicated that the maximum of 42.3%, 23.6% water discharge was recorded in the month of August followed by 28%, 15.1% in the month of July. The lowest recorded months were May and June.

4.3.2.4 Monthly and seasonal average flow variations

As part of a major initiative to provide a complete scientifically based planning for sustainable water management in the ungauged mountainous watershed, a monthly discharge estimation procedure based on spatiotemporally continuous daily data was also analyzed. Analyses of the monthly data represented similar patterns of the flow seasonally over two flow gauges of the Upper Aglar and the Paligaad rivers. From the beginning of the water year in April, the flow has increased until the month of May reaching the first peak in the month of June and then continued to increase again in the months of July and August, when more rainfall occurred. It started decreasing between the months of September and January due to less or no rainfall. Rainfall was clearly the most influential factor causing the temporal differences in the flow. The spatial variation in the flow was believed to be caused by the rainfall, land use and soil type, however, this assumption has to be explored further. The monthly box plot of the daily discharge indicated a great dispersion and more spread in the upper quartile of the Upper Aglar whereas it was in the lower quartile for Paligaad. It was noticed that even the monthly median flow was not the same in any of the months. The seasonal variation of water discharge revealed that out of the total water discharge of the first year about 70.1% water discharge occurred during the rainy season. Very low percentage of water discharge was found in the winter and the summer periods at 10.3% and 11.6% respectively.

4.3.3 Best-fit probability distribution of daily discharge

The daily discharge configuration and its amount at a gauging station are significant factors affecting flood defense, management of water resources, reservoir operations, etc. and often required for design of hydraulic structures. The frequency of discharge can be used to obtain the return period. The aim of the analysis is to determine the best-fit probability distributions at Upper Aglar and Paligaad sub-watershed using monitored daily discharge with different statistical distribution types. The probability distribution such as Beta distribution, Cauchy distribution, Exponential distribution, Gamma distribution, Log Pearson distribution, Uniform distribution, Pareto distribution and Log logistic distribution were applied. To find the best-fit distribution of daily discharge at both sub-watersheds, find the lowest sum of the rank from used goodness of fit (Kolmogorov Smirnov, Anderson Darling and Chi-Squared). The summary of best distribution for seasonal flow (July-September), low flow (April-June) and water year (June -May) is summaries in table 4.6 with the obtained parameters value.

Table 4.6: Summary of best-fit distribution (a) Seasonal flow (b) Low Flow and (c) Water Year for Upper Aglar and Paligaad sub-watershed

(a) Seasonal flow

Location	Year	Best Distribution	p Value	Parameters
Upper Aglar	2014	Beta	0.085	0.951,1.251, 0.508, 0.824
	2015	Cauchy	0.742	0.583, 0.014
	2016	Cauchy	0.192	0.274,0.01
Paligaad	2014	Uniform	0.282	-0.583, 6.298
	2015	Exponential	0.82	0.593
	2016	Exponential	0.656	0.439

(b) Low flow

Location	Year	Best Distribution	p Value	Parameters
Upper Aglar	2014	Beta	0.085	0.951,1.251, 0.508, 0.824
	2015	Cauchy	0.742	0.583, 0.014
	2016	Cauchy	0.192	0.274,0.01
Paligaad	2014	Uniform	0.317	0.433, 0.943

	2015	Cauchy	<0.001	0.189, 0.077
	2016	Pareto	0.049	0.0141, 3.297

(c) Water Year

Location	**Year**	**Best Distribution**	**p Value**	**Parameters**
Upper Aglar	2014-15	Cauchy	<0.001	0.627, 0.085
	2015-16	Cauchy	<0.001	0.305, 0.158
Paligaad	2014-15	Log logistic	<0.001	0.701, 1.949
	2015-16	Pareto	<0.001	0.115, 1.235

In all the circumstances (seasonal flow, low flow and water year) the goodness fit results in different types of best distribution. In the case of Upper Aglar it follows same distribution whereas this is not same with Paligaad. Analyzed results is just to develop the better understanding of the distribution trend which can be later used to develop better understanding of risk and damage from extreme flow and low flows.

4.3.4 Rainfall-river flow characteristics

Attempts to understand the flow characteristics in the lesser Himalayan and impact of land use at micro watershed level are very rare to study the impact of forest coverage and anthropogenic activities. The intensity of the rainfall and the runoff from the land surface causing discharge fluctuations, which is also one of the central issues of hydrology. Another important aspect in hydrology is the impact of vegetation on the water budget of the watershed. Use of water for vegetation can closely be linked to the river flow patterns on a variety of time scales (Bond et al. 2002). A theoretical understanding of the discharge volume, lag time along with the major controlling parameters is required to develop hypothesis of flow response from different watersheds. The studied sub-watersheds were basically similar from the point of view of forest coverage, however displayed some minor differences in runoff generation. In the Paligaad 55.1% of the catchment’s area is forest cover whereas in the Upper Aglar the total forest cover is 42.7 %, mainly with deciduous (Pine and Oak), are at the headwater in the difficult terrain thus not studied earlier. The total agricultural land available in Paligaad is 27.3% and in Upper Aglar, it is 16.7%. The curve number (62 for Upper Aglar and 57 for Paligaad) which is calculated based on the land coverage and soil type also provide the opportunity to understand the flow characteristics. The differences in the curve number (land use pattern), geology and agricultural land availability have different impacts on the hydrological behaviors.

4.3.4.1 Event based Rainfall-Runoff response

No past hydrological study was available that leads to comprehend the response to separate the rainfall-runoff (R-R) events in the Lesser Himalayas of Tehri Garhwal district. The response of rainfall on the discharge in a mountainous watershed is the direct result of complex hydrological phenomenon such as loss through evaporation, transpiration and the runoff coefficient that depends on the watershed land use and soil properties. Many times the response depends on the antecedent moisture conditions and the maximum rainfall intensity. In this section, two sub-watersheds one having more forest cover and agricultural land as compared to others has been studied to explain the R-R variability of the Upper Aglar and the Paligaad sub-watersheds as displayed in Table 4.7 and to identify the major influencing factors.

Table 4.7: Characteristics of the Upper Aglar and the Paligaad sub-watersheds

Characteristics	**Upper Aglar**	**Paligaad**
Area (km^2)	*99.65*	59.78
Elevation		
Maximum	2674	2975
Minimum	1115	1111
Average Slope (%)	*2*	4
Land *Cover*		
Agriculture	27.3	16.7
Bare	14.8	12.4
Urban	1	0.5
Forest	42.7	55.1
Shurbs	11.5	13.8
Stream	*2.7*	1.6
Soil *Type*		
B	37	38
D	25.5	26.45
Others	37.5	35.2
Precipitation		
Total Rainfall	2704 ± 10	
Monsoon (%)	70	
Discharge		
Total flow (mm)	1293.6	508.7

For the present study, the R-R events that were selected which met the requirement of the discharge that surpassed the preceding discharge by at least 10% and the rainfall was over 10mm in a day. The requirement has allowed to identify 15 R-R events, 7 for the Upper Aglar and 8 for the Paligaad, during the complete monitoring duration of the 31 months. The response from the Upper Aglar and the Paligaad sub-watershed as shown in figure 4.10 towards rainfall, demonstrating a nonlinear behavior suggested that the total flow recorded for the sub-watershed not only depend on the amount of the rainfall and its intensity but also on the baseflow which is the characteristic of a watershed, a similar relationship reported by Merz and Bloschl (2009).

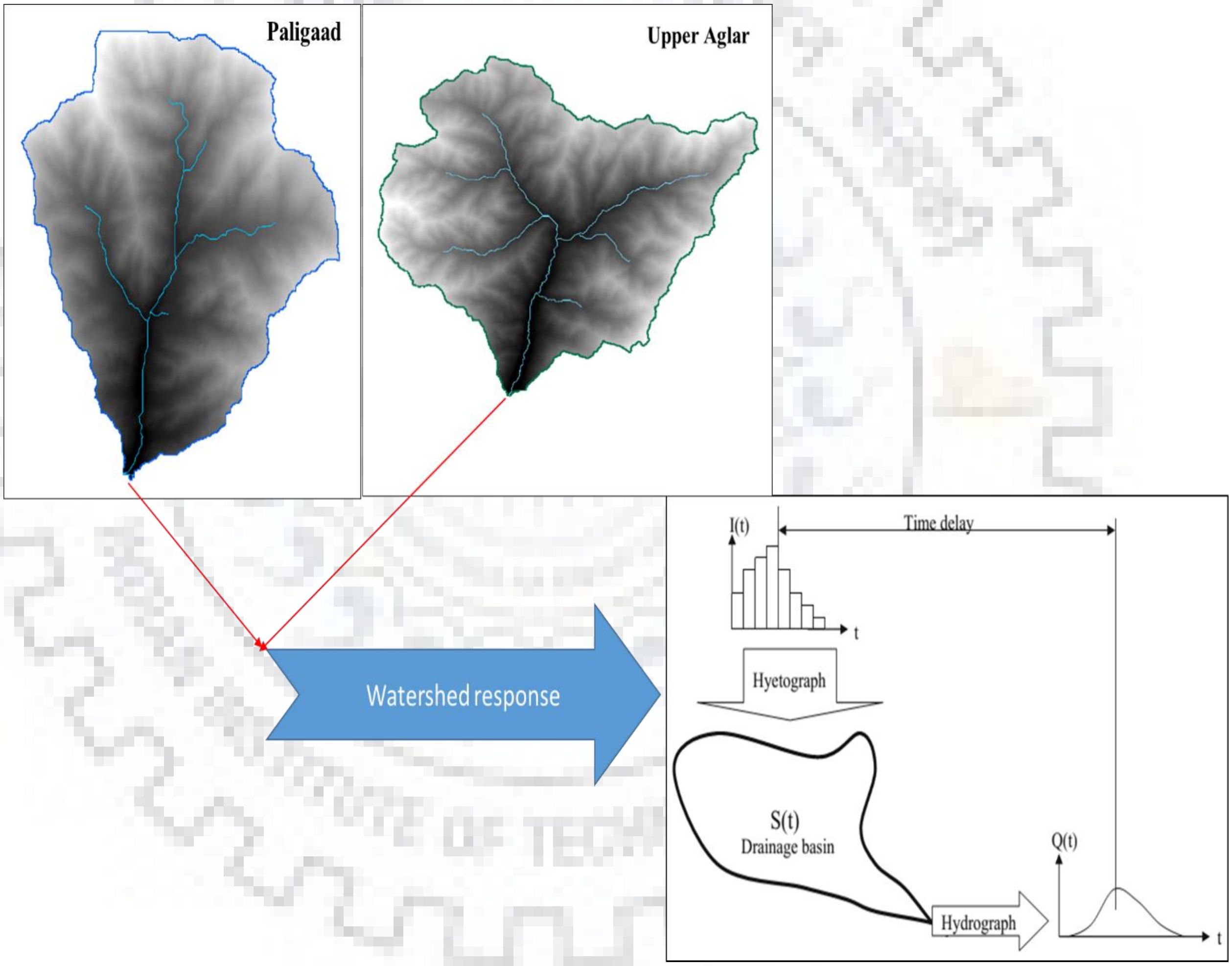


Figure 4.10: Typical hydrological response from Upper Aglar and Paligaad sub-watersheds

The summary of all R-R events is presented in Table 4.7, with a scatter plot in Figure 4.11. All of the stream flows were articulated in terms of '*mm*' to allow the evaluations of the R-R response irrespective of the size of the watershed. To ascertain the main possible hydrological variable that might influence the discharge of a watershed, the total river flow in '*mm'* from the sub-watersheds were compared with the total rainfall, rainfall intensity, runoff coefficient and the baseflow. The result of the regression between the two parameters and the coefficient of the determination were shown in the Figure 4.9. The non-appearance of a strong correlation between the total rainfall and the total runoff confirmed the influence of additional hydrological variables in regulating the outflow from the watershed. Even the runoff coefficient did not show a substantial relationship in the Upper Aglar watershed with its total river flow as it was similarly expected to that of Paligaad. At last, the total runoff with the baseflow of the hydrograph exposed a strong positive correlation of > 0.98 and revealed the baseflow variability as a key parameter for the R-R response in the experimental mountainous watershed.

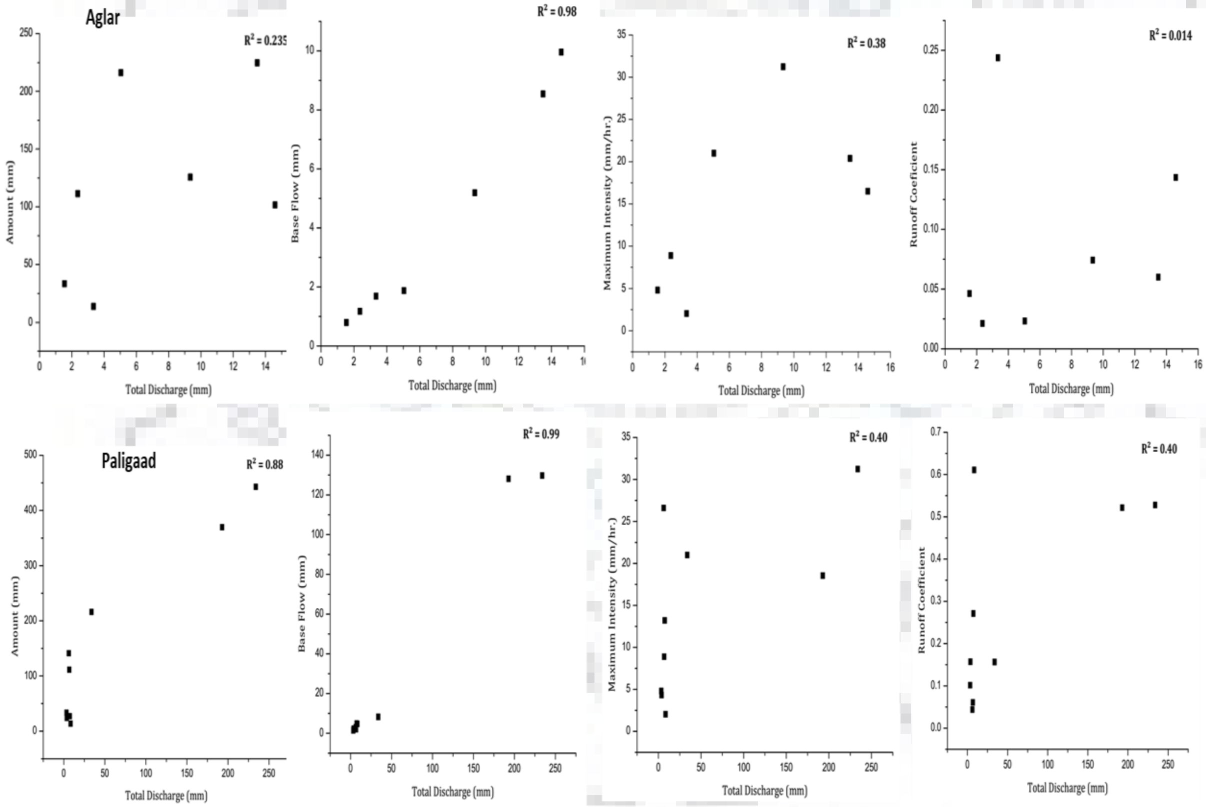


Figure 4.11: Relationship between rainfall amount, baseflow, rainfall intensity and runoff coefficient with total runoff

Table 4.8: Summary of rainfall - runoff characteristics of Upper Aglar and Paligaad watershed

			Rainfall			Discharge(mm)				
Upper Aglar	**Event No.**	**Duration(days)**	**Amount(mm)**	**Intensity(mm/day)**	**Max. intensity (mm/hr)**	**Total**	**Direct flow**	**Baseflow**	**5 day Antecedent rainfall (mm)**	**Ratio of Direct flow to baseflow**
10 May - 16 May 2014	1	7	13.7	5.8	2.03	3.34	1.66	1.69	39.62	0.98
13 Aug. - 22 Aug. 2014	2	10	125.7	69.9	31.24	9.34	4.15	5.19	22.94	0.80
28 Feb. - 4 Mar. 2015	3	5	111.5	78.2	8.89	2.37	1.19	1.17	36.83	1.02
5 Aug. - 26 Aug. 2015	4	22	101.7	53.1	16.51	14.59	4.63	9.96	21.84	0.46
06 Feb. - 11 Feb. 2016	5	6	33.4	33.2	4.80	1.55	0.75	0.79	0	0.95
11 July - 21 July 2016	6	11	216.2	89.8	21.00	5.04	3.16	1.88	0	1.69
8 Aug. - 25 Aug. 2016	7	18	224.8	54.2	20.40	13.49	4.95	8.54	11.2	0.58
Paligaad										
10 May - 16 May 2014	1	7	13.7	5.8	2.03	8.38	3.67	4.72	39.62	0.78
30 June - 08 July 2014	2	9	27.2	17.0	13.21	7.37	2.53	4.84	29.99	0.52
11 July -19 Aug. 2014	3	40	442.9	69.9	31.24	233.87	104.13	129.74	1.27	0.80
01 Feb. - 05 Feb. 2015	4	5	23.9	23.4	4.32	3.75	1.45	2.29	0	0.63
28 Feb. - 4 Mar. 2015	5	5	111.5	78.2	8.89	6.77	4.70	2.06	36.83	2.28
09 July - 04 Sep. 2015	6	58	369.6	74.4	18.54	192.82	64.69	128.13	27.43	0.50
06 Feb. - 11 Feb. 2016	7	6	33.4	33.2	4.80	3.39	1.92	1.47	0	1.31
11 July - 21 July 2016	8	11	216.2	89.8	21.00	33.83	25.58	8.25	0	3.10

The figure 4.11 depicts that in the Upper Aglar and the Paligaad sub-watersheds, numerous causes could be involved in the temporal variability of the direct and baseflow for different events. During the summer period, when the rainfall is less, the watershed has less ability to generate the direct runoff. Thus, it has been revealed that a rainfall event of 13.72mm recorded in the month of May of summer resulted in 1.66mm and 4.72mm of direct runoff in the Upper Aglar and the Paligaad sub-watersheds respectively during the Event 1. However, the rainfall event of 33.40mm which was two times higher happened in the month of February of winter and has generated only 1.55mm and 3.39mm of direct runoff in the Aglar during the Event 5 and in the Paligaad during the Event 7, because a portion of the total rainfall was used to recharge the soil moisture reserves. From Table 4.8, it can be concluded that, as the watershed turn out to be wet during the rainy period, the R-R response increased and, subsequently, indicated a larger percentage of occurrence of the rainfall. It was assumed that the antecedent condition might have possibly played an essential role in the R-R response of the watershed.

During the Event 2 for the Upper Aglar and the Event 3 for the Paligaad an antecedent condition was followed. Under these conditions, a 125.7mm and a 442.9mm of rainfall event with the highest intensity of 31.24 mm/hr has produced a runoff of 9.34mm and 233.8 mm respectively. These events were considered with a relatively small time lag, a reasonable response during the rising limb, with a peak total flow of (9.34mm and 233.87mm), however with a fast decay after the peak discharge. For the small rainfall events, the R-R response from the watershed was mainly governed by the baseflow in the beginning of the event with an antecedent precipitation index, while, for the major rainfall events, both the antecedent precipitation index and the baseflow along with the total rainfall volume affect the degree of the R-R response. In the months of July and August, the amount of the rainfall in general was more than the loss by evapotranspiration with an excess of antecedent precipitation index in the soil. Therefore, the major excess rainfall during the months of July and August, displayed a maximum total runoff during the said period and the total flow indicated that it not only depends on the amount of the rainfall but has also influenced the antecedent precipitation index distressing the ability of the soil pores to accumulate new rainfall water.

During the water deficit time period, events 3, 5 and 6 in the Upper Aglar sub-watershed and events 1, 2, 4, 5, and 7 in the Paligaad sub watershed, evapotranspiration has dominated the amount of the rainfall. The rainfall that occurred was limited to a few '*mm*' that resulted in the low generation of the total flow from the watershed, as an extensive amount of the rainfall was lost by evaporation from the open surface and by transpiration of the plants and the trees.

In case of the Event 6 from the 11th – 21st of July, 2016, the rainfall began on the 12th of July at 03:00 a.m. in the morning and ended at 02:00 a.m on the 18th of July with a total rainfall of 216.2mm with the peak value on the 15th of July at 12:00 hours. Due to the influence of the antecedent precipitation index, the Upper Aglar sub-watershed generated a total outflow of only 5.04mm whereas the Paligaad sub-watershed generated 33.83mm. Furthermore, the watershed stored the maximum percent of the rainfall, probably due to low soil moisture conditions before the event began. Under the wet conditions, the response was steeper topography suggesting slow decay from the peak when compared to the drier ones.

The *runoff coefficient* – (**R_c**) which is calculated as the ratio of the total runoff and the total rainfall during the R-R event which has differed significantly from event to event for each sub-watershed. The values of R_c varied between the minimum of 2% to the maximum of 24% in the Aglar sub-watershed with an average value of 6% and between the minimum of 6% to the maximum of 61% in the Paligaad sub-watershed with an average value of 30%. The comparatively low values of R_c in the Upper Aglar sub watershed could be associated to the low water transport ability of soils in the catchment and the high soil infiltration capacity -I_c. The R_c that ranged from 2% to 24%, in case of the Upper Aglar sub-watershed indicated that 80% of the events displayed R_c less than 10% with only two events where the R_c exceeded 10% which lead to a high flow during the month of July, 2016. In the Paligaad sub-watershed most of the events have R_c greater than 10% and only one event lesser than 10%. It was noticed that, for the lesser < 50 mm rainfall events in a day, the total flow was restricted to 3.34mm in the Aglar sub-watershed and 8.38mm in the Paligaad sub-watershed, whereas for all of the major rainfall events, a noteworthy increase in the total flow was observed.

In monsoon (June to September), the maximum number of R-R events were noticed. The total rainfall was more than the other time duration where 6 out of the 15 events were with rainfall less than 50 mm. Where as in spring season (March – May), both the rainfall and the runoff have reduced considerably. The dissimilarities in the total runoff generated must be connected to the internal hydrologic properties of each of the watershed like the rainfall that was interrupted by the dense forest cover at the top and the water intake by shrubs and the other agricultural plants. The shape of the hydrograph in the Upper Aglar and the Paligaad sub-watersheds, was characterized by quick increase, fast and slow recession which can have negative ecological impact. The Paligaad sub-watershed displayed a flashy response towards the rainfall events whereas the Upper Aglar sub-watershed exhibited a wide range of dampening runoff responses for different rainfall events (Figure 4.12). The flashy response in the Paligaad sub-watershed indicated that the watershed could be more sensitive as compared to the Upper Aglar sub-watershed with variations in the amount and intensity of the rainfall. Increased frequency of large discharge events may create problems of scouring, widening of river, and flooding.

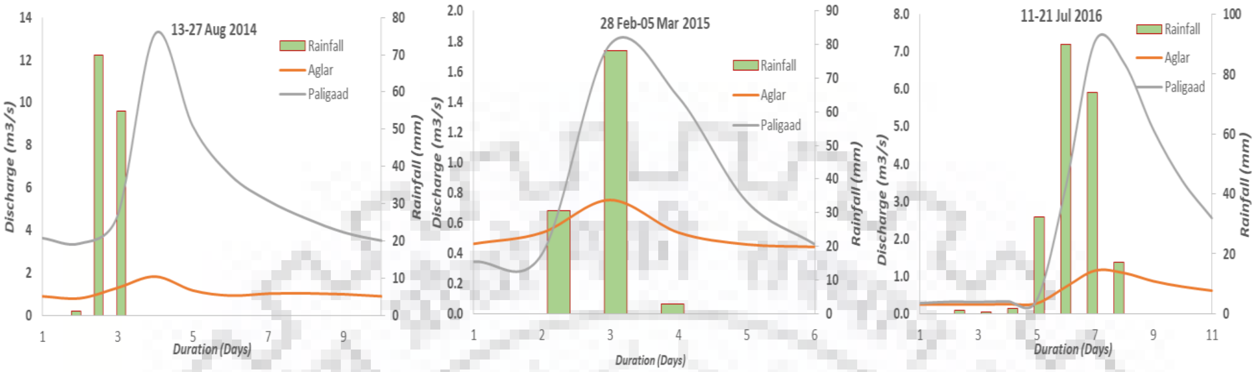


Figure 4.12: Rainfall-runoff events for three different years

Multiple R-R events are required to understand the variability of climatic conditions (example wet and dry) and it is quite difficult to decouple the watershed characteristics from the land cover. Three different R-R hydrographs as shown in Figure 4.12 for each year indicated that the utmost significant difference among the watershed was the intensity of the discharge. It was much higher in the Paligaad, where the rising and falling limb of the hydrograph was steeper with a short time lag. The Paligaad sub-watershed response to all of the rainfall events, even though with changing rainfall intensity (data not shown here). But in case of the Upper Aglar sub-watershed, the rainfall events during the dry period of the summer did not respond to all of the rainfall events which resulted in a significant increase in the total outflow. The total river flow response from the Upper Aglar sub-watershed increased only when there was enough antecedent soil moisture present. In the case of the Paligaad sub-watershed, the quick response of the rainfall may also have occurred due to the very limited capacity to reserve the water. The average total flow from the Paligaad sub-watershed was obviously more than that of the Upper Aglar sub-watershed, due to different land cover and soil structure. Compared to the Paligaad sub-watershed, the average porosity and high moisture capacity at the Upper Aglar sub-watershed lead to a less total flow. It is also concluded that, the R-R events also increase with the increase in the watershed area. Beside this the peak discharge and rate of change of discharge also increases with the watershed area, stream length, drainage density and slope of the watershed. Collectively, the analysis shows that substantially enhanced discharge in Paligaad but not in the agriculture dominating Upper Agalr sub-watershed especially during the drier months of the growing season and decrease in the discharge timing.

The influence of rainfall over the runoff (rainfall-runoff response) in different land cover was the key finding from the present section which could be helpful for watershed management as well as total flow received are the lifeline for many people living downstream of the watersheds.

4.3.4.2 Baseflow analysis

The baseflow in a river is a significant factor for the river flow generation from the groundwater flow. It can be separated from the river flow data by means of hydrograph separation procedures such as the graphical technique, the analytical technique, the recession-curve technique and the digital baseflow filter techniques (McNamara, 1997; Szilagyi and Parlange, 1998; Rorabaugh, 1964; Hoeg et al., 2000; Nathan, and Mcmahon, 1990). Originating from the groundwater outflow, the resultant baseflow patterns display a characteristic annual rhythm. This rhythm was mainly influenced by longer rainfall periods filling up the pores in the soil and seeping out. The total outflow from each of the sub-watershed was divided into two components as the baseflow and the direct flow using the recursive digital filter method (Eckhardt, 2005).

$$Q_k = f_k + b_k \tag{4.2}$$

where Q_k = total stream flow, f_k = direct flow, b_k = base flow, and k = time step

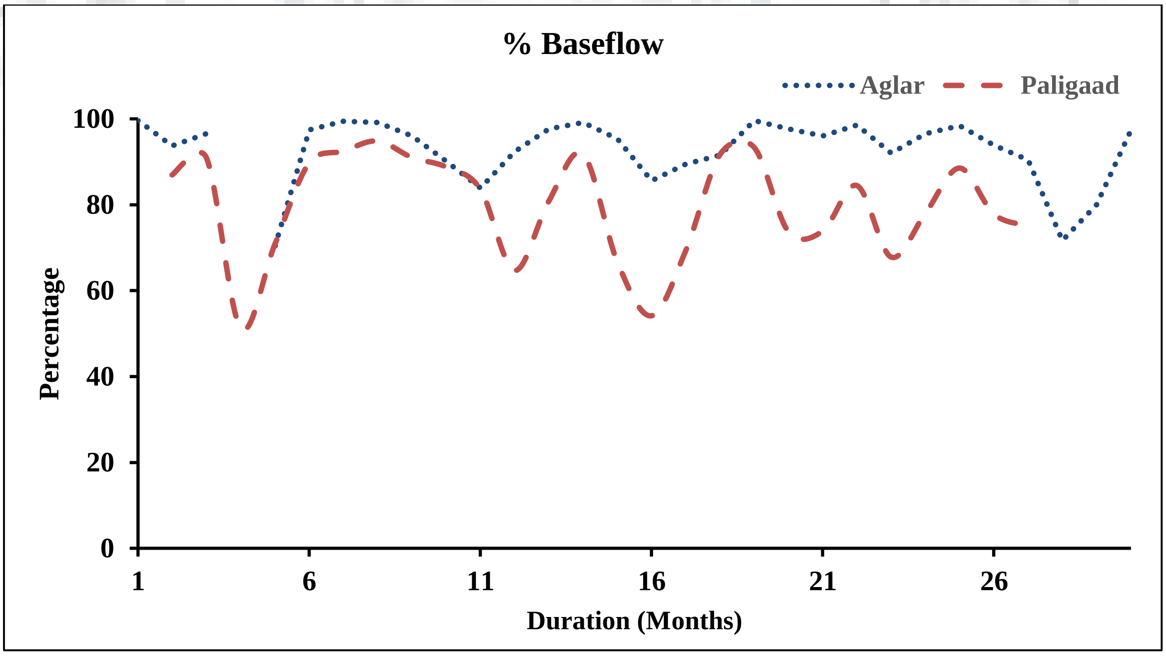


Figure 4.13: Percentage baseflow in Upper Aglar and Paligaad sub-watershed (2014-2016)

The total duration considered for the events was based on the analysis that indicated noticeable changes in the rainfall both in terms of the amount and the intensity, the runoff coefficient and the total flow because of the unevenness in the rainfall variation and the antecedent precipitation index. The average monthly baseflow contribution varied with the percentage of the baseflow ranged from 70.4–99.6 and 54.1–94.6 in the Upper Aglar and Paligaad sub-watersheds respectively for the duration from 2014–2016 during the study (Figure 4.13). The baseflow percentage varied between 24.39 and 68.27 of the total out flow from watershed of each event with a mean of 58.05%, indicating that it was more during the wet events as compared to the dry events. In general, the rainfall was the main recharge source of the river flow and the slopes of the watershed lead to moderate groundwater inflow and high peak flow. The baseflow in the Upper Aglar was higher than the baseflow in the Paligaad, as the Upper Aglar sub-watershed was dominated by the permeable coarse deposits at the top providing favorable conditions for groundwater storage. It should be noted that the sub-watersheds were covered principally by coarse materials and natural vegetation which contributed to the high proportions of groundwater to the rivers and low percentages of groundwater discharge, a process associated with watersheds having large proportions of imperviousness. The difference in the baseflow percentage between the Upper Aglar and Paligaad sub-watersheds could be explained by the fact that the Upper Aglar watershed had large proportions of agricultural land at 27.3% and bare land at 14.8% as compared to the Paligaad watershed at 16.7% and 12.4%. The watershed was also dominated by the hydrologic soil group B and rocky type, which influenced the infiltration of the underlying aquifer and groundwater discharge into the rivers. The presence of the permeable soils, and a large variability in the topography facilitated high groundwater inflow into the rivers.

4.3.4.3 Flow Duration Curve (FDC)

A FDC illustrates the percentage of time, or probability of equal or exceed a particular value of the flow in a river. The FDC analysis is a method involving the frequency of the historical flow data over a specified period. When the flows are arranged according to the frequency of occurrence and a flow-duration curve was plotted, the resulting curve indicated the integrated effect of the various factors that affect the runoff. Figure 4.14 displayed the flow duration curve for the daily mean discharge during the period from 12/4/2014 to 15/10/2016. The duration curves can also be used to examine discharge relationships and to assess long-term trends, specifically, how often the flow volume exceeds the flow conditions by 10th percentile which is high and/or decreases the flow conditions by 90th percentile which is low for a watershed. Typically, low flows during prolonged dry spells or when there was hardly any rainfall exceed majority of the time, while high flows, such as those resulting in floods, were supposed to be barely exceeded. To aid the comparison between the two different watersheds of differing sizes, the mean daily flow (m^3/s) from the gauge records was converted to the daily volume (m^3/d), then scaled by the drainage area (m^2) and converted to *mm* to calculate the water yield.

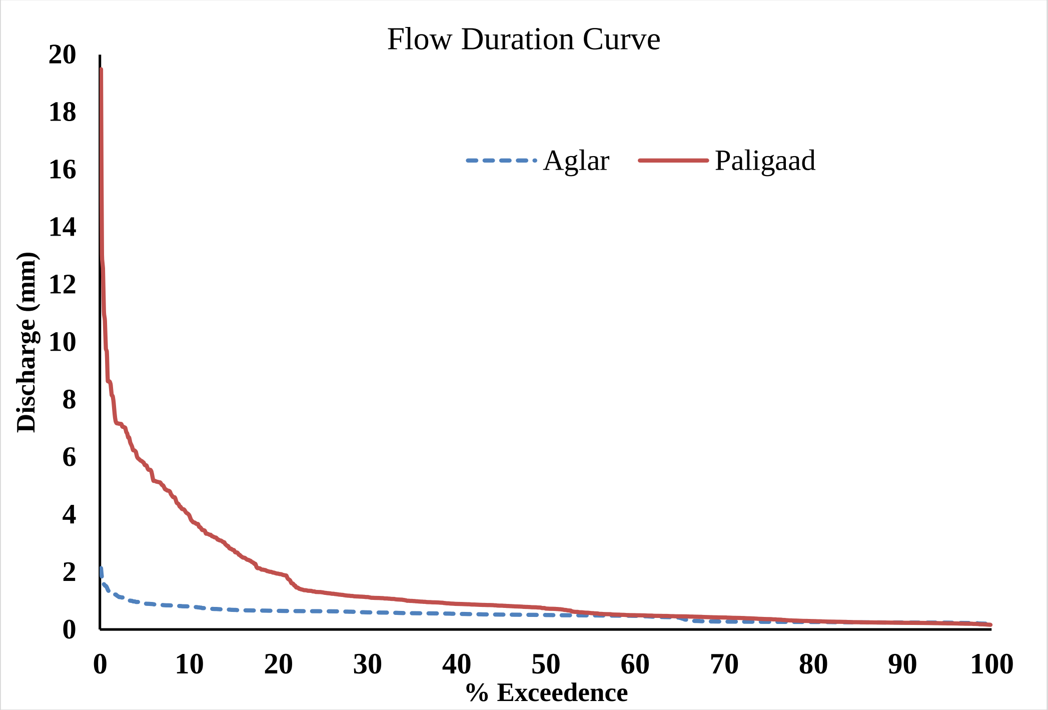
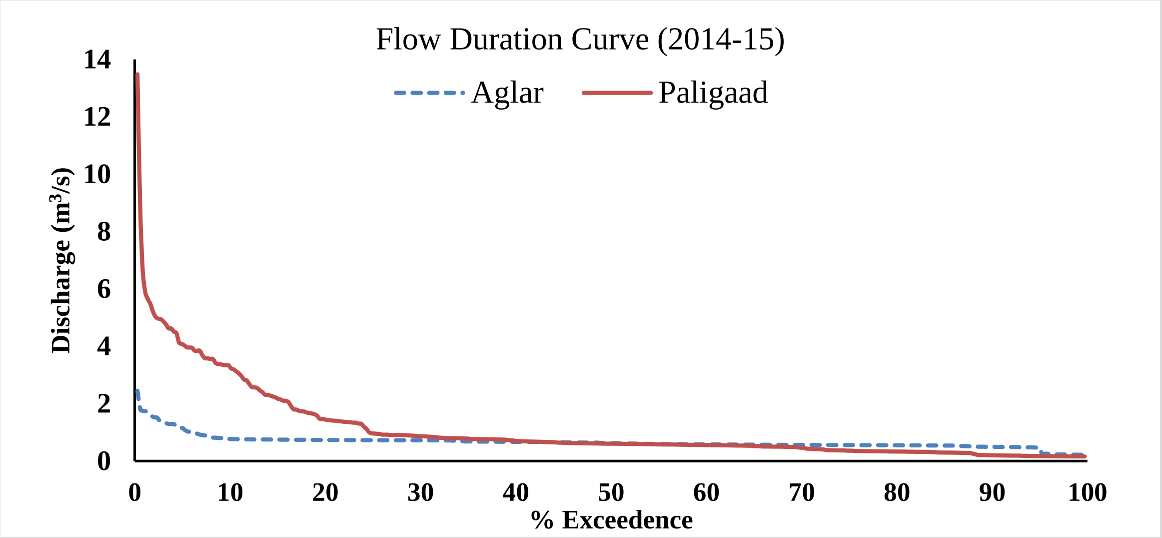


Figure 4.14: Flow duration curve for daily mean flow

For the analysis of FDC, the duration curve can be divided into 3 parts, with the upper third corresponding to the high flows, the middle third to the slow flow response of the catchment and the lower third to the low flow response (Yokoo and Sivapalan, 2011). While the upper third of the FDC is mainly related to the precipitation intensity, the lower third is more related to the properties of the watershed itself (Yaeger et al., 2012). The shape of the two FDCs for the same watershed constructed for two separate periods can be different due to the variations in the meteorological conditions, such as rainfall, and changes in the watershed’s geophysical characteristics, such as the land use type. However, the variations in the meteorological conditions took place over a fairly long time; hence its effect on the shape of the FDC could be less significant. In this way, the change in the shape of the FDC could be attributed mostly to the changes in the land use. The longer the record, the more reliable and representative was the constructed FDC.



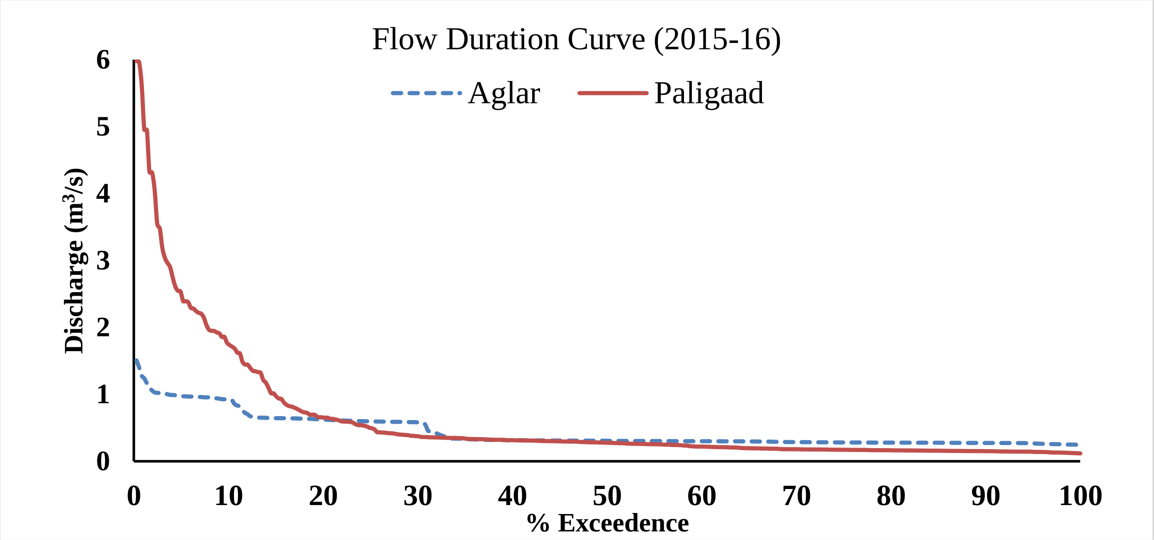


Figure 4.15: Flow duration curve for water year (2014-15 and 2015-16)

As compared to the Upper Aglar, the FDC of Paligaad sub-watershed has higher “high flows”, representing more frequent extreme conditions, coupled with lower “low flows”, representing less groundwater contribution. In general, a curve with a steep slope throughout indicated a highly variable river whose discharge was derived from the direct runoff. A flat slope in both the sub-watersheds indicated significant effects from the surface and the groundwater storage on runoff relationships, including prolonged duration flows resulting from the storage. In case of Paligaad sub-watershed, the high flow conditions have changed over a period while the Upper Aglar remained almost the same. The flow of 0.95m^3/s during the year 2014-15 for the 25 % exceedance went down to 0.43 m^3/s in the next year. There was less variability in the lower tail with 35 %–100 % exceedance in both the watersheds, possibly because of the baseflow contribution to the flow (Figure 4.15). The upper limb of the FDC, which represented the high flow conditions at each gauge, indicated a high variability in case of the

Paligaad as compared to the Upper Aglar. From the FDC, it was noticed that both the sub-watersheds had not experienced zero daily flow. If the FDC for seasonal flow from 1stJuly to the 30th September for the three years was considered there was less variability in the high flow for the Upper Aglar as compared to the Paligaad (Figure 4.16). There is no globally accepted guideline available for the design of low flows for particular purposes. A general consensus for estimating the design low flows was to lower the limb (70–99%) of the FDC for the daily discharge of the available period to protect the environment of the water with a marginal safety (Smakhtin, 2001). Q95 which was often used to determine the environment flows in the downstream reaches the impoundment in a river system to maintain good health of the ecosystem (Jha et al., 2008). It has been computed that the required Q95 for the Paligaad and the Upper Aglar values vary from 0.17 to 0.14 m^3/s and 0.47 to 0.27 m^3/s respectively for the years 2015 and 2016.

The steep slope of the Paligaad as compared to the Upper Aglar (Figure 4.16) during the high flows denoted a highly variable river whose flow was largely from the direct runoff, whereas a curve with a flat slope revealed the presence of the surface- or the ground-water storage which tended to equalize the flow. The slope of the lower end of the duration curve of both the watersheds indicated the characteristics of a perennial storage in the drainage basin. A flat slope at the lower end indicated a large amount of storage and a steep slope indicated negligible amount. The distribution of the low flows was controlled chiefly by the geology of the watershed. Thus, the lower end of the flow-duration curve was a valuable means to study the effect of geology on the ground-water runoff to the river.

The Geological Survey of India (1920) has adopted the flow that was available 50 percent of the time (Q_{50}) and the flow that was available 90 percent of the time (Q_{90}) as the standards of flow for waterpower statistics. The Q_{90} is a measure of the prime power and the Q_{50} is an index of the power potential with the storage. Together, the two indicate the variability of the flow. For Q_{70}, Q_{80}, Q_{90}, Q95 and Q_{99} percentile flows, the precipitation influence may be low since the low flow most likely come from the soil, the groundwater or the releases from the channel storage. As a result, the baseflow index was found to be a good low flow predictor. The flow exceeding the given value of 95% of the year -Q_{95} is often taken as the characteristic value for the minimum river flow from that watershed. A flatter seasonal FDC of the Upper Aglar as compared to the Paligaad, characterized more uniform river flow. It indicated that the total seasonal flow will be spread more evenly over the season, providing a useful flow for a longer period, and less severe floods.

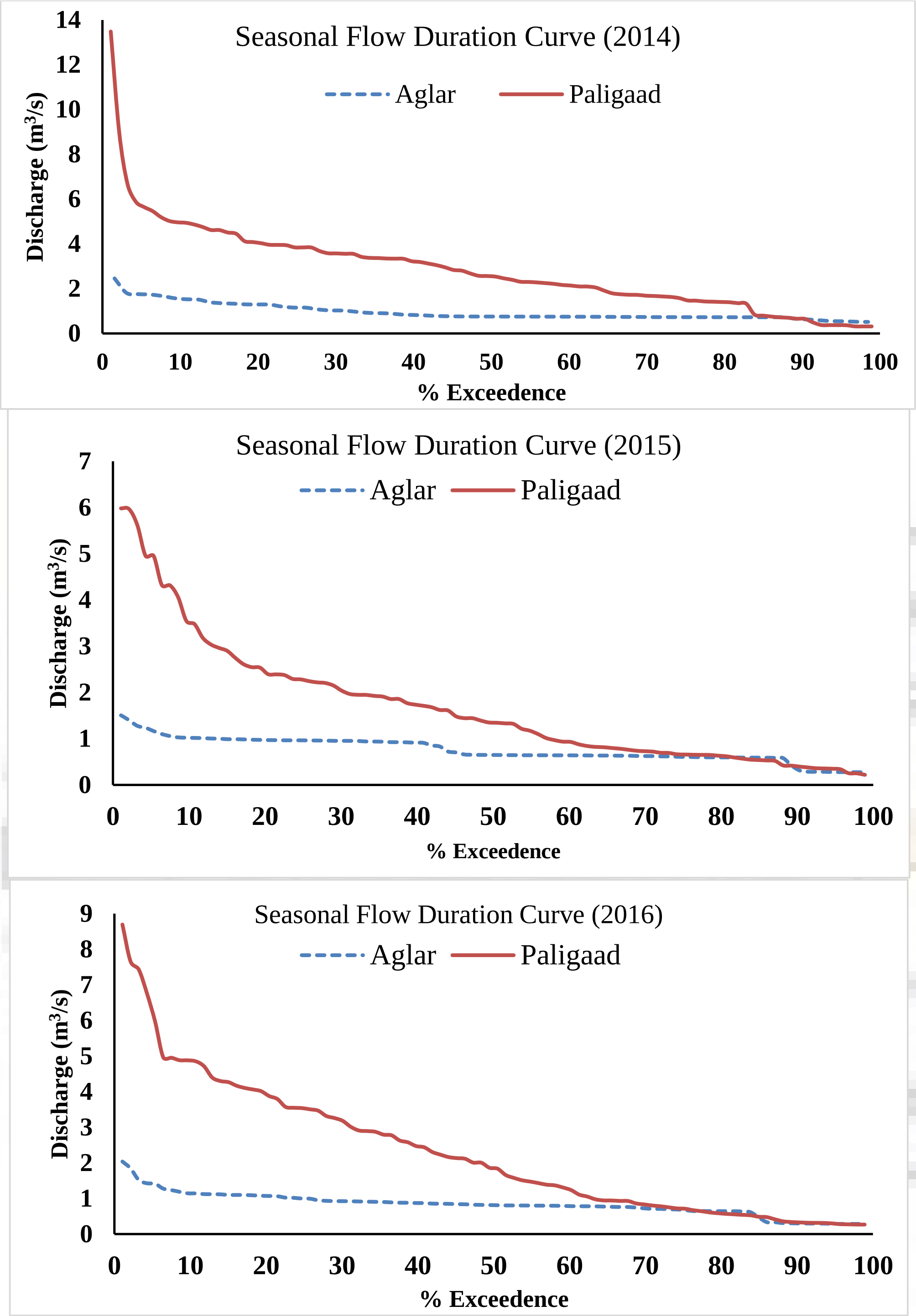


Figure 4.16: Seasonal flow duration curve for different years

It is anticipated that the basic data and analysis presented in this chapter will be of value for a wide range of subsequent analyses by scientists and engineers. In this chapter, an understanding has taken to comprehend the hydrological responses of two sub-watersheds under the different land cover.

CHAPTER 5

RATING CURVE DEVELOPMENT AND UNCERTAINTY ANALYSIS

Precise measurement of continuous river discharge is interesting and challenging topic for hydrologists and water resource planners as compared to stage measurement. The river stage-discharge relationship known as the rating curve for a gauging location is often subjected to various factors that are not easy to understand, nor easy to quantify, especially in a mountainous watershed. Thus the present chapter focused on developing a rating curve using the power law and uncertainty estimation at three headwaters of the Lesser Himalayas – the Aglar, the Paligaad and the Balganga by utilizing the conserved water level record i.e. stage measurement and discharge measurement by salt dilution method for the period 2014-2016. Other novelty in this chapter is the development of weighing factor concept which correlates the uncertainty with the morphological parameters of watersheds.

5.1 INTRODUCTION

Appropriate quantification of river discharge is important for designing canals, dams and other hydraulic structures and for effective management of water resources which affect the project cost and thus economic returns. Discharge is therefore an important hydrological variable and difficult to monitor continuously in many of the major rivers in order to manage flood and high flows. Understanding the variations in discharge during low flow conditions is also equally important to decide the requirement of the environmental flow and to cope with the quality of water, or with the releases of pollutants. Alteration in the river discharge may be due to effective rainfall, aquifer recharge, intensity and the duration of the rainfall, seasonality and timing of the flow (Beavis et al., 2010). In the mountains, quantification of the available water resources is very rarely conducted as the field-based measurements are sparse because of difficult terrain and safety of the instrumentation. However, it is important for food production and security, regional water resources policy and security. Despite the importance of the mountainous catchments which provide freshwater, there is very limited understanding of the discharge variation and the hydrological processes (Scanlon et al., 2006, Viviroli et al., 2007). Since the mountains, - the water towers for human beings, are equally important for the ecosystems. Thus it becomes essential to quantify the discharge in the river at the mountainous watershed (United Nations, 2011). The rivers, mainly, have to be monitored first as it is important to quantify the discharge at the ungauged major rivers by developing the rating curve (*RC*) and ascertain the presence of uncertainty in the *RC*. Quantification of the discharge using the *RC* are gradually growing due to its extensive use in the prediction of the impact of land use - land cover (LULC), flood forecasting, climate change studies, operation of dams and other hydraulic structures and to research the discharge of adjacent or similar ungauged watersheds.

To establish a *RC* for any ungauged river, an empirical relationship has to be developed between the river discharges (Q) and the gauge height (H). Appropriate selection of the site for gauging and measuring the discharge are important predictors for the development and maintenance of rating curves (*RCs*). The method for developing *RC* involves monitoring of multiple paired measurements of river discharge and gauge height and estimate the *RC* parameters. While establishing the parameters for a *RC*, key hypothesis of the best fitting curve is that the river discharge and gauge height (*Q*, *H*) are mutually independent and have the same probability distribution. Many times access to the gauging location can also impact the frequency of the measurement, the timing and the accuracy of the *Q* and the *H* measurements. During the monsoon period from July to September, when there is intense and long spells of rainfall, the access to the field sites for discharge measurements is restricted. For these days, the *RC* was developed on the basis of the river profile (geometry, slope and the roughness of the river) without the measurement of the river discharge and gauge height (Szilagy et al., 2005; Perumal et al., 2007, 2010; Christopher et al., 2010), using additional parameters other than the stage (H) (Sahoo and Ray, 2006), based on the capabilities of remote sensing (Birkhead and James, 1998) and the uncertainty present in the rating curves (Clarke, 1999; Jalbert et al. 2011). To accept the measured discharge at the site according to USGS guidelines, that is the difference between the measured discharge and the predicted discharge should be less than 10%. In a situation where error in a modelled discharge is more than 10% and less than 30% of the observed discharge then the Generic Rating Curve (*GRC*) could be used (Kevin, 2012). The main objective for developing the GRC was to generate a *RC* with some minor adjustments in the *RC* parameters to reduce the river discharge and gauge height (*Q*, *H*) measurements.

It is challenging to understand the dynamics of the river system in the mountains as there are several problems to measure (*Q*, *H*), thus making it difficult to measure the stage and the stochastic nature of the discharge precisely (Figure 5.1). The river discharge (*Q*) not only depends on the stage (*H*) but also depends on the profile - the geometry and the slope, and the roughness of the river along with the morphometry of the watershed. The relationship of the river discharge and the gauge height (*Q*, *H*), of cross-section of a river is not always the same as the river discharge is often influenced by various parameters which are not easy to measure (Sefe, 1996). Hence the power law $Q= a(h + ho)^c$ to develop a rating curve for a particular cross section is not exact but an approximation only (Henderson, 1966). Many times, the *RC* changes its shape from parabolic to other curvilinear shape which influences the parameters over a certain limit (Guven and Aytek, 2009) which are not easy to find and so sometimes makes it impossible to obtain the correct values. Imprecise or inaccurate estimation of the *RC* parameters leads to an over or an under estimation of the flood design which have a high risk of failure and involves cost. If the presence of an error or an uncertainty in the rating curve *RC* is quantified well, then it would be able to enhance the assessment of the discharge and ensure positive decision making. Quantifying the uncertainty present in the rating curve (*RC*) as a standard protocol could save money indirectly and increase the credibility in decision making. Representative confidence bound for rating curve uncertainty measurement is rely on gauge location and river profile (Westerberg et al., 2016).

The uncertainty in the rating curve (*RC*) can broadly be classified as follows:

i) *Observational uncertainty* is associated primarily to the observation used (e.g. stage and discharge) to develop a rating curve which generally has errors due to stage as well as the discharge along with the instrumental errors.

ii) *Model uncertainty* is linked to the formulation of power law to develop a rating curve with approximations involved in the mathematical equation.

iii) *Parameter uncertainty* is caused due to the failure in deciding the input parameters involved in the development of a model as there was insufficient data.

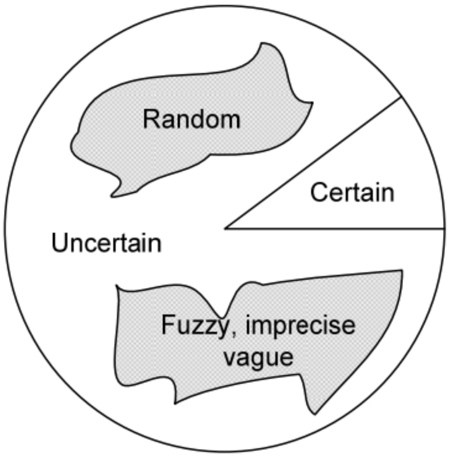


Figure 5.1: Certainty and uncertainty in information world

To analyze the above described uncertainty in the river discharge measurement, Domeneghetti et al. (2012) proposed an outline and described the effects of uncertainty on calibration of the model. Pappenberger et al. (2006) developed a decision tree model to represent different causes of uncertainty. According to Montanari, (2007), there are different uncertainty methods which can be categorised into (a) analytical methods (Tung, 1996), (b) approximation methods (Melching, 1992) (c) methods based on the analysis of model errors (Montanari and Brath, 2004), (d) Monte Carlo methods (Kuczera and Parent, 1998), (e) Bayesian methods (Beven and Binley,1992) and (f) methods based on fuzzy set concept (Maskey et al., 2004).

The recorded measurement of stage using a water level recorder placed in a stilling well generally causes less errors than the river discharge which involves calculation of the discharge by measuring the velocity of the entire river cross-section (Clarke, 1999; Pelletier, 1988). Inadequate temporal measurement of the river stage (*H*) for an average daily discharge pose an additional doubt and error (Petersen-Overleir et al., 2009). During the peak river discharge, it is hard to monitor flashy and uncontrolled turbulent flows, which are often tough to measure accurately, which contribute to the uncertainty (Leonard et al., 2000; Shrestha et al., 2007). Among the traditional methods to measure discharge, evaluating the river discharge by salt dilution method proved better especially in the mountainous or remote areas where suitable hydrologic profile is hard to find (Radulovic et al., 2008). Also, the river discharge (*Q*) measurements using the salt dilution method can be accurate about ±5 % (Day, 1976). Thus objective of the present study in this chapter is three fold: (1) to develop a rating curve for the three different headwater rivers of the Aglar, the Paligaad and the Balganga in the Lesser Himalaya. The developed stage discharge relationship later could be used to compute the river discharge by monitoring the stage alone (2) to estimate the uncertainty involved in the developed stage-discharge relationship. The uncertainty measurement was involved using the evaluation of the codes that state the uncertainty of each gauge at 95% confidence intervals and (3) to develop a concept of a weighing factor to correlate the uncertainty with the morphometry of the Aglar sub-watersheds which governs the flow behaviour. This detailed rating curve and uncertainty analysis at the mountains especially in the Himalayas, which are considered as water towers, play a crucial role for better quantification of water availability for agriculture, optimal planning and management of water resources. The above said analysis will deliver a suitable method for practitioners of hydrology and water resources to develop the rating curve and evaluate the uncertainty in the river discharge.

5.2 METHODOLOGY AND DATA

The three sub watersheds or rivers in the Lesser Himalaya - the Aglar, the Paligaad and the Balganga were instrumented from April 2014 to collect continuous rainfall and stage measurement. The discharge of the river was measured time to time to develop a rating curve. A detailed description of the methodology involved is discussed in the last chapter.

Most in-stream flow studies use the daily river flow data as a starting point of any hydrological analysis. The daily data may be from the measurements and from the data received from other locations by various techniques. In this study, the river flow data was derived from stage measured at 15-minute intervals using the Odyssey water level logger. The data was transformed to discharge using a rating curve and was aggregated to the daily values for both the gauging stations at the Upper Aglar and the Paligaad watersheds as displayed in Figure 5.2.

Figure 5.2: Location of Gauging station with deployed water logger and caging to protect the logger

5.2.1 Rating curve (RC) development

Continuous monitoring of the river discharge proved very expensive, time consuming and impossible especially during the high flows. To overcome such hurdles, a continuous stage was observed which is easier to monitor comparatively to be converted later to the river discharge with the stage-discharge power equation, commonly recognized as the rating curve. The monitored value of the river stage and corresponding discharge were plotted on an arithmetic and logarithmic graph. The plotted graph represented the combined consequence of a wide range of the depth and the discharge parameters. If the stage-discharge relationship for a gauging river section does not change with time, the control is said to be ‘permanent’. If it changes with respect to time then it is called ‘shifting control’. The ideal situation of a control channel is when the energy gradient line is parallel to the water surface gradient and to the bed gradient. Hydraulics formulas for control section and channel can be represented as power law (WMO, 2010; ISO 1100, 2010) and the power law parameters were assumed to be constant (Subramanya, 2006).

$$Q= a(h + h_o)^c \tag{5.1}$$

where ‘Q’ is the discharge of the river, ‘h’ is the depth of the water in a river which is also the stage of the river, “*a*” is the power law coefficient that relates to the features of the controlling section or channel, h_o is the offset, and “*c*” is the exponent related to the type of hydraulic control (Le Coz et al., 2014).

The best fit curve which governs the value of a, h_o and c in the equation 5.2 for a given range of the depth could be obtained by the least square error method. For this, considering the logarithmic scale, equation 5.1 becomes

$$\ln Q = \ln a + c \times \ln (h + ho) \tag{5.2}$$

A linear trend line equation between ‘log Q’ (Y-axis) and ‘log (h – ho)’ (X-axis) was fitted in Matlab and the slope of the straight line gives ‘c’ and the Y intercept gives ‘log a’ (and thereby ‘a’). Thus, the stage discharge relationship was developed as in the equation 5.2. The developed relationship for all of the three gauging locations was considered as an epitome of all the channel characteristics. Occasionally the stage-discharge curve was in a parabolic shape which changed to a composite curve and vice versa, and the parameters varied through the limit (Guven and Aytek, 2009). Thus it was not simple to estimate the rating curve parameters (a, h_o and c) for all of the cases and occasionally was difficult to acquire the true values. In general, at least 15 sets of stage discharge were needed to develop a rating curve that included both low and high flow.

5.2.2 Assessment of rating-curves uncertainty

Estimation of uncertainty in the rating curve (*RC*), which was initiated from a false measurement or the method described in the earlier section that was built from less stage discharge pair measurements is very important. Taking into consideration the error (ε) in power law, the equation (5.1) can be re-written as

$$Q = a(h + ho)^{c}(1 + \varepsilon) \tag{5.3}$$

The basic assumptions for the equation (5.3) were that ε was the normal distributed with a zero mean value and a constant variance (σ^2). No correlated errors were assumed (cov[ε_i, ε_j] = 0) for different samples of the stage discharge. The log transformation of equation (5.3) became

$$Q = \ln(a) + c \times \ln(h + ho) + \varepsilon \tag{5.4}$$

Upon minimizing the ε term, the equation became 5.5 which was the objective of this study.

$$S^2 = \sum \varepsilon^2 = \sum[ln(Q_i) - (\ln(a) + \mathrm{c} * \ln(\mathrm{h} + \mathrm{ho})]^2 \tag{5.5}$$

The following equations could be used to assess the uncertainty in the estimated discharges from the power model rating-curve relationship for a specific level (H=b), and calculate the variance

$$\mathrm{var}(\ln(\mathrm{Q_i})|\mathrm{H} = \mathrm{b}) = \mathrm{D_i}^{\mathrm{T}} * \mathrm{var}(\theta^*) * \mathrm{D_i} \tag{5.6}$$

$$D_i = \left[1, ln(b + H_o), \frac{C}{(b+H_o)}\right] \tag{5.7}$$

$$\mathrm{var}(\mathrm{Q}) = \mathrm{Q}^2 \mathrm{var}[\ln(\mathrm{Q})] \tag{5.8}$$

$$\mathrm{var}(\theta^*) = \mathrm{I}^{-1} \tag{5.9}$$

To calculate the value of $\mathrm{var}(\theta^*)$, the (I) has to be solved first which is the Fischer information matrix, solved by Venetis in the year 1970.

$$I = -\begin{bmatrix} \frac{\partial^2 l}{\partial ln(a)^2} & \frac{\partial^2 l}{\partial ln(a)\partial c} & \frac{\partial^2 l}{\partial ln(a)\partial H_0} & 0 \\ \frac{\partial^2 l}{\partial ln(a)\partial c} & \frac{\partial^2 l}{\partial a^2} & \frac{\partial^2 l}{\partial a \partial H_0} & 0 \\ \frac{\partial^2 l}{\partial ln(a)\partial H_0} & \frac{\partial^2 l}{\partial c \partial H_0} & \frac{\partial^2 l}{\partial H_0^2} & 0 \\ 0 & 0 & 0 & \frac{\partial^2 l}{\partial \sigma 2} \end{bmatrix} \tag{5.10}$$

$$l = -\frac{n}{2} ln(2\pi\sigma^2) - \frac{1}{2\sigma^2}\sum\left(ln(Q_i) - \left(ln(a) + c * ln(H_i + H_o)\right)\right)^2 \tag{5.11}$$

Then the value of variance was estimated using the relation

$$\sigma = \sqrt{\frac{S^2}{n-k}} \tag{5.12}$$

Adopted maximum likelihood methods have desirable optimality properties such as it become minimum variance unbiased estimators as the sample size increases. The method of maximum likelihood provides estimators that have both a reasonable intuitive basis and many desirable statistical properties. A disadvantage of the method is that it frequently requires strong assumptions about the structure of the stage-discharge. The analysis of the uncertainty in the rating curve was one of the major concerns in the investigation of the consistency of water and hydrology related projects. Furthermore, the point of zero flow (H_0) was difficult to determine in deep rivers and in mountainous watershed where the profiles are rocky (Dickinson, 1967) hence assumed zero. Therefore, if the uncertainty is taken into consideration, it can support the hydraulic design modeler in planning as well as designing the operation models and to forecast probable forthcoming insufficiencies.

5.3 RESULTS AND DISCUSSIONS

5.3.1 Rating curve development

The link between the river water level (stage) and the river discharge (*Q, H)* was influenced by the character of the river channel and its bank. With the increase in the river discharge, the excess water caused the river to expand leading to an increase in the depth of the river as well as in the widening of the river banks. The highly correlated multiple data points of the stage and the discharge (*Q, H)* after the quality control were used to obtain the rating curve (*RC*). The river stage and the corresponding discharge value of all of the gauging stations was measured from September, 2014 to December, 2015. A non-linear curve fitting algorithm in the MATLAB using the function “nlinfit” and the power equation 5.2 were used to develop the rating curve (*RC*).

The developed stage discharge relation with the coefficient of determination was shown in Figure 5.3 and the rating curve power law coefficients in Table 5.1. It was understood that the developed (*Q*, *H*) could be considered to be the best approximation of the stage and the discharge data series as the curve’s best fit. The shape of the (*Q, H)* curve was inhibited by the analysis of the constraints based on the collected data. The extrapolation of the curve other than the calibrated range was realistic and was sustained by the accompanying evidence.

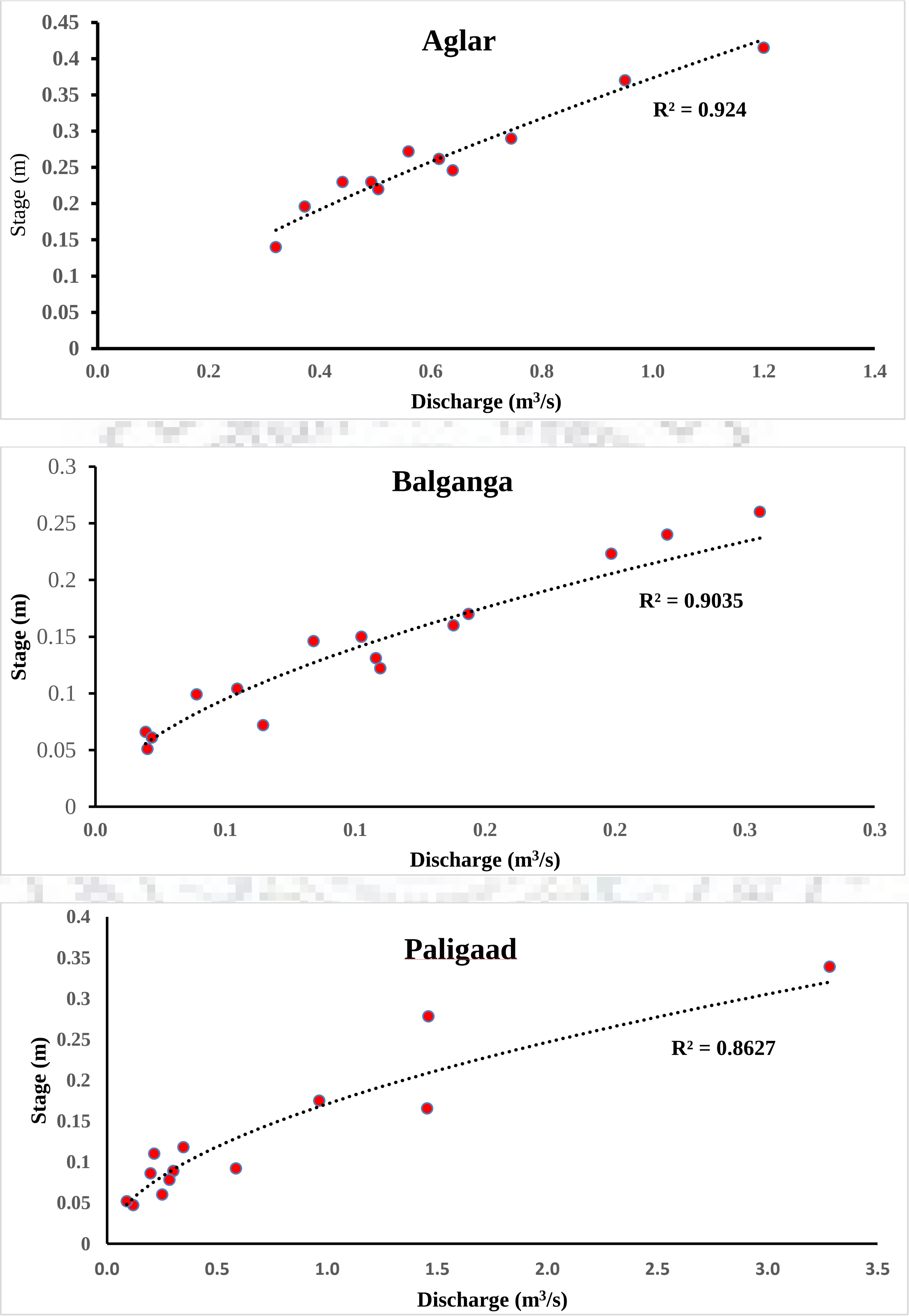


Figure 5.3: Stage discharge relationship for different ungauged river of Aglar watershed

Table 5.1: Rating curve coefficients of Aglar sub-watersheds

Parameters	**Aglar**	**Paligaad**	**Balganga**
c	1.27	1.63	1.61
a	3.35	15.93	2.33
R^2	0.92	0.86	0.90

From the monitored (*Q*, *H*) data for the three rivers, the non-linear relationship between the stage and the discharge were similar for the Aglar and the Paligaad which had relatively less relief ratio of 0.002 and 0.004 when compared to the Balganga which had a relief ratio of 0.007. The rating curve (RC) parameters were different for the three gauging stations as shown in the Table 5.1. For the unconfined bedrock rivers of the Aglar and the Paligaad, the coefficient of determination (R^2) were 0.92 and 0.86 whereas for the Balganga it was confined to the control section with R^2= 0.90. Hence, understanding the channel geometry which governs the *Q*, *H* relation was the fundamental component to develop the stage discharge relationship. The rating curve for the Balganga was usually influenced by the section control where the flow was low when compared to the Aglar and the Paligaad. The high flow in the Paligaad was influenced by the channel control whereas the Aglar was influenced by a combination of the section and the channel control. As the depth of the water increased in the Paligaad, due to higher flows, the control section was submerged and no longer controlled the relation between the *Q*, *H*. The flow in the rivers were controlled either by the additional downriver control section or by the channel profile and by the Manning's roughness (i.e. channel control). In addition, the dimensions of the control in the channel differed when subjected to river discharge. Generally, the coefficient of the power law "*a*" and "*c*" were explicit to some of the characteristics of the river channel which could be correlated to the physical features of the river. The parameter "*a*" is the scaling factor that embraces the river width, and the Manning coefficient. It can be inferred from Table 5.2 that the value of "*a*" was more for the Paligaad at 15.93 followed by the Aglar at 3.35 and the Balganga at 0.0014. The parameter "*c*" embraces the river geometry, and displayed the type of control in relation with *Q*, *H*. The more value of "*c*" at 1.63 in case of Balganga indicated a section control and the less value of "*c*" at 1.2 in case of the Aglar indicated the channel control.

The observed discharge was not fixed for all of the gauging sites for a specific stage and all of the gauging sites displayed different trends in discharge. There was variability in the rating parameters at different stages and gauging stations. The presence of seasonal component at all of the gauging sites was observed but it was mostly noticeable at the Aglar and the Paligaad gauging sites. The discharge from the river for a particular water height may possibly change by more than one factor. To validate the computed river discharge by salt dilution method at the Aglar, the Paligaad and the Balganga, the details of the cross-section at these gauging stations were plotted and the river velocities were measured precisely using the current meter to obtain the discharge (Figure 5.4). The riverbed configuration of all the three rivers had different flow resistances, therefore all of the three rivers have different *Q, H* associations. The resistance to the flow generally increased with the increase in discharge, with noticeable discontinuities in the course of transitions between the channel profiles.

Figure 5.4: Cross section plotting and discharge measurement using current meter

The well-developed relationship between the stage and the discharge (*Q, H)* and its effectiveness with respect to the change in the river behaviour could be a research topic for future investigation in detail. With the limited observation during the study, it was very difficult to identify a particular cause for the variability. The interchanging sequences of scour and fill in the river bed, with deposition throughout the non-rainy season, the rate of erosion and subsequent deposition in the river channel during the rainy season had the ability to alter the river channel's conveyance which are typical hydraulic properties. On the other hand, vegetation changes could also play some important role by yielding an altered friction slope as it might mature throughout the non-rainy season on the side of the river. In case of steep slope mountainous rivers, the effect of backwater could be very limited that could be ignored. In the study, no attempt has been made to clear any different processes, or grouping of processes which gave rise to the inconsistency in the stage and the discharge (Q, H). The development of relationship among the (Q, H), which was not available previously has been made using discrete stage-discharge data for the gauging stations.

5.3.2 *Uncertainty analysis*

The river discharge evaluations from the developed rating curve (*RC*) in the present study was subjected to some amount of uncertainty as there were errors as mentioned earlier. The inconsistency in the *RC* was more pronounced than what the present estimation methods permit for. The general recommendation was to change the *RC* parameters when the developed *RC* produced greater than 5% change in the observed discharge or understand the errors associated with it and compensate those errors in the final discharge estimation.

Even though caution has been taken during recording of the data, as described in the methodology, the recorded data contained with few outliers. As the depth of the river that deviated more than 2 cm was considered to be an outlier, it was not used in the analysis. The diurnal fluctuations in the recorded stage exhibited variation with a maximum depth in the river flow which commonly occurred between midnight and 10:00 AM in the morning during the wet period whereas the pattern was different in the dry period with less stage between late night and 10:00 AM of the day. (Figure 5.5). This diurnal discrepancy in the recorded stage (depth) underscored the prerequisite to consider the uncertainty in the measurement of the discharge at different times with only a few measurements of the stage during the day.

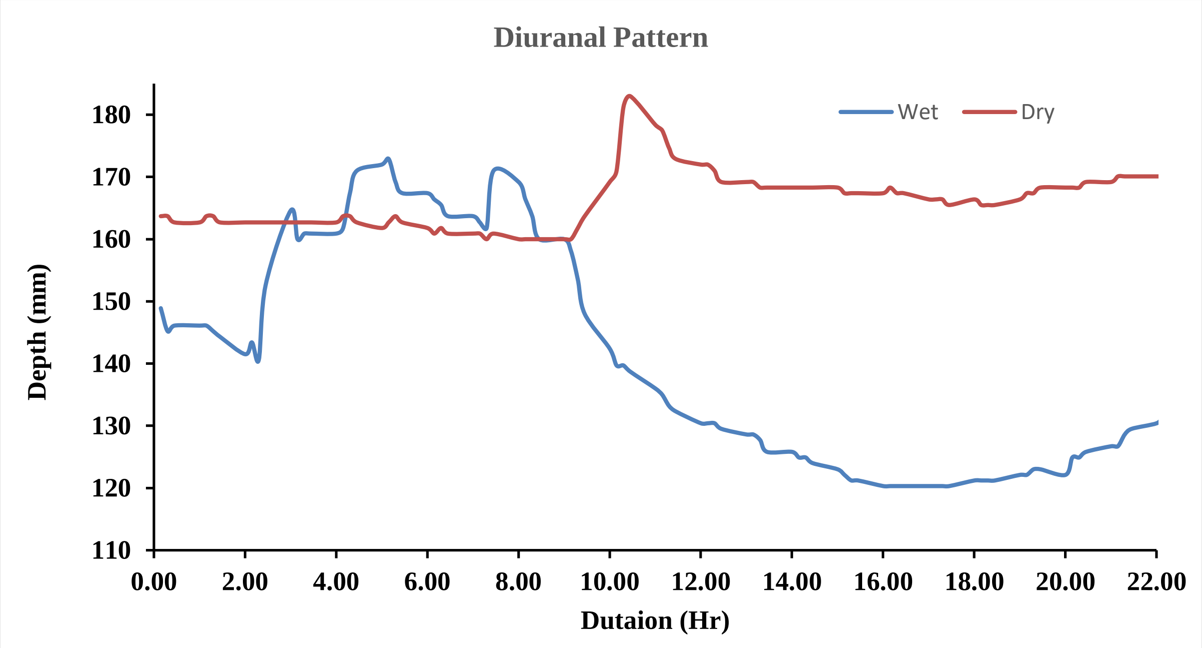


Figure 5.5: Average 15 min stage variation for dry and wet period

In the absence of any past uncertainty data of discharge in the mountainous watershed or any evidence about the sources of uncertainty in the *RC* in the Aglar watershed, the uncertainty in the discharge measurement was estimated to 11.9% in the Aglar sub-watershed, 43% in the Paligaad sub-watershed and 28% in the Balganga sub-watershed (Figure 5.6). The Paligaad river was flashy when compared to the Aglar and the Balganga. Hence, the promising discharge measurement consisted of only a few measurements, and the error was as much as 43%. The outcome from the uncertainty analysis was that the relation in the uncertainty in the stage discharge was more where less data (pair of Q, H) was observed to generate the rating curve during the high flows. In case of the Paligaad, 95% of the uncertainty prediction interval (bound) was much wider for larger values of the stage measurement when compared to the Aglar and the Balganga (Figure 5.6) due to less observation during the high and the flashy river flow.

The magnitude of the errors in the rating curve was measured by the pair of (Q, H) that bound between the uncertainties. To determine the confidence intervals band of uncertainty involved in *RC*, it was presumed that the residuals in the developed RC have a normal distribution with a fixed variance value. Figure 5.6 represents the overall uncertainty in different confidence intervals for the Aglar watershed. The commensurability error produced by the inadequate number of the stage and discharge measurements were required to understand separately if the high discharge passed between the two measurements. The investigation delivered insight into the capability of the measurements in different rivers - each with their own parametrization to distinguish between how the high or low flow measurement could influence the understanding of availability of water. This obviously could lead to wrong conceptualization of the hydrological processes which are important for the conversion of the rainfall to the river discharge.

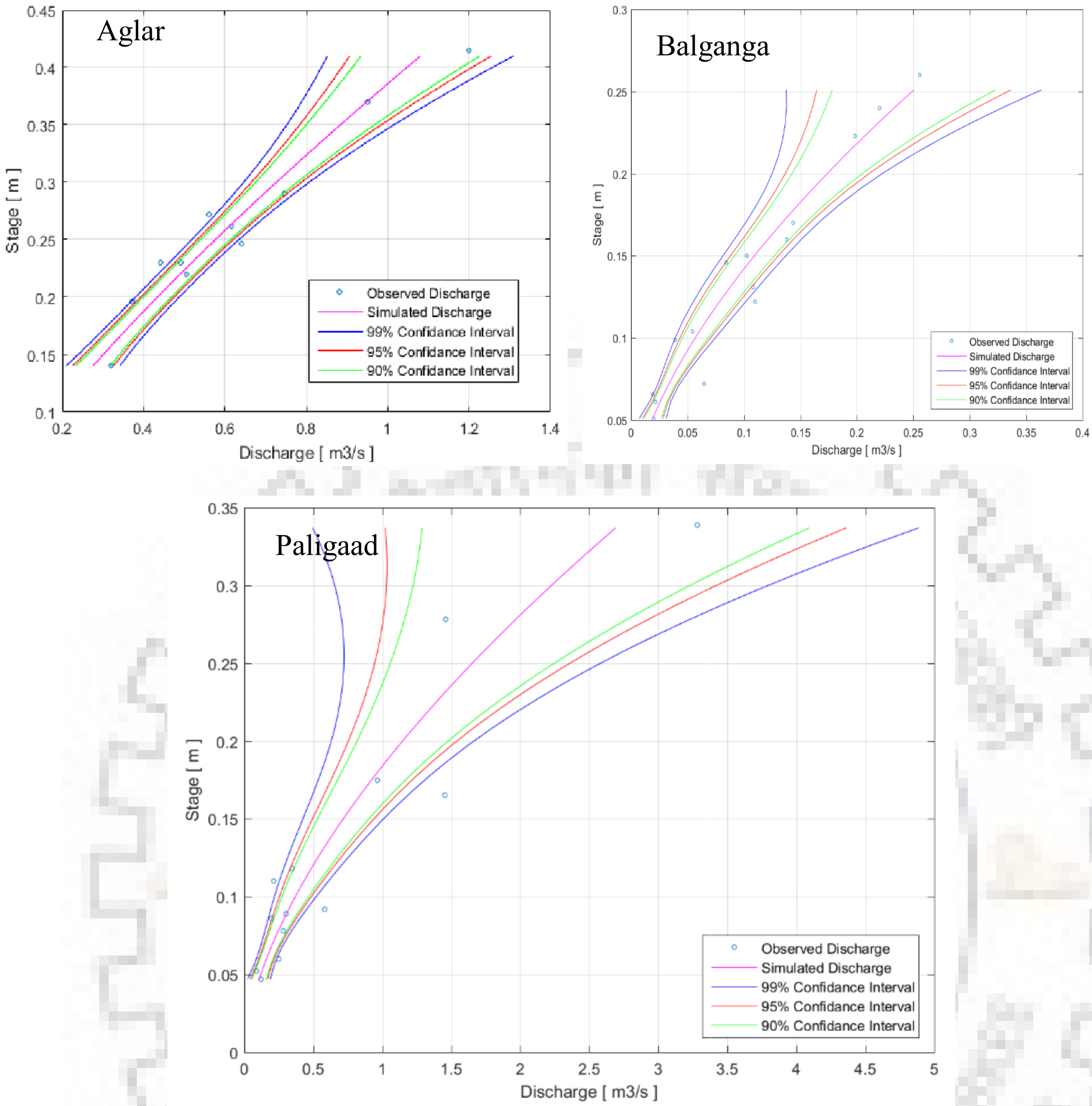


Figure 5.6: Uncertainty in different confidence intervals for Aglar sub watersheds

The geomorphology of a watershed has a significant role in the transformation of rainfall to the river discharge and the associated process. For example, the reaction from a poor drainage network with good vegetation cover will be slower than that of a well-developed drainage network with less vegetation cover. From the geomorphology point of view, the ratio of the average width/depth for all of the monitoring stations were less than 12, therefore according to the cross sectional and the plan view, these rivers were either of A, E and G categories as per Rosgen classification (1996) . The "A" type rivers initiate within a valley, have a great sediment transport potential due to intrinsic channel gradient, and have a relatively less sediment storage capability. Although the "A" type rivers follow the low-order rivers which can range from the 1st order to the 5th order or larger, they are located at the upper catchment.

The "E" types of rivers characterises the developmental "end-point" of the river channel stability for certain alluvial rivers which undergo a natural dynamic order of the system evolution. These types of rivers exhibit very low channel width/depth ratio, and display very high channel sinuosities that result in a major meander width ratio. The type "G" rivers are entrenched with low to a moderate channel sinuosity. The channel gradients are generally steeper than 0.02, and have a very high bank erosion rates and a high sediment delivery ratio. In conclusion, the Aglar sub-watershed displayed low sensitive to disturbance, with excellent recovery potential, low sediment delivery, less erosion possibility, and reasonable influence of vegetation. Whereas the Paligaad sub-watershed was highly sensitive to disruption, has good recovery potential, moderate river bank potential and very high influence on vegetation.

A weighing factor was developed in the present study to understand the influence of the catchment geomorphology on the uncertainty and the geomorphological parameters taking into the consideration are: the area of the watershed (A), drainage density (D), relief ratio (R), form factor (F) and elongation ratio (E) and its corresponding values for each watershed is summarized in (Table 5.2). The weighing factors for the calculation is given as

$$W_i = \frac{k_i}{\sum_i^I k_i} \tag{5.14}$$

$$k_i = \frac{A_i \times D_i \times R_i}{F_i \times E_i} \tag{5.15}$$

Where, I was the number of sub-catchments (3 in the present case).

Table 5.2: Morphological characteristics of Aglar sub-watershed

Morphological parameters	*Aglar*	*Paligaad*	*Balganga*
Drainage density (D)	0.27	0.32	0.31
Relief ratio (R)	0.02	0.04	0.07
Elongation ratio (E)	0.18	0.21	0.19
Form factor (F)	1.59	1.43	0.61
Area (km^2) (A)	99.65	59.78	13.12
Weighing Factor Value (W_i)	**0.27**	**0.37**	**0.35**

The higher the value of weighing factor (W_i), the more the uncertainty, thus there were chances for more errors in the Paligaad sub-watershed when compared to the Balganga sub-watershed and less in case of the Aglar sub-watershed. The data from the weighing factor in this study supported the degree of the uncertainty in estimated the stage-discharge which could further be reduced by investments in the hydrometric field instrumentations, particularly by generating more and more data, developing new methods based on data, technologies and techniques for high flow measurements and monitoring the winter river flow. The findings also indicated that the monitored number of the stage discharge measurements to generate the rating curve must be more than 15 to compensate the large uncertainty requirements as mentioned in the WMO guidelines.

The study mainly aimed to estimate the uncertainty which was propagated into the instant discharge values that were obtained from the rating curves built from less pair of stage-discharge measurements. Further research required to revise the rating curve with the measurement of the discharge during high flows and to reduce the uncertainty propagation in the daily and the monthly discharge values. The improved rating curve with less error would result in better hydrological modelling and calculations, such as water scarcity indexes or flood designs for hydraulic structure dimensioning.

5.4 CONCLUSION

An assessment of the relationship between the stage and the discharge data and the errors in the developed relationship should be considered as a significant step in the quantification of water resources in any watershed. The key parameter “discharge” in the Aglar watershed or in the Lesser Himalayan rivers, is derived from the stage-discharge relationships only (rating curves). To unravel and understand the hydrological process and to quantify the water availability, the collection of the hydrometric data for stage and discharge is one of the most reliable, consistent, and attractive data collection process. Hence, the present study focused on the development of the rating curve using the power law at three headwaters of Lesser Himalayas - (the Aglar, the Paligaad and the Balganga by installation of water level recorders for stage measurement and used the salt dilution method for discharge measurement for the periods between 2014 and 2016. Even though the presence of uncertainty was inherent, an attempt was made to ascertain the uncertainty in the developed rating curve by using the maximum likelihood method.

Analysis of the monitored (Q, H) data for the three rivers indicated that the non-linear relations between the stage and the discharge were similar for the Aglar and the Paligaad which relatively have less relief ratio of 0.002 and 0.004 when compared to the Balganga which has a relief ratio of 0.007 with different rating curve (RC) parameters for the three gauging stations. For the unconfined bedrock rivers of the Aglar and the Paligaad, the coefficient of determination (R^2) were 0.92 and 0.86 whereas for the Balganga it was confined between the control section with an $R^2 = 0.90$. A comparatively more value of power law coefficient “c” at 1.63 in case of the Balganga indicated a section control and the less value of “c” at 1.2) in case of the Aglar indicated channel control. The diurnal fluctuations of variation recorded in the stage exhibited the uncertainty in the rating curve which underscore the analysis of the uncertainty in the rating curve. Further a weighing factor was developed to understand the influence of the catchment geomorphology on uncertainty. The higher the value of the weighing factor the more the uncertainty, thus there were chances of more error in the Paligaad when compared to the Balganga and less in case of the Aglar. The extent of uncertainty due to the high flow remained indeterminate as no field data were collected due to flashy flow. It was expected that the development of the rating curve and the uncertainty analysis would inspire the design of forthcoming research required to address the scarcity of data at high flow. Findings from this preliminary study would become the benchmark for further research and would also help policy creators and watershed administrators for improved planning and management related to water in the rural part of the Lesser Himalayas.

CHAPTER 6

SPRING DISCHARGE DYNAMICS USING RECESSION CURVE ANALYSIS

6.1 INTRODUCTION

Water is a foremost need for survival of human and ecosystems, therefore sustainable management of water resources becomes major challenge in arid and semi-arid regions, which are 30% of the total earth’s area (Middleton and Thomas, 1997). With increasing concern of population growth and climate change there is an urgent need to understand discharge variability and water availability at a source. Quantification of distribution of discharge in streams and springs has major role in water resources planning and development (Hajkowicz and Collins, 2007). Development of socioeconomic relies on quantification of available water resources of an area and helps in reducing poverty (UNSECO-WWAP, 2006).

Especially in the data-scarce region like the Himalayas, monitoring of hydrological data could be beneficial for better understanding of hydrological processes and management of water resources if sufficient data of rainfall, surface and subsurface flow is available. On the basis of regional studies there has been a growing concern for Himalayan hydrology due to natural as well as anthropogenic activities (Beniston, 2003). Chaulagain (2006) pointed out the change in climatic conditions in terms of lesser number of rainy days, and decrease in rainfall amount could cause severe water scarcity especially in Himalaya. For example in lesser Himalaya, the rocks are highly weathered and fractured which regulate the groundwater path for spring.

Himalayan springs are one of the important sources of domestic water supply in various mountainous regions (Fiorillo, 2009). Problem at large is that discharge from these springs are either drying up or reducing by deforestation in hillslope (Valdiya and Bartarya, 1991). Not many studies in the Himalayan region were conducted to understand the impact of land use and land cover change or climate variability on spring discharge. Spring discharge is varying in nature due to variation in storage and recharge behavior (Valdiya and Bartarya, 1991; Negi and Joshi, 1996, Peleg et al., 2010). However, with the advancement of affordable and efficient experimental techniques, our ability to quantify the water resources and monitoring of watersheds becomes easy using continuous hydrological data. Spring discharge time series are often used for understanding the hydrological processes and for characterization of the aquifer systems (Amit et al., 2002).

Discharge hydrograph is a representation of the flow rate with time, which comprises of rising limb, peak flow and falling limb, respectively (Amit et al., 2002). Recession curve is the portion of discharge hydrograph in the falling limb that originates after the peak flow and progressively decreases. Analyzing the behavior of hydrograph during recession time of springs flow could provide information related to hydrogeology especially in fracture-type or conduit flows. Studying the hydrograph by recession curve approach is favored over other geophysical and geological techniques (Bakalowicz, 2005). Generalization of results obtained from recession curves are still challenging (Krakauer and Temimi, 2011) in the Himalayan region, where frequent rainfall disturbs the continuous recession period. Therefore, by selecting two or more recession events and then considering it as single recession events to get master recession curve (MRC), characterizes the behavior of discharge during rainless period (Sujono et al., 2004; Kale and Goyal, 2013). Discrete recession events reflect variability in discharge response subjected to antecedent rainfall and hydrogeological characteristics of aquifer. Brutsaert (2005) suggested that use of long term decay rather than short for analyzing the average value of recession coefficient. Therefore, analysis of MRC provides an average representation of discharge response (Nathan and McMohan, 1990).

There are external and internal factors which influence the shape of hydrograph (Solyom and Tucker, 2004). Physical features, climate variability and land use/land cover which primarily control the net recharge are considered as external factors, whereas the hydraulic properties of aquifer system such as hydraulic conductivity, transmissivity and aquifer thickness are internal factors. Beside the above factors rainfall characteristics such as intensity, spatial-temporal distribution and duration also influence the shape of discharge hydrograph and peak discharge. On assessment of spring hydrograph recession curves located in different geology, it was noted that the behavior of recession curves, such as gradient and slope (i.e., recession coefficients) were mainly influenced by the intensity of rainfall and geometry of fracture system (Kovacs et al,. 2005).

Discharge from springs characterizes combination of the number of hydrogeological processes that decide the total amount of recharge and storage in an aquifer system (Kresic

1997). Spring discharge hydrograph analysis makes it possible to gain information about hydraulic stresses, characterization of aquifer flow, and hydraulic properties of a system (Baedke and Krothe, 2001; Bonacci, 1993). A wide numbers of different techniques such as graphical method, time-series analysis, and spectral analysis techniques have been applied and are reviewed by (Ford and Williams 1989 and White 1988) for characterizations of flow behavior. Kresic (1997) describes step-by-step review of the recession analysis technique. Analysis of recession curve has been progressively drawing the focus of hydrologists and other scientists to predict the flow behavior in absence of rainfall.

The dynamics of spring discharge have been explained and forecasted using hydrograph (Vashishta and Sharma, 2007). Therefore, analysis of discharge hydrograph behavior can be treated as a main signature for the aquifer features. Most of the analysis of a spring discharge hydrograph is based on Darcian theory (Mero, 1963), and the same concept is being used by (Baedke and Krothe 2001; Padilla et al. 1994). The method of characterizing spring flow is based on the equation below, whereby the recession curves of spring hydrographs are analyzed to calculate the value of alpha (α):

$$Q_t = \mathrm{Qo} \times e^{\propto \times (t-\mathrm{to})} \tag{6.1}$$

where: t is any time since the beginning of the recession for which discharge is calculated, t_o is the time at the beginning of the recession, usually set equal to zero, Q_t is spring discharge at time t, Q_o is spring discharge at the start of the recession (t_o), and α defines the slope, or recession constant, that expresses both the storage and transmissivity properties of the aquifer. Recession characteristics are hardly linear and it can be approximated only section wise by linear reservoirs with different retention constant values. The value of the retention "constant" is smaller for the upper part of a recession hydrograph and increases continuously with the recession of the discharge. Thus, there would not only be one k value to describe the recession, but an arbitrary number of different k values.

The behavior of recession curves obtained from spring discharge hydrograph typically reveals the features of flow rate of spring. The fast flow in an aquifer is governed by the presence of conduit inside aquifer systems along with distribution of rainfall over it whereas the low flow is largely governed by low hydraulic conductivity (Padilla et al., 1994). The model suggested by Maillet (1905) has been extensively used (Vogel and Kroll, 1992) but according to Boussinesq (1904) the general behavior of spring discharge is non-linear from aquifer systems. Extensive use of exponential equation is an approximate solution, however the equation solved by (Boussinesq, 1904) is in the form of quadratic and is an exact solution that describe the flow behavior. According to (Dewandel et al., 2003) solution of equation derived by (Boussinesq, 1904) can give quantitative information of aquifer characteristics. The solution obtained from quadratic type (hyperbola) mostly fits the recession behavior, but the solution by linear exponential model overemphasizes the duration of flow depth therefore it underestimates the storage volume of an aquifer system.

Continuous discharge series is also useful in understanding the behavior of aquifer by plotting the flow duration curve (FDC). Estimation of FDC at gauge, partial gauge and ungauged stations in Illinois were developed by (Mitchell, 1957) using drainage area map and flow characteristics. Same concept was also being applied in other different gauging locations to understand the flow behavior (Dingman, 1978). Spring FDC gives the signature of aquifer in term of probability distribution of discharge, therefore it can also be considered for regional studies (Yu et al., 2002). Application of FDC has been used in irrigation planning and other water resources planning (Chow, 1964; Alaouze, 1989). Nowadays FDC have been used to validate the results obtained from hydrologic models such as IHACRES (Hansen et al., 1996).

In this chapter study is organized as follows: firstly behavior of observed daily spring discharge series and its monthly variation has been presented followed by analysis of different recession curve with a newly developed decay relationship and then compare it with the other methodologies that describe best recession curve for Mathamali spring. Secondly, development of MRC using continuous, daily spring discharge data for two water year (2014-15 and 2015-16). Finally, FDC analysis and its implication for spring flow utilization. This kind of investigation has not been performed beforehand for this region. It is believed that present study will give valuable information to evaluate the issues of spring discharge and allow engineers, water resources planner and policy maker to take suitable action.

6.2 SPRING LOCATION AND CONCEPTUAL DIAGRAM

6.2.1 Spring location

The Mathamali spring, which lies in the valley of Aglar watershed, lesser Himalaya, Uttarakhand and it is the only perennial spring available in the vicinity for the domestic water supply. Aglar is sub-catchment for Yamuna basin and lies in the geo-coordinates

N38^{0}25’ to N30^{0}25’and E77^{0}58’ to E78^{0}18’, (Figure 6.1). According to the observed mean daily discharge from 1 February 2014 to 30 June 2016, the Mathamali springs had daily mean average of 14.9 liter per minute (lpm), a maximum discharge of 45.2 lpm (2 September, 2014), and a minimum of 4.7 lpm (28 March, 2014). Rainfall is the primary source of recharge to the aquifer of this region.

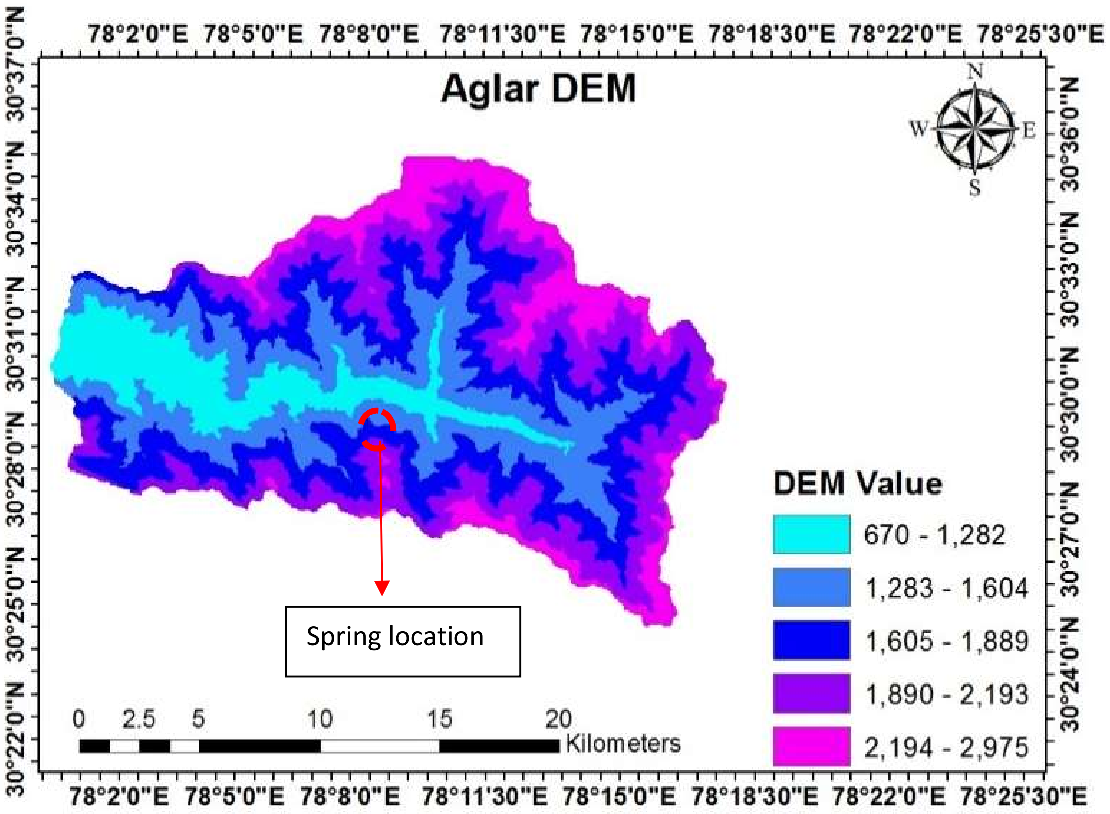


Figure 6.1: Location map of Mathamali Spring

Geology comprises of different types of rocks such as quartzite, shale, lime stone, slate and phyllite (IIRS 1989). Study area falls in the rock of Krol formation which has karst features as they are rich in limestone.

6.2.2 Conceptual diagram of Mathamali spring

The Mathamali spring is gravitational fractured spring, originating from the sequence of rocks which is spread over the surface with layer of colluvial sediments at the base. Top rocks at higher elevation are phyllite and quartzite which results more fracture and allow rainfall to recharge the springshed. The dip direction of rock is in North East with more vertical and inclined fractures which quickly infiltrate the rainfall to reach up to the base (Figure 6.2). The base of the springshed is composed of different grain size and shape having different porosity (ACWADAM, 2009). The drainage from this base depends upon the recharge and hydraulic conductivity.

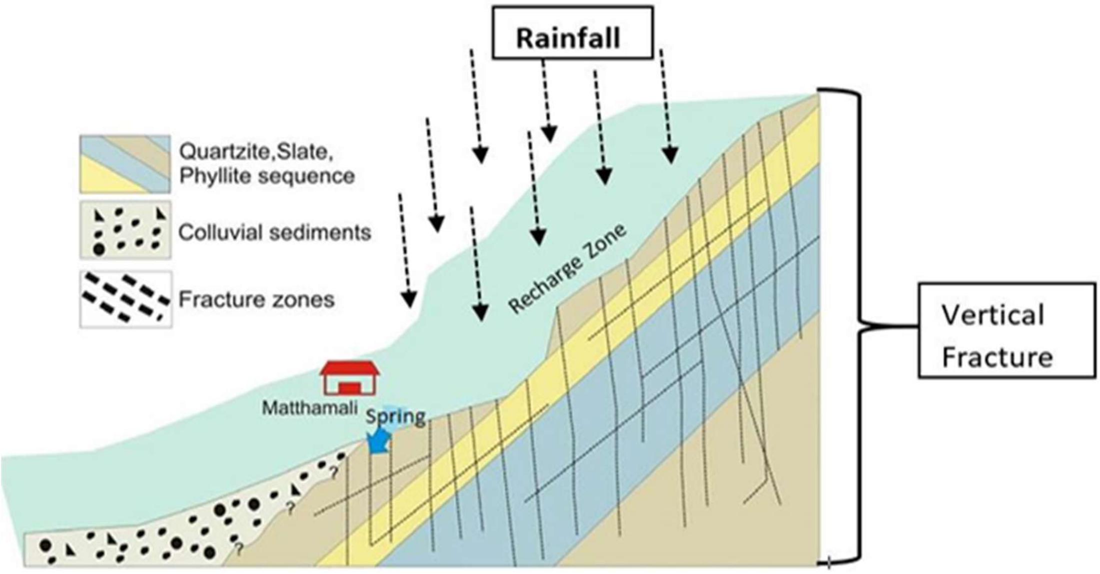


Figure 6.2. Conceptual diagram of Mathamali Spring (*Modified from AWADAM Report, 2009*)

The geological settings permit two types of flow through the aquifer i.e., quick and matrix flow. The initial rainfall is being absorbed by top soil which is having high moisture deficit and with the further rainfall, the soil moisture increases and later rainfall would be allowed to permeate into fracture layers. The water that infiltrate through vertical fracture causes increase in depth of storage and fluctuate according to rainfall distribution and helpful for considering the impact of recharge dynamics. After rainfall, recharge water flows quickly though the fractures and quick flow rate becomes slow through the small pores which dominates the recession behavior. There will be decrease in spring flow after quick recharge because of lowering hydraulic head through the conduit and fracture system.

6.3 METHODS OF ANALYSIS

6.3.1 Data characteristics

Continuous mean daily spring discharge data from February 2014 to June 2016 was monitored from Mathamali spring location (Figure 6.3). From this figure, spring discharge fluctuates regularly and monthly mean discharge varies therefore discharge from the Mathamali spring is non-stationary. The rainfall data was collected from a tipping bucket rain gauge, which is located about 200 m from the location of spring whereas spring discharge level fluctuations was measured using capacitance-based water level recorder with data logger (Odyssey water level, Dataflow System Pty Ltd.) installed in 0.6-inch HS flume (Figure 6.4).

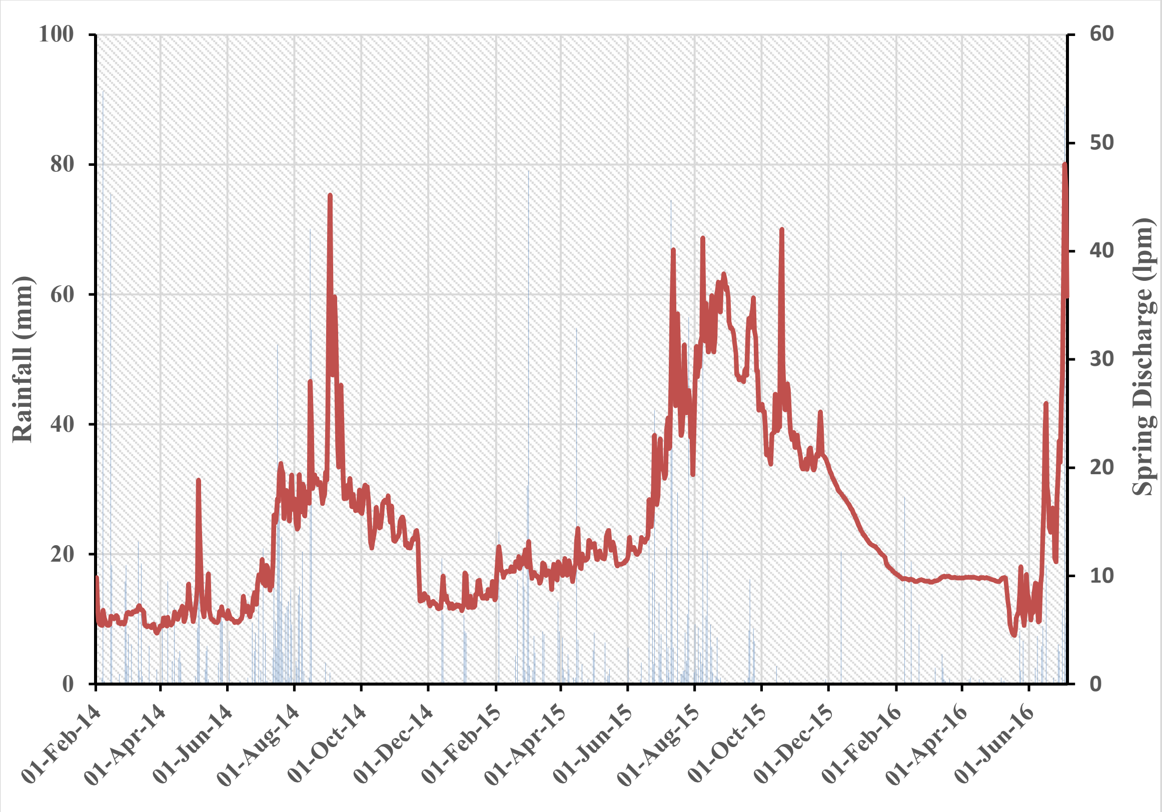


Figure 6.3 Spring discharge and rainfall variation with time

Measured depth by water level sensor was compared with regular manual measurements during each data downloading and a good agreement has been found (± 2 mm).

Figure 6.4: Field instrumentation (a) Tipping Bucket (b) HS Flume with data logger

Seasonal rainfall is most common in July - September and December - January which influence behavior of spring. Rainfall response to spring discharge was weekly correlated ($R^2 = 0.11$), suggesting that geology, recharge rate and antecedent moisture conditions are other factors that might have an influence on discharge. Rising part of hydrograph is generally not smooth as compared to falling part (Figure 6.3) because of increase in spring discharge on basis of uneven recharge rate from different rainstorm intensities. Conversely falling part of hydrograph (recession) is comparatively smooth due to lack of catchment recharge. Therefore, falling part (recession) has been opted for various hydrology related studies (Vashisht and Bam, 2013).

6.3.2 *Data Analysis*

Number of methods has been used in the past for calculating base flow recession (Toebes and Strang, 1994; Gilman, 1977a, 1977b; Stichler and Herrmann, 1982; Youngs, 1985). Four methods have been applied in this study and are briefly discussed below.

6.3.2.1 Simple Exponential

The widely used equation for recession are perhaps of exponential forms in different types (Barnes, 1939; Laurenson, 1961; Knisel, 1963; Toebes et al., 1969; Singh and Stall, 1971; Yates and Snyder, 1975; Anderson and Burt, 1980):

$$Qt = Qo \times \exp\left(-\frac{t}{a}\right) \tag{6.2}$$

where Q_o is flow at a selected time or at t = 0, Q is flow at unit time which is often taken as one day, α is constant and t is time.

A parameter k, called decay factor or recession constant which is calculated by

$$k = -\left(\frac{1}{a}\right) \tag{6.3}$$

The value of recession constant is always less than unity (usually more than 0.9). The constant α is known as storage delay factors and has the dimension of time. For example the constant α denotes the time required for the flow to decrease by a factor equal to e or one natural cycle as shown in Figure 6.5.

6.3.2.2 Least Squares Method

Least squares method was used by (James and Thompson, 1970) to determine the recession constants. Alternatively, equation (6.2) can be written in the form of

$$Q_t = kQ_{t-1} \tag{6.4}$$

and k can be estimated by minimizing

$$R = \sum_{t=1}^{N}[Q(t) - kQ(t-1)]^2 \tag{6.5}$$

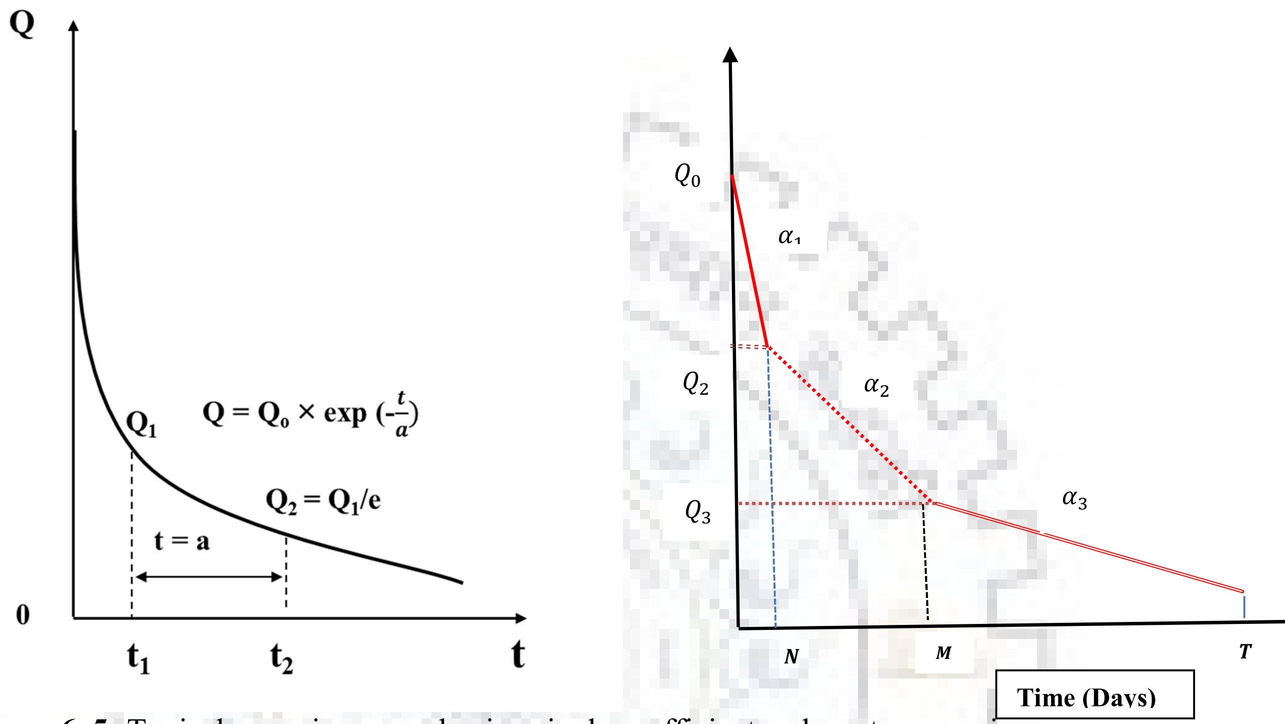


Figure 6. 5: Typical recession curve having single coefficient and master recession curve with three coefficients

Least square estimate of k can be obtained by setting the derivative of R with respect to k equal to zero and solving for the value of k which yields

$$k = \frac{\sum_{t=1}^{N} Q(t)Q(t-1)}{\sum_{t=1}^{N} Q(t-1)^2} \tag{6.6}$$

When we substitute the value N=1 in equation (6.6), result is same as given by equation (6.4). If the data series are free from errors, then this method is a convenient method. (James and Thompson, 1970) further noted that k would be more reliable if the flow sequence is longer and for higher flows.

6.3.2.3 Hyperbola

An equation developed by (Boussinesq, 1904) for the horizontal impermeable lower boundary and having water table in curvilinear shape with zero water level is in the form of

$$Q = \frac{Q_0}{(1+at)^2} \tag{6.7}$$

where a is constant. This equation is more suitable where no further rainfall occurred until flow ceased. Another general equation is derived by replacing the exponent 2 in equation (6.7) by an exponent, for characterizing water table recession in uniform soils drained by parallel drain lines (Young, 1985).

The parameter α, is calculated by

$$\alpha = \frac{1}{t}[(\frac{Q_0}{Q})^{0.5} - 1] \qquad (6.8)$$

However, the value of α in this approach will be influenced by the choice of Q.

6.3.2.4 Combined power law and exponential

Authors' (Amit, 2002 and Blume et al., 2007) claim that using an exponential form with constant recession coefficient (Equation 6.1) represents better recession curve fitting. It is also believed that performance of this simple linear model is more suitable only for homogenous aquifer but non-linear models might be the most suitable for systems having heterogeneity in aquifer. Main cause of this non-linearity in response of spring discharge is the antecedent moisture condition (Wittenberg 1999). Since the recession coefficients are time independent which determined the decay without rainfall, Cheng in (2008) suggested that recession is not only proportional to the discharge itself but it also decrease with time. Authors have developed new program in MATLAB for recession analysis by combining exponential and power-law derived from a non-linear differential equation (6.9) with a variable coefficient and applied for spring discharge recession analysis.

$$Q(t) = C \times t^{-\lambda_1} \times e^{-\lambda_0 t + \frac{\lambda_2}{t}} \qquad (6.9)$$

where λ_0, λ_1, and λ_2 represent the coefficients of the first three orders of decay rate and C is constant. Recession estimation from equation (6.9) is characterized by combination of three forms: normal exponential, power-law and exponential of inverse time. First term, $e^{-\lambda_0 t}$ and the third term, $e^{\frac{\lambda_2}{t}}$ are monotonically decreasing functions of time (t) representing the decay of discharge Q(t) as time increases. Alternatively, equation can be written as

$$log\ Q(t) = C - \lambda_0 \times t - \lambda_1 \times \log(t) + \lambda_2 \times t^{-1} \qquad (6.10)$$

Parameters involved with equation (6.10) can be easily find out by doing regression analysis of logQ(t), against t, logt and 1/t. The correlation coefficient (R^2) later can be applied as a check for overall likelihood fitness.

The choice of methodological decisions, including ones that have received little attention in the literature, can impact parameter value estimates and model goodness of fit. Recession parameter distributions are method-dependent, but roughly catchment-independent, such that changing the choices made about a particular method affects a given parameter in similar ways across most catchments; and the observed correlative relationship between the power-law recession scale parameter and catchment antecedent wetness varies depending on recession definition and fitting choices.

6.3.2.5 Master Recession Curve Analysis

The spring flow is generally recognized to have contributions from ground water and subsurface. Discrete recession events reflect variability in discharge response subjected to antecedent rainfall and hydrogeological characteristics of aquifer. The MRC provide an average representation of discharge response. Mailet (1905) introduces the equation for decay of recession curve, which is given by

$$Q_t = {Q_0}^{e^{-\propto t}} \tag{6.11}$$

The above equation (6.11) is modified for three recession components and decay of continuous spring flow is given by

$$Q_t = \left[\sum_{t=1}^{N} {Q_0}^{e^{-\alpha_{1\times(t-0)}}}\right] + \left[\sum_{t=N+1}^{N+M} {Q_1}^{e^{-\alpha_{2\times(t-N)}}}\right] + \left[\sum_{t=N+M+1}^{T} {Q_2}^{e^{-\alpha_{3\times(t-N+M)}}}\right] \tag{6.12}$$

where, Q_0, Q_1, and Q_2 are initial discharge value before decaying from one component to another and α_1, α_2, and α_3 are the slope of three recession components. Time varies from t = 1 to T (Figure 6.5).

6.3.2.6 Flow Duration Curve

FDC is a commonly used tool in water resources, which gives the graphical representation of frequency distribution of total flow from a watershed. It represents the percentage of duration in which discharge is equaled or exceeded from an aquifer. FDC can be easily constructed for a desired gauging location at daily or monthly time series. Information from FDC can be adopted for water resource assessment which includes design of irrigation system, water supply, design of hydropower and evaluation of flow for ecological balance and many more. The spring flow duration curve is constructed using daily observed spring discharge of entire duration.

Weibull equation is used to determine the spring discharge at different percentages.

$$\text{Pm} = \text{P}\,[\text{Q} \geq \text{q}\,(\text{m})] = \frac{m}{n+1} \tag{6.13}$$

Whereas p_m is probability of exceedance of q (m), q (m) denotes daily observed spring discharge, m is the rank obtained after arranging all the discharge data in decreasing order, and n is the number of data. The x-axis of FDC represents the percentage of time that a certain discharge value is equaled or exceeded whereas y-axis signifies the flow quantity associated with the given duration. In FDC, on x-axis zero indicates the maximum discharge value in the observed record and 100 corresponds to the minimum discharge value. For example, a flow duration interval of 25% related with a spring discharge of 18.6 lpm (liter per minute) suggests that 25% of all observed daily average spring discharge values equal or exceed 18.6 lpm.

6.3.2.7 Performance evaluation

The method for evaluating the performance of applied recession approaches requires to make estimates of the "closeness" of the modeled behavior to the observed discharge. Model efficiency criteria is defined as mathematical measures of how well a model fits with the observed values (Moriasi et al., 2007). The ability to forecast accurate spring discharge with appropriate choice of methodology helps in taking decision during dry periods. In this study performance of best fit observed recession curve by linear and nonlinear recession approach are assessed by

a) *Coefficient of determination* (r^2)

$$r^2 = \frac{\sum_{i=1}^{n}(O_i-\bar{O})(P_i-\bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i-\bar{O})^2}\sqrt{\sum_{i=1}^{n}(P_i-\bar{P})^2}} \tag{6.14}$$

b) *Nash-Sutcliffe efficiency* (NSE)

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i-P_i)^2}{\sum_{i=1}^{n}(O_i-\bar{O})^2} \tag{6.15}$$

c) *Root Mean Square Error (RMSE)*

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i-P_i)^2}{n}} \tag{6.16}$$

where O_i is observed discharge and P_i is predicted discharge through model at time *i.* and $\bar{P}$ and $\bar{O}$ are mean of observed and predicted discharge.

6.4 RESULTS AND DISCUSSION

6.4.1 Spring flow analysis

The daily observed discharge and rainfall of the Aglar watershed is shown in Figure 6.3. The quick response of spring discharge towards the rainfall can be easily identified by peak of rainfall and spring discharge which shows discharge begins to respond to rainfall after 1 or 2 days. The spring discharge response is varying from season to season because of recharge and drainage properties of aquifers leading to heterogeneity in the aquifer system. The monthly variation in maximum, minimum and average spring discharge proves the dynamic behavior of discharge (Figure 6.6). Intra-annual recession during the wet season (July–September), interrupted by the rainfall and recharge processes progressively increase the water table level of the aquifer. The monthly variation in maximum discharge (7.3 – 5.2 lpm) indicates varied flow. Average domestic water requirement as per Bureau of Indian Standards, BIS (2003) for adults is 45 l/d and 25 l/d for minors. However, on an average observed daily available spring discharge is calculated as 21,600 liters and a large amount of discharge from spring goes unused during night (12,600 liter).

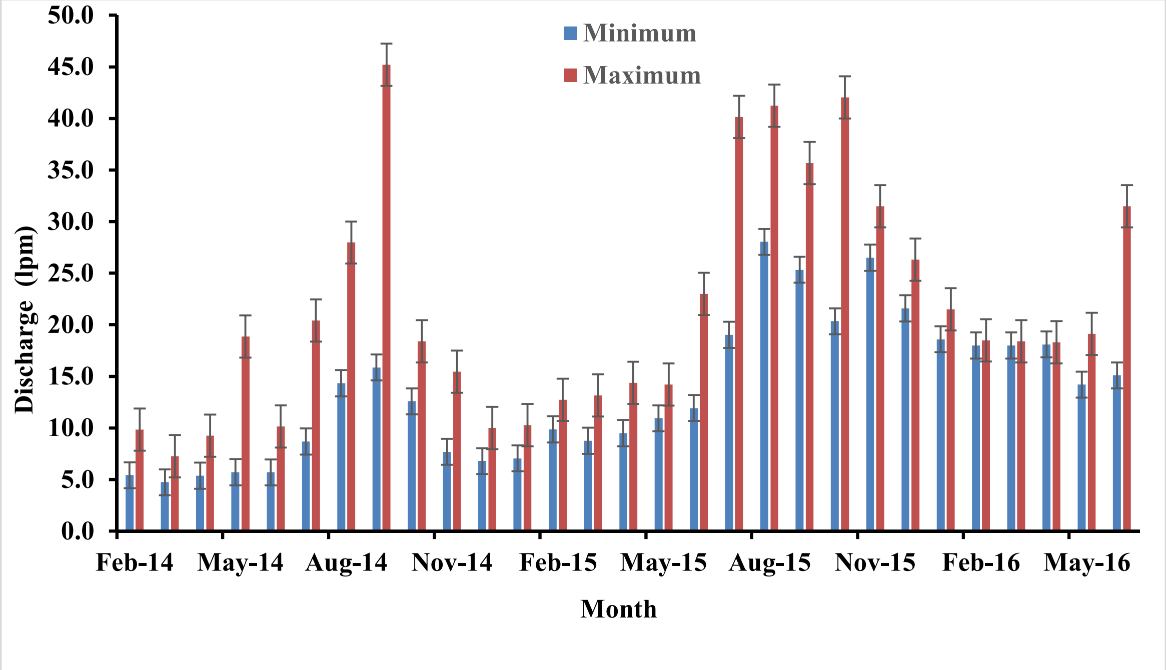


Figure 6.6: Plot of monthly minimum and maximum discharge variation of spring

Therefore, the surplus water (daily unutilized during night) could be stored and properly managed during dry periods or it could be supplied to water deficient nearby areas. The spring discharge was higher in the months of (July–September) suggesting that infiltration and transmissivity was relatively more as compared to remaining months of the year.

6.4.2 Recession curve analysis

One of the main factors which is required for the estimation of flow behavior in an aquifer system is the recession rate of discharge. Therefore, to understand the recession behavior of Mathamali spring, from the daily observed discharge series, major 10 events were selected. Each event has been selected only when the daily average discharge falls continuously for a period of at least 5 days and no rain within this period. The recession rates of 10 events varied between 9 and 97 days, showing heterogeneity in aquifer response. It was also observed that conversion of rainfall to spring discharge differ significantly in dry as well as wet period (Table 6.1). Further to say that, these temporal variations in recession rate not only depend on rainfall but also the capacity and permeability of porous media. These recession events have been categorized into quick flow events (1, 2, 5, 7 and 9) whose storage value (*k*) varies between (9– 32) days and long flow events (3, 4, 6, 8 and 10) having *k* values between (38 – 97) days. Higher storage value for long flow events reflecting that aquifer have more holding capacity after the rainfall during the wet period. Identification of this relationship is hindered by lack of geological data in this region. Kinsel (1963) pointed that relationship between recession and geological factors is complex and influenced by aquifer connectivity with surface water and degree of fracture.

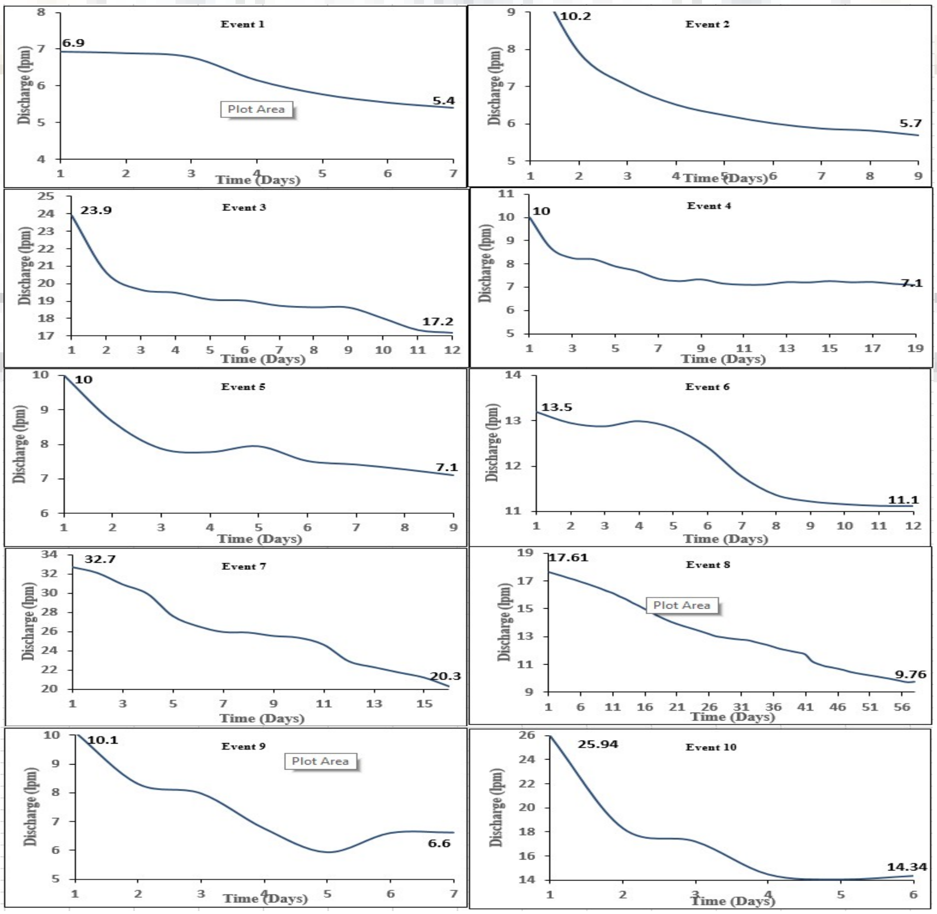


Figure 6.7: Different shape of recession events

As it can be seen from (Figure 6.7) each recession event is almost concave, indicating non-linear reservoir behavior. However, changes in the recession coefficient from event to another event, indicate a dependence on the antecedent rainfall conditions, and spring initial discharge (Q_0). Description for recession curve variability because of evapotranspiration, initial storage and antecedent rainfall is well described by Riggs (1964). Winter recession curve (events 4 and 8) usually have longer recession duration than the summer recession curve because of not only evaporation loss but inclusion of interflow component during summer and in winter it reaches to base flow condition.

Variation in recession coefficient of Mathamali spring shows different behavior as it has been observed in Bagnara spring located in Italy having same average rainfall characteristics and recharge area which shows that the spring always follows the same exponential decay (Angelini and Dragoni, 1997). Recession events during winter (4, 5 and 8) are significantly different from the summer because of environmental phenomena associated to low temperature (Russo, 2015). The large value of recession coefficient (α) for events (1, 2, 5, 7, and 9) having recession duration low as compared to events (3, 4, 6, 8 and 10) signifies quick drainage with little storage. Higher α value (more than 0.031) probable provides degree of fracture and internal connectivity and lower value of α (less than 0.031) correspond to the base flow condition. Different values of α in the same catchment shows the existence of heterogeneity in aquifer system (Petras, 1986). Temporal variability of α during inter-seasonal recession provides signature of geological fracture. Different initial discharge in recession events shows dependency on antecedent rainfall condition as it can be seen that events (2, 4, 5 and 9) have almost same initial discharge of 10 lpm but values of recession coefficient varies between (0.013-0.071) because of antecedent rainfall. Other than the antecedent rainfall for these events, rate of evapotranspiration for event (2 and 9) during summer was more than the event (4, 5 and 8) during winter which effect on infiltration rate. Past rainfall and evapotranspiration together with other geological process makes distinct recession rate in different season (Figure 6.7).

The values of α for all events in studied spring is higher than the values of spring studied by Padilla et al. (1994) in four different karst springs. This could be due to different lithology and others hydro-geological parameters. Rate of decrement of daily spring discharge for recession events (1, 4, 5, 6 and 8) is less (0.09-0.23) as compared to events (2, 3, 7, 9 and 10) which vary between (0.35– 1.9). This is probably due to the dry periods where change in hydraulic conductivity of partially saturated medium decreases with decrease in moisture content (Fetter 1988). Recession events 2 and 10 particularly recedes from peak to base (44%) much faster, because the catchment had experienced two major rainstorms (13.3mm and 50mm) and three rainstorms (5.9mm, 8.9mm and 18.4mm) for events 2 and 10 respectively prior to recess and aquifer storage became fully saturated, so all rainfall has contributed to spring discharge during these recession events. Recession event 8 also recedes 44% but it took duration of 58 days because the major rainfall occurs (20.4mm) in a day and it happens after a long period. Behavior of recession event 4 and 8 is entirely opposite to recession event 2 and 10 which recedes slowly and has long recession period about 19 and 58 days respectively. Due to the long dry spell (no rainstorm) of more than 45 days, all the rainfall (20.4mm) for event 8 and (30.1mm) for event 4, which occurred before the recession infiltrated the system and took time to respond and had an average recession rate of (0.144 lpm/d) which delayed the recession.

Storage discharge relationship $-dQ/dt = aQ^b$ obtained by Brutsaert and Nieber (1977), further confirms the dynamic nature of Mathamali spring behavior. A plot between $-dQ/dt$ $[(Q_j-Q_{j+1})/\Delta t]$ and Q $[(Q_j+Q_{j+1})/2]$ for each recession events has different values of a and b (Figure 6.8). The subscript j and j+1 are time value at t and $t + \Delta t$, and the value of Δt is one for all the recession events. In this figure plot for $-dQ/dt$ and Q, for events (3, 6, 7 and 8) value occupy the right side which means that $-dQ/dt$ vs Q has lower a value as compared to events (1, 2, 4, 5, 9 and 10). Different values of "a" indicate different physio-climatic process which governs the system. The decay for events (3, 6, 7 and 8) from peak discharge are more than 10 days indicating low hydraulic conductivity as compared to events (1, 2, 5, 9 and 10). The scarce behavior of event 4 is because of less evapotranspiration (ET) during the month of winter. Higher potential evapotranspiration during April-June have low soil moisture and storage (Miller et al., 1983), whereas during the July-September, rainfall compensate the evapotranspiration loss and it infiltrate to recharge the aquifer. If the aquifer is wet then it would have less value of "a" and vice versa. The different value of *k* can be linked with changes in the hydraulic gradient due to variation in evapotranspiration (Datta et al., 2012).

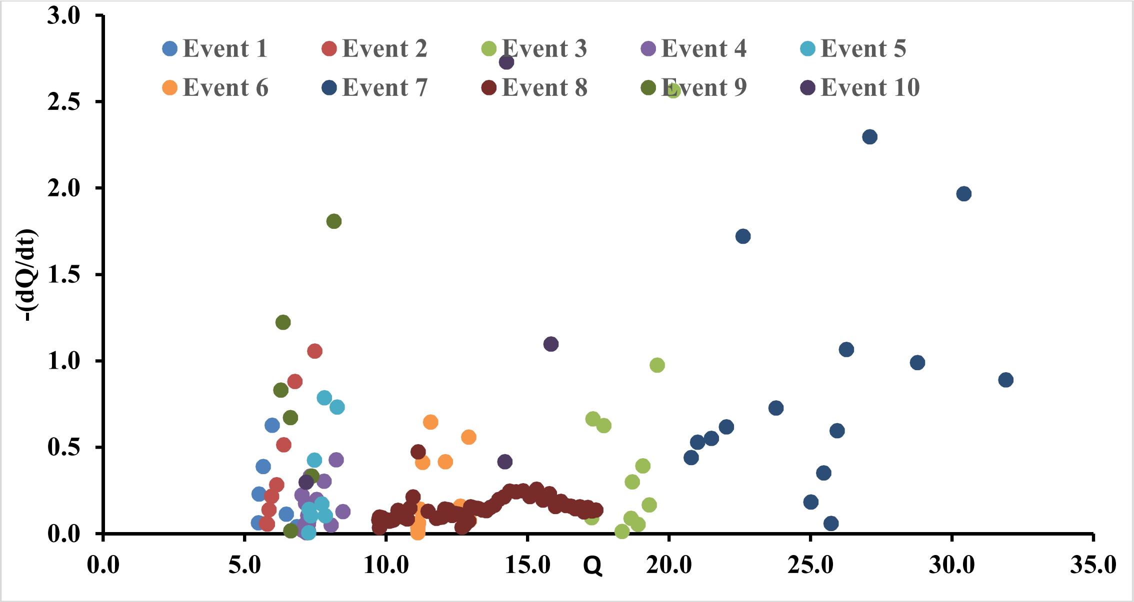


Figure 6.8: Plot between –dQ/dt and Q curve for all recession events

The different value of "a" could also be related to theory of active drainage network (Biswal and Marani, 2010) and geomorphic properties or drainage density (Tague and Grant, 2004). The linkage between value of "a" and previous discharge indicates the ability of aquifer to store water. The coefficient of correlation between aquifer storage and observed spring discharge for all events are weak and varies between (0.17 – 0.51). The reason could be that in subsurface flow there is uneven hydraulic conductivity and thus water distribution shows distinct behavior (Sophocleous, 2002).

It has been mentioned that antecedent rainfall influences the hydrograph as well as plays an important role in aquifer recharge (Fiorillo and Wilson, 2004). The 5-day antecedent rainfall and one day maximum rainfall for all recession events has been summarized in Table 6.1. A rainfall event with long duration, low rainfall intensity characteristics produces high degree of recharge (Sen et al. 2010). For the present study, the events were classified into two groups (A and B) on the basis of rainfall distribution. Dry season are considered in group A and wet season in group B. Influence of these rainfall conditions on the recession timing and decay of spring discharge yield is summarized in (Table 6.1).

Table 6.1. Summary of recession events and rainfall observed at Mathamali spring

Event No.	Recession Duration (Days)	5-day Antecedent rainfall (mm)	1 day Max. Daily Rainfall (mm)	Recession Curve		Recession Group
				Start (lpm)	Finish (lpm)	
1	14-20 Mar. 2014 (7)	24.0	21.9	6.9	5.4	A
2	14-22 May 2014 (9)	13.3	5.9	10.2	5.7	B
3	16-27 Aug. 2014 (12)	71.7	70.1	23.9	17.2	A
4	14 Dec. 2014 -01 Jan. 2015 (19)	19.4	19.4	10	7.1	A
5	04-12 Jan. 2015 (9)	10.7	10.7	10	7.1	B
6	15-26 May 2015 (12)	9.0	6.4	13.2	11.1	A
7	24 Sept. -09 Oct. 2015 (16)	34.2	16.2	32.7	20.3	B
8	12 Dec. 2015 -07 Feb. 2016 (58)	20.4	20.4	17.61	9.76	B
9	29 May – 04 June 2016 (7)	8.6	8.2	10.1	6.6	A
10	16 – 21 Jun 2016 (6)	33.2	18.4	25.94	14.34	A

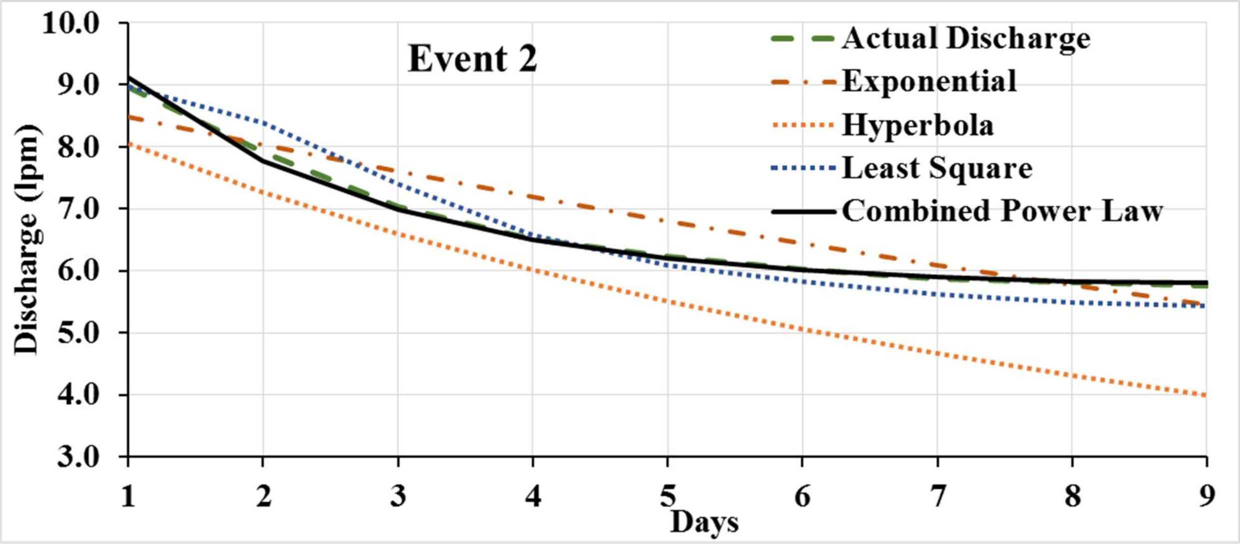
The behavior of individual recession curve is varying with different methodologies. The difference in the recession behavior for each event depends on the aquifer storage and time gap between two rainfall events. Widely adopted methods for analyzing recession curve such as simple exponential, least square, hyperbola and newly developed combined power law and exponential approach have been applied for understanding the Mathamali spring discharge behavior. Performance evaluation such as RMSE, r^2 and NSE criteria were applied for all four approaches to assess the performance of these recession models. Performance of predicted spring discharge with observed spring discharge is summarized in (Table 6.2).

Results indicate that the non-linear method, for example, least square method for wet season and combined power law and exponential for dry season, in which the recession parameters is related to the preceding flow magnitudes, provides a considerably better fit to the observed spring discharge data than that of the simple exponential and hyperbola method. In combined power and exponential method, the exponential component takes care of the base flow during the dry season whereas during the wet period often flow don’t reach to base flow condition.

Table 6.2. Comparison of model performance

Event No.	Exponential			Hyperbola			Least Square			Combined Power Law		
	RMSE	**NSE**	**r**	**RMSE**	**NSE**	**r**	**RMSE**	**NSE**	**r**	**RMSE**	**NSE**	**r**
1	0.44	0.53	0.96	1.12	-0.24	0.95	0.19	**0.9**	0.95	0.35	0.66	0.83
2	0.43	0.83	0.92	1.05	-0.03	0.96	1.08	0.93	0.98	0.07	**0.99**	0.99
3	0.69	0.65	0.93	2.54	-1.7	0.91	0.21	**0.99**	0.99	0.44	0.94	0.96
4	0.37	0.52	0.86	0.67	-0.19	0.89	0.14	**0.94**	0.97	0.37	0.35	0.85
5	0.31	0.77	0.9	0.94	-1.01	0.92	0.28	0.82	0.94	0.21	**0.99**	0.95
6	0.27	0.91	0.97	1.24	-0.95	0.96	0.22	**0.95**	0.97	0.91	0.55	0.73
7	0.75	0.96	0.98	4.69	0.7	0.98	1.81	0.78	0.9	0.56	**0.97**	0.99
8	0.23	0.99	1.00	2.35	0.14	1.00	0.07	**1.00**	1.00	0.18	0.99	1.00
9	0.66	0.75	0.89	1.24	0.13	0.92	0.62	0.77	0.92	0.44	**1.00**	0.94
10	1.81	0.81	0.90	3.85	0.13	0.94	1.79	0.79	0.93	0.53	**0.99**	0.99

However, event 6 and 10 shows distinct behavior because of intermittent wet condition. With the rise in the depth of the aquifer system, discharge from aquifer increases (Mero, 1963) and this is confirmed by the solution proposed by Jacob (1943) for Darcian flow in aquifer. However, analysis of recession curve of Mathamali spring proves that nonlinear fitting by least square and combined power law and exponential fits the recession curve better than the widely used exponential and hyperbola method (Figure 6.9).



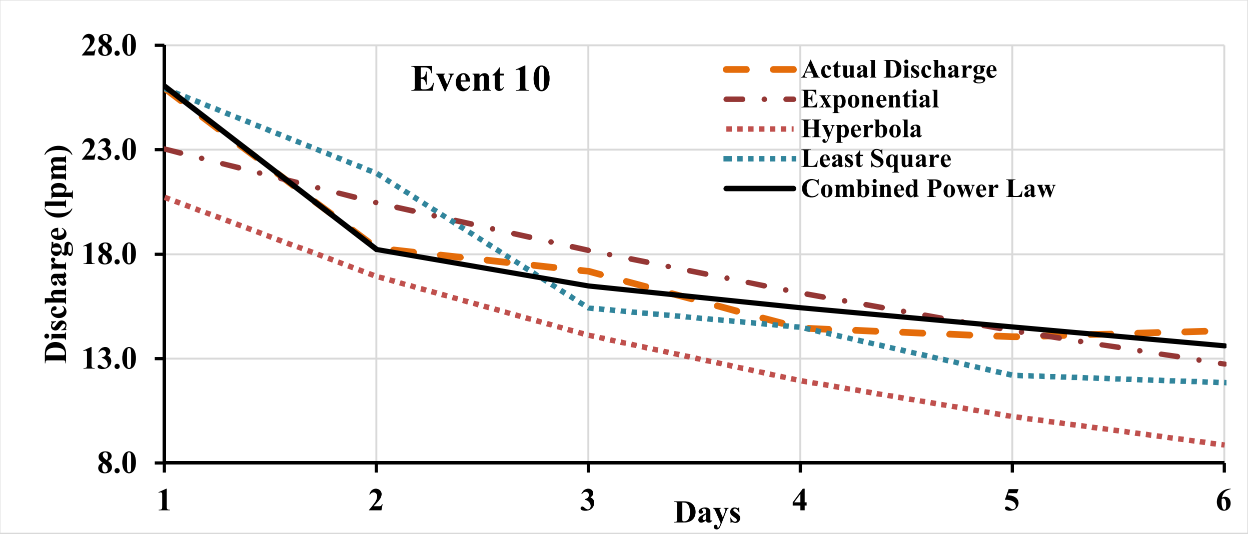


Figure 6.9: Temporal variation of forecasted and actual flow for recession event 2 and 10

Recession behavior was over-estimated by exponential method whereas it was under-estimated by hyperbola approach. The spring discharge at Mathamali varies from 5lpm to 45lpm with a mean discharge of 15lpm, which is almost same as that of a spring discharge measured at Pauri (13lpm) having similar geological characteristics (Tarafdar, 2013). The high, mean and low flow from spring should be quantified accurately so that it can help me evaluating dependable minimum available water during dry period and surplus flow during monsoon (Mero, 1963). However, the variation between the observed minimum and maximum spring discharge with (Tarafdar, 2013) is large comparatively. The quick recession of spring discharge at Mathamali suggests that the spring has restricted storage capacity because of large fractures in aquifer system with more permeability. On the basis of observed hydrograph shape during the recession period the hydraulic behavior of the aquifer can be estimated during dry periods and droughts (Fiorillo et al., 2007).

6.4.3 Master Recession Curve Analysis

Considering the importance of master recession curve (MRC) as discussed in earlier section and to understand the behavior of spring flow an attempt has been made to develop the MRC for the study area using daily spring discharge value for two water year (2014-15 and 2015-16). After selecting the recession period for both year and applying the exponential decay law with two and three exponent components as described in equation 6.12, it was found that the recession curve is well fitted by three components rather than two exponential components (Figure 6.10). Three different exponent represents the heterogeneity of the aquifer. The recession curve for these two years shows different behavior because of rainfall intensities and antecedent rainfall conditions as summarized in Table 6.3.

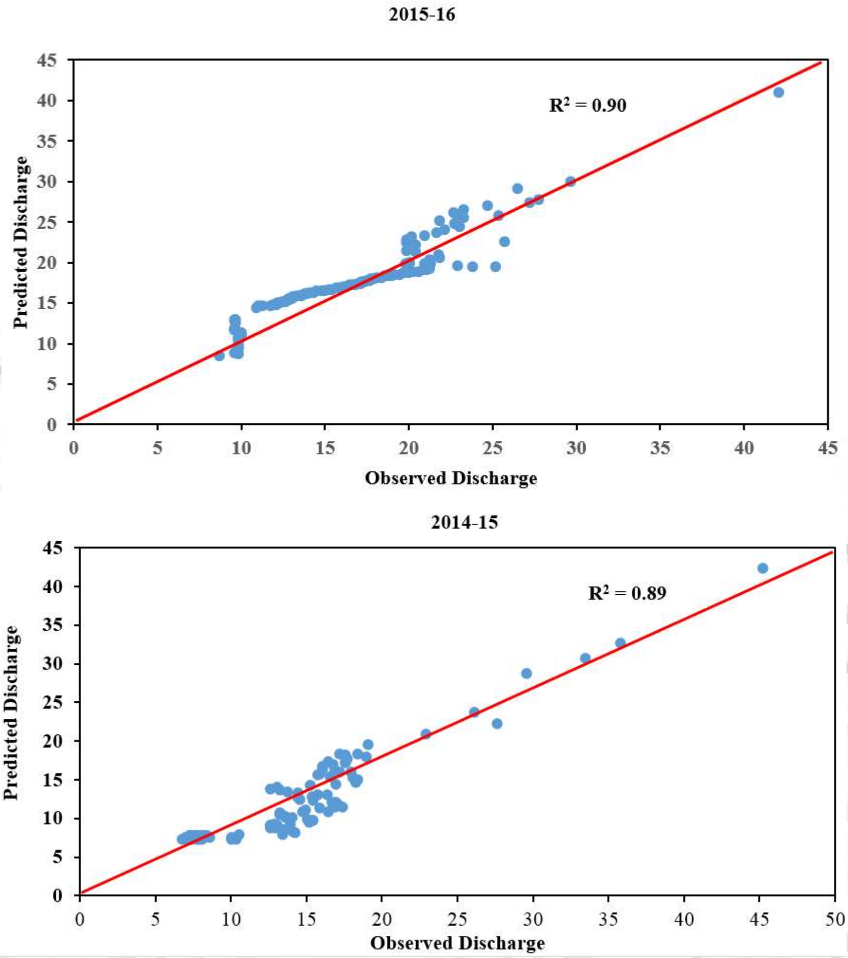


Figure 6.10: Results from master recession curve for water year 2014-15 and 2015-16

Table 6.3. Summary of MRC and rainfall observed at Mathamali spring

Year of Recession	**Recession Period**		Duration (Days)	Rainfall (mm) during recession	**MRC constant**		
	From	To			**α_1**	**α_2**	**α_3**
2014-15	2-Sep-14	10-Jan-15	131	59.2	0.0646	0.0129	0.0014
Discharge(lpm)	45.2	7.3					
2015-16	19-Oct-15	11-May-16	206	97.66	0.1236	0.0141	0.0048
Discharge(lpm)	42.04	8.62					

Further analysis shows that the values of recession coefficient (α_1) for the both year are high as compared to (α_2) and (α_3), which indicates the turbulent flow in a fracture and conduits because of rainfall, followed by transitional flow in which the flow is in between turbulent and laminar and reflects flow from small fractures and rock matrix because of rainfall and ground water (Shoemaker et al., 2008). The top area of spring aquifer has higher hydraulic conductivity because of more fracture development. The last coefficient α_3 represents the base flow condition which reflects the dominance of diffuse flow. Since the rainfall in year 2014-15 as compared to 2015-16 is 40% less so recharge of the spring is less which leads to lower the values of α_1 as compared to year 2015-16. With the almost same initial discharge (45 lpm), time to recess to its base in water year 2014-15 (131 days) is 36% less as compared to year 2015-16 (206 days) because of more recharge during the dry period increase the base of the recession curve. Change in the ratio of recession coefficient (α_1/α_2) from 5 to 8.76 and (α_2/α_3) from 9.21 to 2.9 shows the dynamic behavior of aquifer storage. The change in these ratio could be related to change in the effective porosity (Fiorillo, 2011). The lower value of α_3 suggest the low hydraulic conductivity thus have long tail which represents the slow depletion. Discontinuity in recession curve is because of decrease in effective porosity of colluvium sediment present at base.

6.4.4 Flow duration analysis

Flow duration curve is constructed using daily spring discharge data which offers comprehensive way of observing flow duration characteristics of a spring or stream. Figure 6.11 shows the flow duration curve for both water years of Mathamali spring. The rate of change of flow behavior can be interpreted from the slope of duration curve where a flat slope at the tail of Figure 6.11 indicates a slow response of the catchment to rainfall in this region.

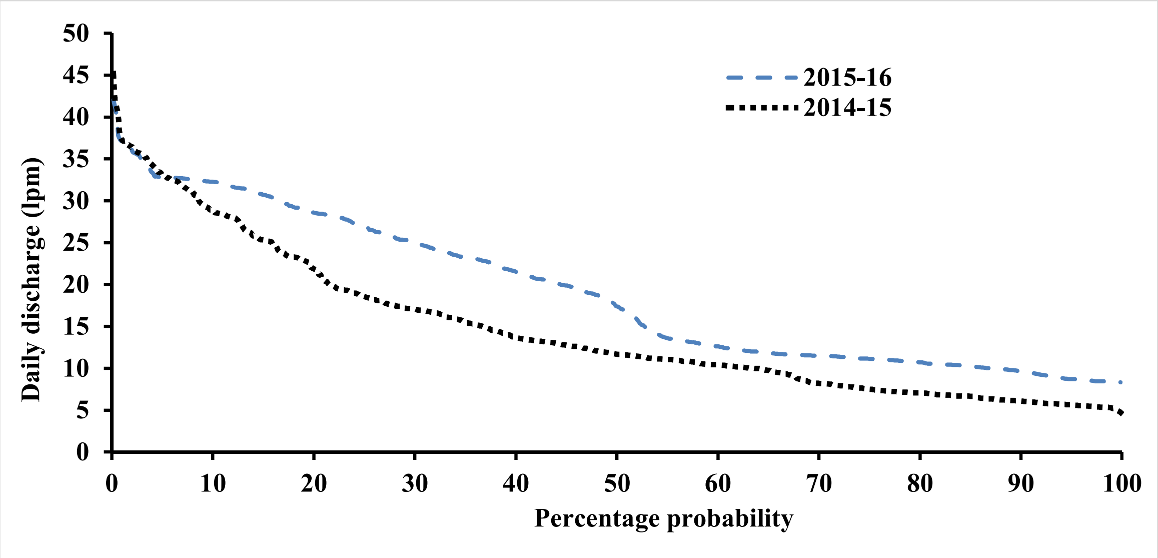


Figure 6.11: Flow duration curve of Mathamali spring

The largest volume from the spring is available during the monsoon period followed by non-monsoon period. Further analysis of the monthly cumulative spring discharge during the monsoon period (July to September) is about 73% of the total spring discharge. This clearly shows a reasonable seasonality in the spring discharge, which is common in such region where rainfall has a significant role.

The duration curve is often used to describe the nature of discharge (flashy or steady). A full year discharge data must be used to make sure that a wet winter period included without the corresponding dryer summer to balance the resulting FDC. Discharge between 1st percentile (Q_1) and 10th percentile (Q_{10}) are considered high flow in which flow correspond to Q_1 would be extreme high flow. Discharge between Q_{10} and Q_{70} would be medium range of flow and discharge from Q_{70} and Q_{100} are the low flow and important for dry period studies. It is observed from figure that average Q_{90} of observed discharge data is less than 30.6lpm which can be taken as the characteristic value for minimum spring flow. This minimum flow data can be considered while framing policy and to address the low flow situations for this type of aquifer system.

6.4.4.1 Domestic water availability

The total domestic water requirement from Mathamali spring for around 300 dependents of nearby villages (200 adults @ 45 l/d and 100 minors @ 25 l/d) is 11,500 l/d. FDC as shown in (Figure 6.12) further revels that daily spring flow is 72% more than required domestic water and 28% less than required domestic water demand indicating water scarcity during dry seasons. Maximum time the spring flow is in surplus which can be stored or transfer to other place. A storage tank can be constructed to store this surplus water and can be utilized it during dry seasons. Further this surplus water could be harnessed for irrigation directly or by conserving it in storage tank.

High and low flow variability of the spring flow measured by the ratio of (Q_{10}/Q_{90}) and (Q_{50}/Q_{90}) (Tarafdar, 2013), which were 4.7 and 1.9 indicating low variability in Mathamali spring. Tail of the FDC is flat which shows weak response of spring with rainfall during dry periods and indicates perennial storage which provide scope to understand low flows which is considered as challenging task for water resource professionals (Milly, 1993). Seasonal analysis of FDC (Figure 6.13) reveals, maximum flow is during monsoon time followed by post monsoon and minimum flow during pre-monsoon time.

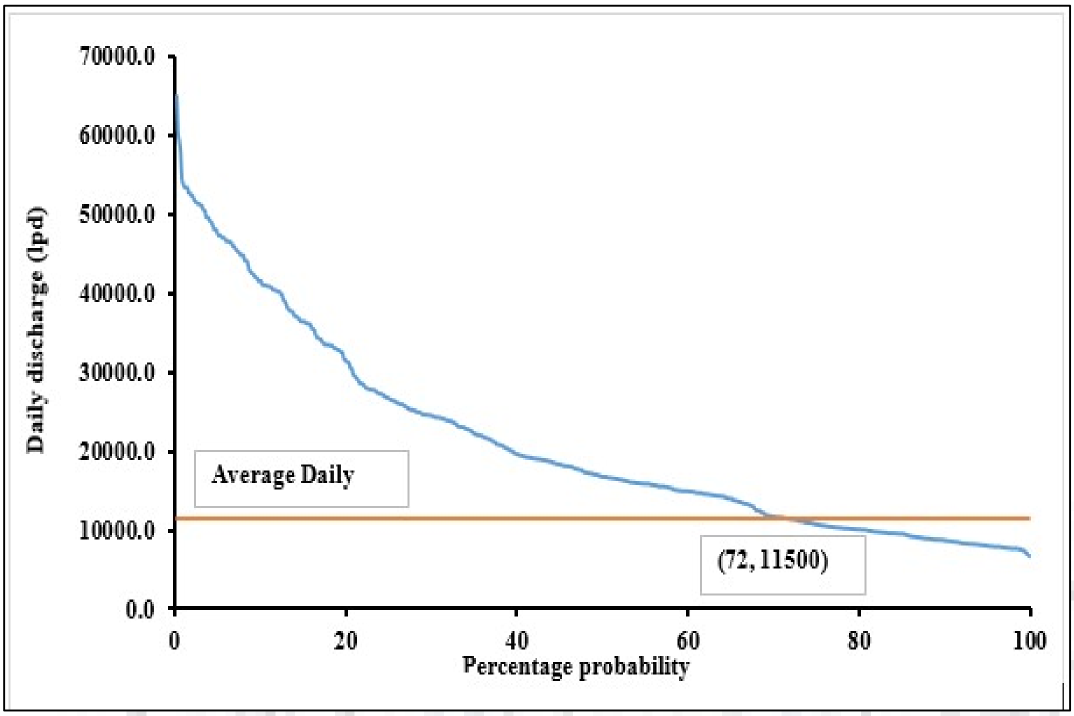


Figure 6.12: Percentage of time indicating discharge was equaled or exceeded

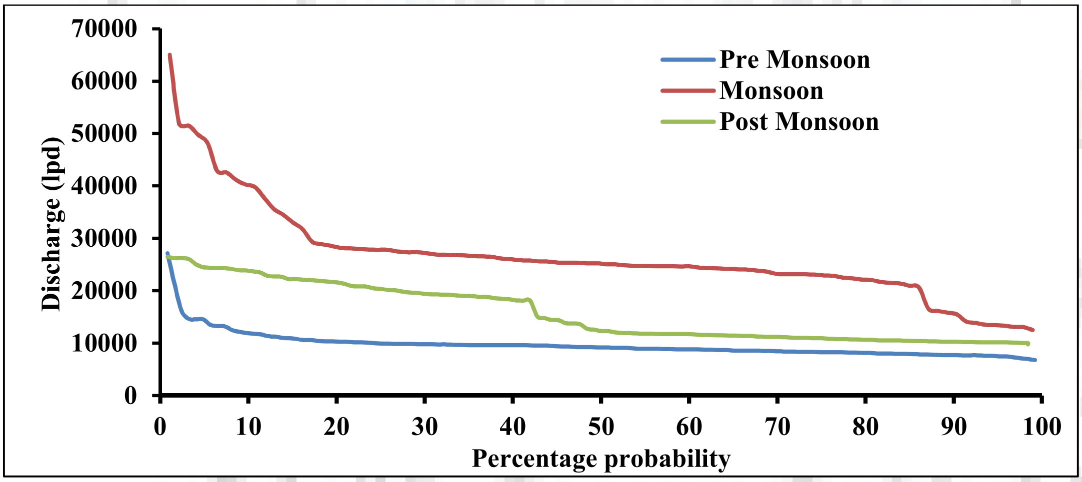


Figure 6.13: Seasonal flow Duration curve of Mathamali Spring

Further to this, it is important to note here that monsoonal FDC shows availability of surplus spring flow during whole duration as compared to pre and post monsoon. Tarafdar (2013), worked out the same in Pauri region of Himalaya and showed that monsoonal FDC is having surplus water less than 40-50% time the exceedance for the monsoonal period.

6.5 CONCLUSION

Understanding of spring behavior in this study is addressed through recession curve analysis. The literature proves the significance and validation of exponential equation and the hyperbola to fit the recession curve but in this study nonlinear least square and a newly developed combined power law fits the recession curve better than the exponential and hyperbola. Analyzed results provide a discharge decay function which helps to gain hydrological significance. Maximum value of recession slope for the present study is 0.06 which is quite more than the Ranichauri spring (0.02) located in same district (Tehri Garhwal) but in different geological location. Least square method best fit for wet period events (1, 3, 4, 6 and 8) with RMSE (0.07-0.22) and NSE (0.90-1) whereas combined power law best fit with observed discharge for dry period events (2, 5, 7, 9 and 10) with RMSE (0.07-0.56) and NSE (0.97-1). It is thus concluded that recession analysis by nonlinear approach provides better result than linear approach for Mathamali spring located in lesser Himalayan Aglar watershed. Analysis of MRC support the use of three exponential coefficients over the use of single exponential coefficient.

On comparison it is also found that recession parameters not only depend on initial discharge but depend on other hydro geological parameters such as evaporation, interaction of water and soil etc. The varying recession behavior of spring discharge may be due to the soil moisture movement, hydraulic conductivity and storage of an aquifer. Analyzed monthly cumulative spring discharge during the monsoon period (Jul.-Sept.) is about 73% of the total spring discharge. Flow duration curve revels that daily spring flow is 72% more than required domestic water and 28% less than required domestic water demand indicating water scarcity during dry seasons. Further analyses of flow duration curve reveals that 90 percentile of observed discharge data is less than 30.6 lpm which can be taken as the characteristic value for minimum spring flow. Planning for proper storage during rainy season and utilization of stored spring water is recommended. Along with this a system to transfer stored water based on requirements, from excess areas to shortage areas, through gravity flow or by pumping, whenever required by seasonal shortages is recommended. Water harvesting structures could be installed to store rainwater in monsoon months in order to increase the flow in selected springs. This study can also be used for long and short term planning to address the water resource issues in this watershed and for comparing the spring characteristics at other mountainous watershed.

CHAPTER 7

SPRING POTENTIAL FOR SUSTAINABLE AGRICULTURE

7.1 INTRODUCTION

With more than 1.2 billion people, India is the second most populated nation on the earth. There are increasing issues of water scarcity and access to fresh water to many people living in the rural areas because of the burgeoning population, urbanization, climate change, etc. The availability of water in India has decreased by 53% and is expected that by 2025 it will further decrease to 72% (Engelman et al., 1993). Water demand for agriculture continues to dominate and is projected that required water for agriculture by 2050 will increase by 11% (Postel, 2003). In mountainous regions, where rainfall is intense leads to scarcity of water needs to secure. Security of water and food for these people unquestionably needs to guarantee of their domestic water supply, water for agriculture, water for livestock, and other exercises needs (Vashisht, 2012). To fulfill the food requirements of the increasing population, expansion of agricultural production and sustainable management techniques are required (Rockstrom et al., 2009). In India, about 45% live in rural areas and 250 crore people rely on agriculture for their source of income and livelihood. Thus, one of the major challenges lies in the proficient management of available water with decentralized responsibilities and local authority to transmit the excess water to water scarce areas (James, 2003). Availability of water at any location is also governed by spatial and temporal climatic conditions (Hammer et al., 2001). In many locations, agricultural water resource accessibilities have suffered from the absence of the right amount of rainfall and its irregular temporal variation (Garg and Dadhich, 2014; Fereres et al., 2011). Varela-Ortega et al. (2011) suggested that climate variability would unfavorably affect the recharge of the soil surface and agriculture productivity. Variability in the rainfall intensity moreover disturbs the overall crop and land productivity of poor and low land holdings whose dependency is on rainfed agriculture (Fauchereau et al., 2003). Climate change will also increase water demand for agricultural and crop evapotranspiration requirements (Lehmann et al., 2013) and affect crop yield and productivity (Palazzoli et al., 2015; Sarker et al., 2012). Reduction in crop yield for different crops because of climatic and other variables such as shortage of rainfall, waterlogging, soil issues are reported by (Askri et al., 2010; Grassini et al., 2007; Jacobsen and Adams, 1958). Therefore, for the management of agricultural productivity and decision making policies require an understanding of agricultural water requirement and its availability (Singh et al., 2007). Furthermore, the water requirement of a particular type of crop in mountainous regions is normally varied and dependent upon the rate of evapotranspiration (ET_0).

Evapotranspiration is the quantity of water which is lost to the atmosphere by the combined process of evaporation and transpiration and its estimation plays an important role for valuation of crop water requirement (Vicente-Serrano et al., 2014; Jain, 2012, Zotarelli et al., 2010). Management strategies for crop planning with increasing crop productivity and water resources varies with different ET_0 values (Brauman et al., 2012) therefore it is essential to accurately estimate the ET_0 values. The common ways to estimate ET_0 are the physical models which require meteorological parameters (Khanal et al., 2013). The estimation of ET_0 from meteorological parameters require an evaluation of a large number of variables and is often difficult to obtain (Christiansen, 1966; Burman, 1976). To estimate ET_0, FAO-56 suggested an approach based on the Penman-Monteith (PM) equation (Allen et al., 1998). The FAO-56 method is physically-based and does not need any correction in its parameters hence, is used globally (Pereira et al., 2015). Artificial neural network is also gaining attention now days in the estimation of ET_0 (Sudheer et al., 2002).

In the Himalayan, the use of water for a small land holder for agriculture and domestic need warns the people to optimize the use of land and water for sustainable development as well as food security (Hellegers et al., 2013). Further, the decreasing trend of rainfall over the previous years (Khandelwal et al., 2015) has threatened the agriculture productivity. The situation of water scarcity will further intensify if the current trend of decreasing rainfall continues, therefore well utilization of the available water becomes a paramount issue. Optimization of the agricultural area and enhancement of water availability are considered as one of the vital parameters to resolve the scarcity and uneven use of water (Moradi-Jalal et al., 2007; Femeena et al., 2018). Georgiou and Papamichail (2008) established a non-linear programming optimization method to decide the reservoir release policies and optimal cropping pattern. A stochastic dynamic programming has been developed for the optimization of water use with single and multiple cropping systems (Bras and Cordova, 1981; Vedula and Nagesh, 1996). Genetic algorithm has been applied for the optimum planning of irrigation to regulate agriculture yield (Nagesh et al., 2006; Raju and Nagesh, 2004). Mujumdar and Ramesh (1998) formulated reservoir operation model for irrigation of multiple crops using linear programming. Mehta and Jain (2008) have developed neuro-fuzzy technique whereas Janga and Nagesh (2006) developed multiobjective evolutionary algorithm for optimal operation of a multi-purpose reservoir optimization. Although the aforementioned techniques are applied for many optimization problems, linear optimization performs better and thus is therefore proposed for this study to allocate optimum area and water for multiple crops.

Rainfall in a mountainous region marginally satisfies crop water requirements, resulting in low yields of essential crops (Moeletsi and Walker, 2013). Review of literature indicates that there is much scope to enhance the water and land efficiency so that surplus water during monsoon (July-September) can be stored and later released for irrigation. Water through the springs that emerge through hill slopes is recharged by rainfall that accumulates in aquifers during the monsoon and could be used as an alternative source for agriculture practice. For sustainable irrigation systems, the main issue is to decide the right crop based on the availability of water. Cropping pattern changes that are independent of water availability is leading to heavy reliance on spring water for micro watershed development. Construction of storage tanks, trenching and other interventions in the catchment to enhance food and water security (Wada et al., 2014) can facilitate optimal water allocation across space, time and economic activities, resulting in higher crop yield. It becomes a major challenge to maintain the stability of the rate of increasing crop yield and decreasing of the available water resource. Optimization of land resources, water allocation, and crop planning in a scientific way thus reduce such challenges and provide food security under limited resources (Kang and Park, 2014).

To ensure food security in the Aglar watershed located in the Lesser Himalayas for increasing population and escalating urbanization, increasing water availability and productivity from agriculture will be imperative while addressing the issue of sustainability. Like other mountainous catchment, water resources in this region are highly scarce which effects agriculture that plays an important role in supporting the local economy and guaranteeing food security. In Aglar where sub surface flow meets the ground in the form of spring has some potential for irrigation but is often not considered for any agricultural practices rather than domestic use. This study finds that the crop water requirement for different crops grown in the area and available water potential to provide an alternative solution for sustainable development and strategies for future food security by adopting system rice intensification, and optimum way to use the spring volume.

7.2. DATA

Continuous mean daily spring discharge data from February-2014 to April-2016 was used from Mathamali spring location. The daily spring volume varies between 8.31 to 71.41m^3 with a mean of 22.55m^3. The rainfall was monitored from a tipping bucket rain gauge, which is located nearby spring location. The seasonal rainfall is most common in July-September and December-January which influence the behavior of the spring. The maximum rainfall measured in a day was 71.41mm with a mean rainfall of 2.76mm. Kumar and Sen (2017) describe the behavior of Mathamali spring with rainfall for different seasons. A high standard deviation in the spring volume (11.25m^3) as compared to the rainfall (9.85mm) suggests that the daily variation is high while a low standard deviation indicates low variation.

The meteorological parameters such as temperature, humidity, wind speed, and solar radiation that are essential for the calculation of evaporation were also observed at a daily time scale. An average monthly minimum and maximum temperature, humidity, wind speed, sunshine hours, solar radiation and calculated ET_0 is summarized in Table 7.1. The solar radiation along with the percentage of humidity is one of the important features of climate, which influences ET_0 and found major variations at a monthly scale.

Table 7.1: Aglar monthly average meteorological data (2015-16)

Month	**Temperature (^OC)**		**Humidity (%)**	**Wind Speed**	**Sun shine**	**Solar Rad.**	**ET_0**
	Max	Min		(km/d)	(hrs/d)	(MJ/m^2/d)	(mm/d)
Jan	9.4	8.7	66	68	10.8	16.3	1.57
Feb	14.2	11.4	62	119	11	19	2.27
Mar	18.8	18	57	209	12.8	25.9	4.65
Apr	22.4	21.6	45	197	13.1	28	5.64
May	24.6	23.9	54	313	13.7	30.1	6.7
Jun	26	25.4	72	471	14.3	31.3	6.7
Jul	24.4	24.4	90	534	14.1	30.9	4.97
Aug	23.8	23.3	90	522	13.2	28.5	4.44
Sep	22.6	22.1	81	429	12.2	24.9	4.4
Oct	18.7	18	73	308	11.7	20.9	3.48
Nov	14.6	13.9	70	200	10.9	17	2.32
Dec	10	9.4	72	118	10.5	15.1	1.44

7. 3. METHODOLOGY

7.3.1 Evapotranspiration and Crop water requirement estimation

Evapotranspiration (ET_0): Loss of water from the soil and vegetative cover from two different processes are called evapotranspiration. A large number of climatic (temperature, wind velocity, solar radiation, humidity) and other factors such as crop type, crop height, soil salinity, etc. affect the ET_0. The Penman-Monteith equation is being applied to calculate ET_0 using equation (7.1).

$$\mathrm{ET}_0 = \frac{0.408\times\Delta\times(R_n-G)+\gamma\times(\frac{900}{T+273})\times u_2\times(e_s-e_a)}{\Delta+\gamma\times(1+0.34u_2)} \tag{7.1}$$

where: ET_0 = Reference evapotranspiration, R_n = Net radiation at the crop surface; G = Soil heat flux density; T = Mean daily air temperature; u_2 = Wind speed at 2m height; e_s = Saturation vapour pressure; e_a = Actual vapour pressure, $e_s - e_a$ = Saturation vapour pressure deficit; Δ = Slope of saturation vapour pressure curve at temperature T; γ = Psychrometric constant. Equation (1) requires daily records of air temperature, solar radiation, humidity and wind speed. Other required parameters can be derived using empirical equations.

Crop water requirement (ET_c): Water requirement for the crop under certain specific conditions and to achieve full production is called crop water requirement.

$$ET_c = ET_0 \times K_c \tag{7.2}$$

where ET_c = Crop water requirement and K_c = Crop coefficient

K_c varies with the crop growth, crop type and limited extent of climatic conditions. The value of K_c and growth stages for different crops in the study area is summarized in Table 7.2. Monthly crop water requirement for different crops in different month is given in Table 7.3.

Table 7.2: Crops growth stages and crop coefficients at Mathamali

Crop Type	**Crop growth stages (days)**					**Crop coefficients**		
	Initial	Development	Mid-Season	Late Season	Total	Kc (initial)	Kc (mid)	Kc (end)
Potato	30	25	45	30	130	0.5	1.15	0.75
Onion	15	25	70	40	150	0.7	1.05	0.75
Garlic	40	25	95	20	180	0.7	1	0.7
Rice	25	25	50	25	125	1.05	1.2	0.75
Frence-Beans	15	20	30	15	80	0.5	1.05	0.9
Tomato	35	45	70	30	180	0.6	1.15	0.8
Cabbage	40	60	50	15	165	0.7	1.05	0.95
Capsicum	40	60	50	15	165	0.7	1.05	0.95
Peas	15	25	35	15	90	0.7	0.9	0.85
Radish	10	10	15	5	40	0.5	1.15	1.1

Table 7.3: Crops monthly water requirement (mm)

Sr. No	Crop Type/Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
1	Potato		39.4	136.9	215.6	248.2	67.8							707.9
2	Onion	41.2	58.5	113.6	95.8								55.6	364.7
3	Garlic	49.75	78.01	155.8	185.35	71.47						31.2	38.64	610.22
4	Rice							185.04	195.83	199.81	153.04			733.72
5	Beans					148.4	241.6	108.54						498.54
6	Tomato		46.81	113.41	198.85	270.96	266.19	166.2						1062.42
7	Cabbage				131.21	175.94	210.57	183.2	176.1	69.75				946.77
8	Capsicum				131.21	175.94	210.57	183.2	176.1	69.75				946.77
9	Radish											73.48	19.43	92.91
10	Peas								103.2	186.4	157.8			447.4
	Total	90.95	222.7	519.7	958	1091	996.7	826.2	651.2	525.7	310.8	104.7	113.7	**6411.35**

7. 3.2 Optimization:

Planning and management of available natural water resources and agriculture land are the key drivers for sustainable economic development in hills. A linear programming based optimization model is used for optimal crop planning and spring water distribution. The model maximizes net crops yield subjected to water availability constraints. The model is farmed on the basis of data availability of different crop type and available water on small agriculture land of 20,000m^2. Linear programing is widely used for maximizing or minimizing a linear objective function subject to a given set of linear constraints. The main objective is to maximize the total crop yield in small agriculture land by optimal allocation of the area for different crop type using the spring and rainfall volume.

Mathematical representation of model

Objective function:

1. Maximization of crop yield; Max CY = $\sum_{i=1}^{m}\sum_{j=1}^{n} p_j \times A_{i,j}$ (7.3)
2. Maximization of total crop area; Max A = $\sum_{i=1}^{m}\sum_{j=1}^{n} A_{i,j}$ (7.4)
3. Minimization of irrigation water; Min Vol = $\sum_{i=1}^{m}\sum_{j=1}^{n} CWR_{i,j} \times A_{i,j}$ (7.5)

Subjected to the following constraints:

Land availability: $\sum_{i=1}^{m}\sum_{j=1}^{n} A_{i,j} \leq 20{,}000$ m^2 (7.6)

Monthly water availability: $\sum_{i=1}^{m}\sum_{j=1}^{n} W_{i,j} \leq$ Monthly available volume (7.7)

Non-negativity constraints: All variables should be positive

where: CY = Crop yield; n = type of crop; m = month; p_j = productivity per unit area; A_j = Area of jth crop; CWR$_j$ = crop water requirement for jth crop

7.3.3. System of Rice Intensification (SRI)

The SRI is a set of principles which can increase the productivity by decreasing the water and fertilizers requirements. First principle is to use 8-15 day old seedlings with 2-3 leaves to preserve the crop inherent growth potential for rooting. Second principle is to transplant single seedling per hill as compared to three-six seedlings in a clump with the minimum time (time taken out from the nursery and plantation at a depth of 1-2cm). Planting is to be done at a grid of 25×25cm or more depending upon the fertility of the soil. This will reduce the plant density and have enough space for roots and canopy growth. Supply water to the field upto 2.5cm depth after the water ponded earlier disappear and hairline cracks are formed on top of the soil surface. It is preferred to apply less quantity of water in the field during the evening to allow water sink into the field and soil saturation to occur. This practice will provide sufficient water to meet the need of the crop but not in excess to avoid root suffocation. After 10-12 days of the transplanting, control the weeds which helps in soil aeration and improves the rice growth by benefiting both roots and aerobic soil organisms. SRI offers a great scope not only to overcome the water scarcity but also to increase rice production and to enhance the livelihood of rice farmers at the same time.

7.4. RESULTS AND DISCUSSION

It is impossible to accomplish the sustainable development of an area without quantifying the availability of water resources. The population of Tehri-Garhwal district has also increased from 604747 to 618931 (2.35%) in the past decade that leads to the decline in per capita water availability (Chandramouli and Registrar, 2011). The water demand for India will be increase to 22.5% and 32.3% and the food demand to 44% and 87% by 2025 and 2050 (Amerasinghe et al., 2007). The climate variability further threatens the water to decline and cause food insecurity. To accurately measure the accessibility of spring water for irrigation we require quantification of rainfall, spring flow, and its variation together with evapotranspiration at the micro-watershed level.

7.4.1 Water Availability

The Aglar watershed is categorized as a humid sub-tropical climatic zone with medium slope offers less potential for major development. Rainfall data analysis of observed three years (2014-2017) over Aglar watershed revealed that the total annual rainfall is 2870.08mm with an average of 956.69 mm/year. This region is mainly categorized into non-monsoon and monsoon period, the non-monsoon period occurs between the month of March-June and October-December, and the monsoon period from July-September. During the monsoon, the rainfall depth in July is the highest with an average rainfall of 330.8mm followed by August and February with an average rainfall of 188mm and 120.4mm respectively. The discharge of Mathamali spring analysis revealed that the average annual availability of spring water in this watershed is 7149.5m^3. The volume of spring water varies with the season as shown in Figure 7.1(a), and reached maximum volume (1063.8m^3) in the month of October and minimum volume (293.2m^3) in February. The total monthly average domestic water requirement for 46 households with an average family size of five in study area region is 310m^3. The surplus spring discharge and rain water available during the monsoon is not being utilized by a these resident. The total volume of spring and rainfall (21119.4m^3) which goes directly to the river has some potential to irrigate the small land holdings.

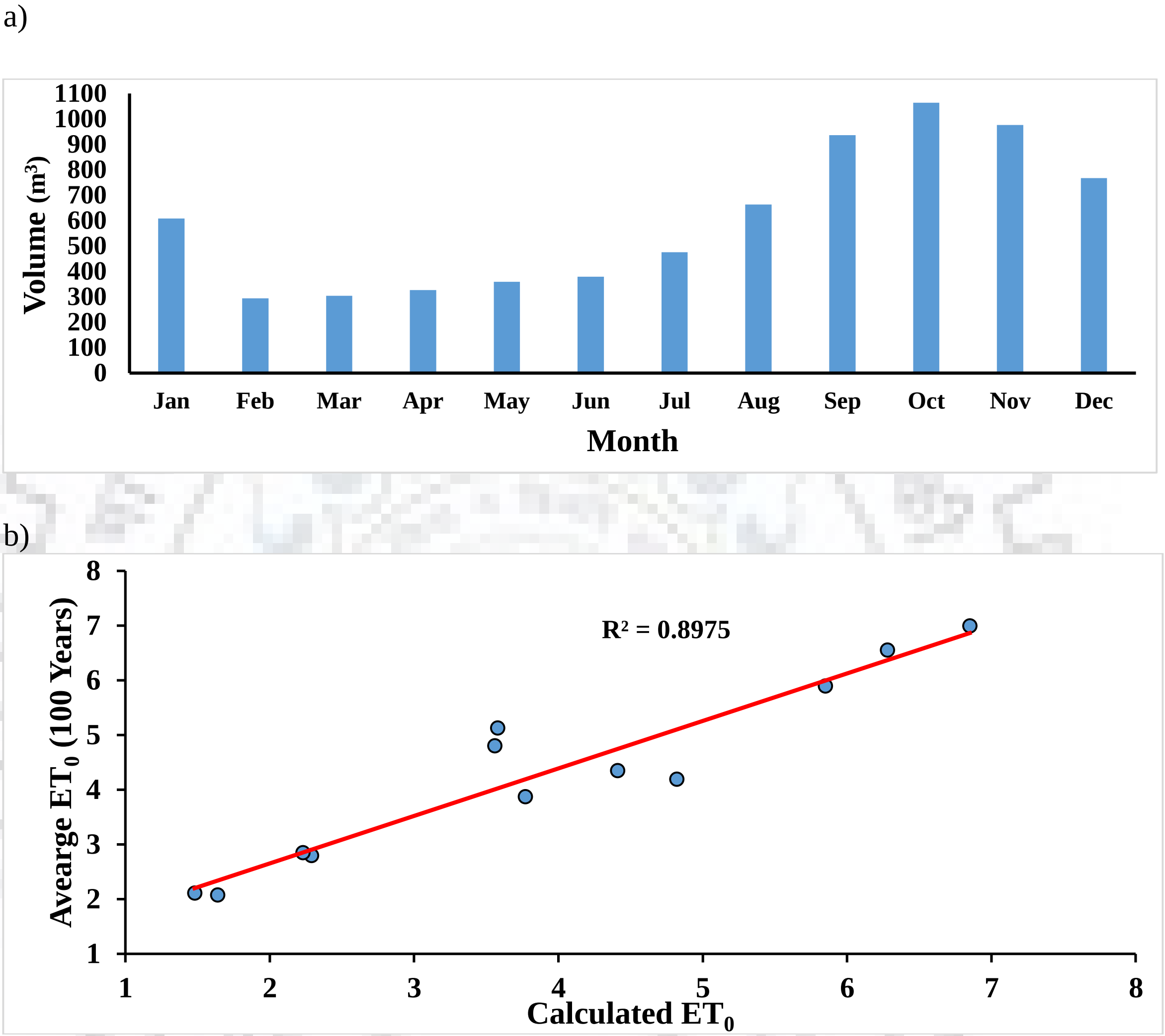


Figure 7.1. a) Average monthly spring volume variation b) Comparison of calculated ET_0 at Aglar with mean of 100 Year ET_0 of district

7.4.2 Crop water requirement

The economy of the Aglar region is mainly dependent on agriculture which is the main user of water. However, the absence of required rainfall, lack of conservation of natural resources such as soil and water hinders the economic growth. The estimation of ETo is a major issue in the estimation of ET_c as well as an understanding of hydrology (Von Zabeltitz, 2011). The FAO PM has been used in this study to calculate ETo which is widely and commonly used. The coefficients of determination (r^2) of estimated monthly average ETo and the monthly average of past 102 years (Portal, 2010) is 0.90 (Figure 2(b)). Calculated ETo in the Aglar during 2015-16 varies between 1.04 to 9.14mm/day with an average of 4.75mm/day. The ETo increases steadily from 1.04mm/day in January to the highest of 9.14mm/day in June, afterward it decreases gradually to 2.6mm/day in December. The maximum ETo in the month of June can be explained by the hot and dry summer as compared to the other months (Hu et al., 2017). The variation in monthly average ETo directs that planting time can affect ET_c.

In the study area, 10 major crops are grown i.e Potato, Onion, Garlic, Rice, Beans, Tomato, Cabbage, Capsicum, Radish, and Peas. The total calculated monthly ET_c of each crop for the study area is given in Table 7.3. The total ET_c for all of the crops in the study area is 6411.35mm with a maximum crop water of 1091mm required in the month of May. Tomato requires the maximum amount of water (1062.42mm) followed by Cabbage and Capsicum (946.76mm each). The minimum water required (92.91mm) is for Radish. The two major crops of the region are Potato and Rice which require 707.5mm and 733.72mm of water. The calculated ET_c proved that the crop evapotranspiration is more (946-1062mm) for crops with extended duration (165-180 days) as compared to (92.91) for short duration (60 days) crops. Also, the ET_c is more (1091 and 996.7mm) in the month of May and June because of higher temperature (24.6-26 °C) and sun shine hours (13.7-14.3 hr.) than in the winter which is similar to the FAO-56 (Allen, 2000). This demonstrates that it is crucial to apply scientific water management in light of the need for the crop yield so that higher crop productivity and water efficiency can be achieved with the optimum amount of crop and water (Vishal et al., 2013). It is important to make a systematical strategy for the release of water from available water resource (spring) to meet the ET_c so that people have an adequate amount of water when needed.

7.4.3 Optimization of area

Optimum use of water and land can help in sustainable development (Janga and Nagesh, 2008). In Aglar, it is most prominent to use the spring flow for irrigation of a small agriculture area of at least 20,000m^2 to grow the major crops. Initially (trial 1), the optimum crop yield from the area of 20,000m^2 is 521quintal with a uniform distribution of an area of 20,000m^2 each to potato, radish, and pea. The benefit to cost (B/C) ratio is used to understand the efficiency of agricultural practices and suggest the possibility to create further benefits from the same resources by altering the approach. The B/C ratio is very low (1.56) for the above allocated area. The optimized allocated area is also not in accordance with the survey and questionnaire prepared with the community (Appendix IV). There was no area allocated during optimization for rice which is the main local crop. After limiting the minimum 5000m^2 (trial 2) of the area for their important crops (Potato and Rice) the total yield reduces to 410 quintals with improved B/C ratio of 2.45 (57%). To increase the B/C ratio by 64 % and to improve the economy by further changing the crop type and optimum area will lead to the increase in the net productivity of 483.1 quintals (trial 3). If excess spring volume during the monsoon is stored by constructing a tank of 1000m^3 and utilizing it for irrigation during the required period will further increase the net benefit. After utilizing the surplus water with the area and monthly water availability constraints (trial 4) the net yield reduces by 35.1% with B/C ratio of 2.46.

Table 7.4: Summary of B/C and water productivity

	Cost (Rs.)			Water Productivity	
Trial 1	**Generated**	**Applied**	**B/C Ratio**	**Conventional**	**SRI**
1	556330	336140	1.56	2.09	2.09
2	487425	198795	2.45	1.78	1.86
3	572336	222594	2.57	1.68	1.73
4	414407	168202	2.46	1.26	1.29
5	433472	161141	2.69	1.03	1.07
6	414207	169750	2.44	1.48	1.52
7	437943	172328	2.54	1.45	1.48

By changing the mind set to increase the net benefit by not growing onion and allocate the area to another crop (trial 5) will result in further decrease in the net productivity and B/C ratio of 2.69. Loss of net productivity in (trial 4 and 5) allows reducing change of crop type and crop area from which we are not gaining more profit (trial 6). Trial 6 provides the net profit of Rs. 244457 with the B/C ratio of 2.44 and have enough water to irrigate cabbage for some area. After considering the available area (trial 7) during the growing period and water requirement the optimum area for this trial is presented in Table 7.4. The net crop yield is 335.84 quintal with B/C ratio of 2.54 (trial 7). The crop yield from the field can be further increased by applying the water through drip irrigation rather than flood irrigation. If we consider the optimized result and the conventional practice of the irrigation, there is net benefit in term of total yield i.e 289.29 quintal which is 1.67 times the conventional practice (Table 7.5). Comparative analysis of optimized and conventional irrigation practice result have shown quantitative improved yield. Optimization analysis can serve as a tools to manage the natural resources, but still have a challenge to decide the standard optimization method.

Table 7.5: Comparison of total yield (Conventional vs Optimized)

Crop Type	Optimised		Conventional	
	Yield (q)	Area (m^2)	Yield (q)	Area (m^2)
Potato	54.36	0.45	72	0.6
Onion	0	0	11..57	0.3
Garlic	19.65	0.5	11.79	0.3
Rice	10.425	0.5	16.68	0.8
Frence-Beans	40	0.5	12.8	0.16
Tomato	27.5	0.55	8	0.16
Cabbage	0	0	15.82	0.16
Capsicum	22.5	0.5		
Radish	24.85	0.5		
Peas	90	1	36	0.4
Total	***289.29***		***173.09***	

7.4.4 Water Productivity

The increasing scarcity of water in the hills and lack of understanding of water management towards agriculture have raised questions regarding the total yield from a field and the net benefit. The major factors on which benefits depend are weather conditions, market conditions, governance and socioeconomic drivers, management of crops and availability of natural resources (Figure 7.2).

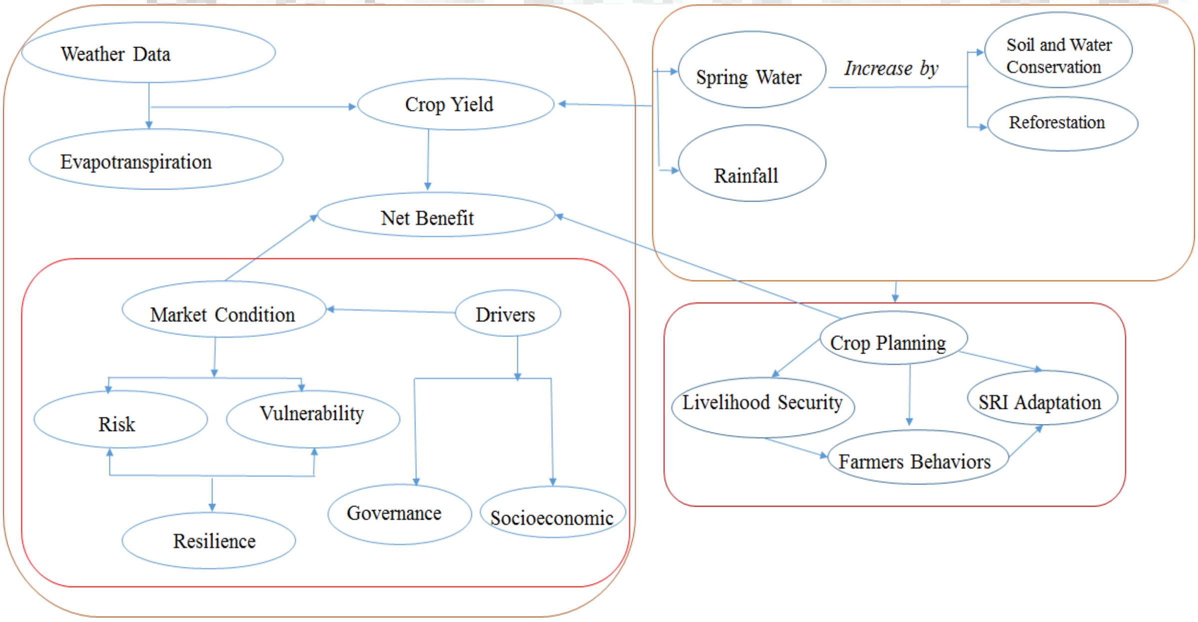


Figure 7.2: Major factors responsible for crop yield

Forecasting of weather has a great potential towards decision making process in relation to agricultural practices (Roncoli et al., 2011). Accurate forecasting of ET_o and rainfall helps to harvest the crop and prevent losses accordingly. The forecast will have no meaning if the choice of crop and management strategies cannot be implemented in the agriculture field before the forecast event. Gain in total agriculture productivity by following timely forecast can be evaluated using the agricultural productivity index (API) equation (7.8).

$$\text{API} = \left(\frac{P}{P_n} / \frac{A}{A_n}\right) \times 100 \tag{7.8}$$

where P and P_n are productions of particular crop per unit area (A) and total production in the whole region having an area (A_n).

There is deficiency in government policies in dealing with climate change and changing water scenarios. Increase or decrease in available water because of climate change or other anthropogenic changes will lead to proper assessment of these changes and planning at the regional level to reduce the risk and vulnerability. The inequality of supply of water among the different users and stakeholders effect the convergence of laws and legislations and need some transparent regulations and monitoring. Socioeconomic is another important driver for market condition and net benefits from the total yield. Sustainable agriculture accomplishes the economic security at the regional level and is related to different production, marketing, and diversification strategies.

The gain in total yield and increase of water productivity by adopting SRI techniques has been summarized in Table 7.4. Overall, it has been found that, SRI produces 49% higher yield with 14% less water and thus increase the water productivity (Thakur et al., 2014). Increase in the total yield by adopting SRI from different countries has also been presented by Kassam et al. (2011) and concluded that stress should be given to water productivity than on water use efficiency. In SRI, all tiller have more time for growth and development resulting ability to form panicles is much higher than the conventional method. All of the factors discussed above improve agricultural productivity/production.

7.4.5 Sensitivity Analysis

With the current crops grown in the hilly area, the net profitability measured in terms of B/C ratio depends on the market selling price and the total yield from the field. Table 7.6 indicates that increase in yield is likely to be more sensitive than the decrease in the market selling price. The reduction of market selling price by 5% results in a decrease of 5.7% in B/C ratio whereas with an increase of 5% in the total yield results in an increase of B/C ratio by 4.9%. Further reduction of market selling price and increment in the crop yield by 10% results in the decrease and the increase of B/C ratio by 13.9% and 9.84% respectively.

Table 7.6: Sensitivity analysis of B/C ratio in Thatyur

Description	**Decrease in market price**						**Increase in yield**					
Percentage Change	5%	10%	15%	20%	25%	30%	5%	10%	15%	20%	25%	30%
B/C ratio	2.3	2.1	2.07	1.95	1.83	1.7	2.56	2.68	2.8	2.93	3.05	3.17

This implies that a change of crop yield can have a significant impact on the B/C ratio. To gain the net profitability of farmer a major increase in market price is required. The increase in the yield by 30% can increase the revenue of farmers by Rs.3687197 which is 217% more than their input costs. A sensitivity analysis suggests enhancing the total yield from the irrigated area in comparison to the market price which is influenced by many governmental and non-governmental policies. This forces to conserve the natural resources such as rainfall and spring volume and utilize it for agriculture to improve the farmer's economy.

7.5 CONCLUSION

Climate change and its variability in recent years play a major role in the total yield from agriculture and especially in the mountainous regions, it becomes more thoughtful. The net gain from the yield that depends on the land and water availability play a key role in food security and livelihood. Dependency on agriculture in Uttarakhand state which is a mountainous state is about 75-85%. The development of people in this mountainous area is mainly associated with the enhancement of yield from the agriculture land and its allied actions. Water and marginal land with moderate to steep slope are some of the major constraints for socio-economic and sustainable development in the mountainous region. Therefore, quantifying the water availability from springs and evaluation of reference crop evapotranspiration at Thatyur region of Aglar watershed helps to prove the importance of springs as an option for agriculture other than rainfall. The present study also focuses on optimization of natural resources (land and water) and on sensitivity analysis of B/C ratio.

The analysis of water accountability shows that the rainfall in July is high with an average rainfall of 330.8mm followed by August and February with an average rainfall of 188mm and

120.4mm respectively. Spring discharge analysis revealed that the average annual availability of spring water in this watershed is 7149.5m^3 and have an option to use the water for agriculture in an optimized way. The FAO PM has been used to calculate ETo for ten major crops that are grown in the study area and found that crop evapotranspiration is higher (946-1062mm) for crops with extended duration (165-180days) as compared to (92.91mm) for short duration (60days) crops.

Excess spring water during monsoon can be stored by constructing a tank of 1000m^3 and utilizing it for irrigation during the required period will increase the net benefit from agriculture. The estimated net crop yield is 335.84 quintal with B/C ratio of 2.54 by utilizing the stored water. The crop yields from the field can be further increased by applying the water through drip irrigation. It has been found that, SRI produces 49% higher yield with 14% less water increases water productivity by adopting SRI techniques. Sensitivity analysis divulges that the increase in the total yield by 30% can increase the revenue of farmers by 217% more than their input costs. Judicious use of these available natural resources require long term planning and accurate database, planning and management, and risks and benefits of agriculture. The findings of this study offer an approach for a sustainable development of agriculture that will help in the progress of the mountainous districts.

CHAPTER 8

REJUVENATION OF SPRING: COPING WITH WATER INSECURITY

8.1 INTRODUCTION

Rapid population growth with unmanaged settlements, changes in the temperature and the rainfall pattern in the mountains lead to a high demand for domestic water. Springs originate in the hills by movement of water that flow from an aquifer and meet the earth's surface. They are the principal source of day to day water needs for domestic purposes, feeding the animals, and for irrigation purposes of the rural community in the mountains (Sharma et al., 2016; Vaidya, 2015). However due to the erratic nature of intensity and distribution of the rainfall pattern, deforestation and steepness of the hills, there is an adverse effect on rural population, agriculture production and livestock. To address the multifaceted problems of drying of the springs or decline in its volume in the rural areas entails an inclusive study of the socioeconomic and the biophysical, which is possible by an integrated study involving the participation of the farmers of the rural community (Timilsina-Parajuli et al., 2014). Changes in the rainfall pattern, land use/land cover that occur in the recharge area and the aquifer’s capacity to store and transmit groundwater directly reflect the nature of the spring discharge. Every spring is different from the other in terms of its type, catchment area, nature of discharge, local slope and the geological structure present beneath the surface (Kresic, 2010). Adapting to global warming and encouraging to increase the water availability which is essential for food security are the biggest challenges in the rural Himalayas (Bharati et al, 2014). The constant change in the pattern of the rainfall in the Himalayas not only effect the water availability and livelihood but also create problems for the people living downstream (Miller et al., 2012).

Limited research on springs were conducted in the Western Himalaya region related to the discharge behaviour of the spring with the rainfall patterns and the catchment characteristics (Valdiya and Bartarya, 1991; Sahin and Hall, 1996; Negi and Joshi, 2004). ACWADAM (2011) report suggested that the outflow from the spring is not only the function of the rainfall but also depend on the character of the aquifers that feed these springs. Climate change has caused changes in the pattern of the rainfall in the Himalayas (Cruz et al., 2007; Agarwal et al., 2012). The changed pattern in the rainfall and the temperature is responsible for the less recharge of the springshed that can be seen by the low outflow from the spring during the rainless time. The characteristics of geology and the detailed soil behaviour and structure also remain unknown. Regardless of the incremental developments in understanding to measure the rates of forest degradation and the impact of climate changes, there is still no decisive understanding of the degree of deprivation of the Garhwal forests in the hills. The opinion of the local community in the past few years towards change in the rainfall pattern and other climatic variables is that there is hardly any rainfall after mid-September to the end of May with just a little rainfall in December/ January resulting in drying of the springs or reduction in the flow. Most of the population believe that the reduction of the flow in these springs could be because of less snow on top of the mountains (Chaudhary et al., 2011) but it could be due to the degradation of the catchment. Hence, there is a need to understand the spring discharge quantification and the influencing factors (Pellikka et al., 2009). A lot of research has focused on the runoff processes on different terrain in the natural conditions and many times by using the rainfall simulator; however less attention was given to understand the sub surface flow characteristics of the springs on the slopes and on the outflow from these springs in extreme rainfall conditions. The hydrological interpretations from the spring hydrographs were based on the time series and the recession curve analysis of a single event or multiple events combined. The time series of the monitored spring discharge and the rainfall investigation offered a mathematical study of the hydraulic response of the recharge events. A number of functions have been formulated to describe the decay of spring during the lean season (Dewandel et al., 2003; Kumar and Sen, 2017). Baedke and Krothe (2001) divided the spring recession into three components, the early component was related to the conduit flow, the last component was linked to the diffusive flow, and the intermediate component was the combination of both the conduit and the diffusive flows. The shape of the recession curves were generally concave and suggest the hydrodynamic properties of the aquifer such as slope, geomorphological properties, hydraulic conductivity, and storage coefficient. The exponential and quadratic equations were the maximum used approaches for recession analysis which were based on fitting the observed recession curve with the calculated discharge (Dewandel et al., 2003). However, the shape of the hydrograph during the recession varied among different seasons due to the variability of the hydrogeological settings and the characteristics of the climate (Atkinson, 1977). The main advantage of estimating the recession coefficients is that it does not require detailed knowledge of the physical characteristics of the springshed as the analysis is mainly based on the observed time series of the spring discharge.

To mitigate the water issues in the hilly area, understanding the relationship between the rainfall and the spring flow has been attempted using regression (Agarwal et al., 2012), SWAT (Bhartati, 2014), field study (Tambe et al., 2012), aspect based studies (Negi and Joshi, 2004) and springshed development (GoS, 2014). The deficiency of water due to natural hazards, the unstable and costly farming and the soil degradation is resulting in labor constraints in irrigation, forcing the migration of farmers for employment, and women to spend more time to fetch water. The negative impact of the climatic change on irrigation was reported by Sharma (2015). Thus the objectives for the present chapter were

(i) to discuss different types of springs that were classified based upon the geological and the geomorphologic structure of the aquifer system and their discharge characteristics,
(ii) to understand the spring hydrograph and the recession behaviour which play a vital role in the quantification of the spring volume during the rainless period ,
(iii) to analyse the impact from intervention (contour trenches, percolation pits along with broom grass fodder plantation) studies while developing the springshed,
(iv) to analyse the significance of the rainfall on the spring flow using the analysis of variance (ANOVA) and
(v) to make recommendations for sustainable management of the springs in the hills.

At the end of this chapter, it is believed that the quantification at the micro level of the spring water, analysis of the behaviour of the spring and formulation of a master recession curve play the key factors for proper springshed development and for better strategies to rejuvenate the springs in the Garhwal mountains.

8.2 METHODOLOGY AND DATA AVAILABILITY

This section discussed the methodology and the data used to determine the different parameters of the recession curve, the analysis of the hydrograph and the rejuvenation work of the springshed to fulfill the objective of the study or to find supplementary information for further analysis and interpretation.

8.2.1 Data Used: The rainfall data used for the present study was extracted from the monitored tipping-bucket rain-gauge installed at the Mathamali village near the location of the spring. The spring discharge was monitored for every 15 minute time interval from a calibrated 0.6 inch HS flume installed at the outlet of the spring. The short time interval monitoring of 15 minutes helped to characterize even the short duration of the rainfall-spring flow events. Considering the small size of the Mathamali springshed, the rainfall that occurred in the region was considered as spatially uniform and therefore only one rain gauge was installed. The daily average spring discharge and the daily cumulative rainfall flow along with the annual rainfall and its correlation coefficient with the spring discharge was illustrated in Figure 8.1.

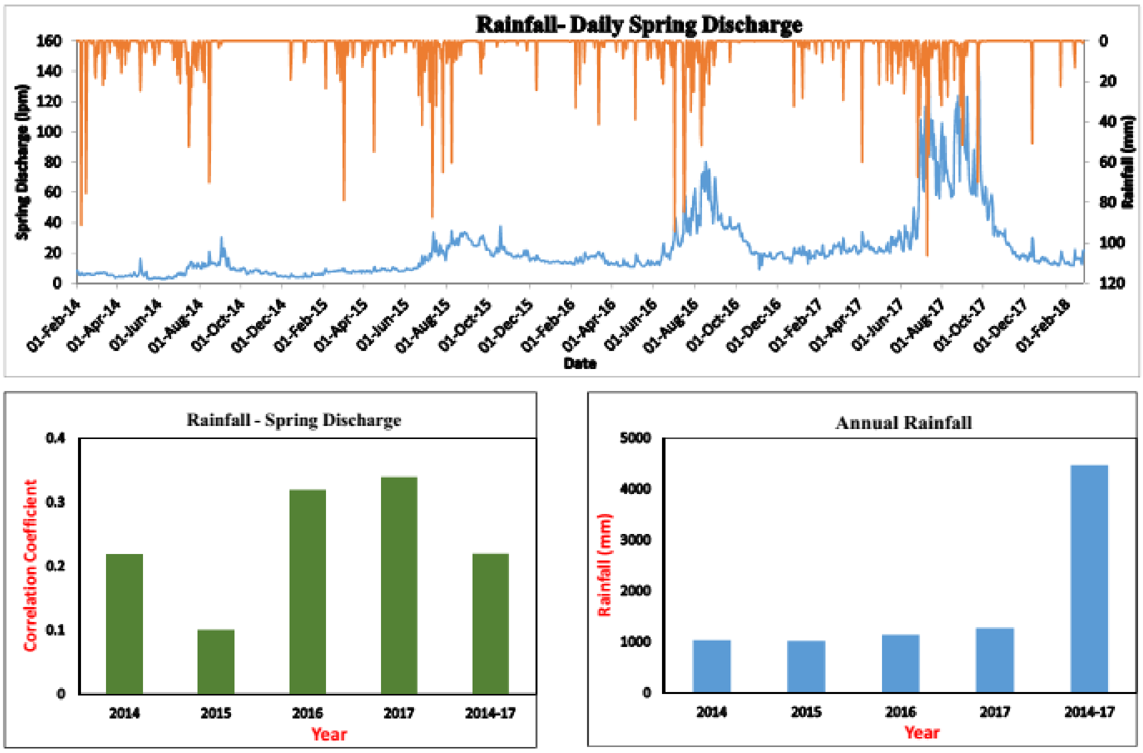


Figure 8.1: Daily observed time series of rainfall and spring discharge and its yearly coefficient

The measured 15 minute data were averaged to the daily average to smooth up the time series for noise corrections and to allow working with the daily data. The observed data indicated that monsoon season has received reduced or short duration rainfall but high intense rainfall with drier winter months. Further data from other types of springs – Panera Gadhera and Pastola - located in the Himalayan region of Uttarakhand State were taken into consideration to compare the spring behaviour. The Pastola spring is located at a latitude of 29˚16’27.9”N and a longitude of 79˚37’44.5”E in the district of Nainital at an altitude of 843 m. It is a depression type of spring with green schist type of underground rock. The Panera Gadhera is a contact type spring located at a latitude of 29˚16’27.9”N and a longitude of 79˚37’44.5”E with quarzite and phyllite type of underground rock.

8.2.2 Methodology:

Recession Analysis: The recession coefficients for Mathamali, Panera Gadhera and Pastola springs were computed using individual recession analysis method and master recession curve

(MRC) analysis method. The recession storage of a spring system could be expressed in an exponential decay form as

$$Q_t = Q_0 e^{-\alpha t} \tag{8.1}$$

Where Q_t = flow at a specified time (t), Q_0 = flow at the beginning of the recession (t_0), α = rate of the decay (1/day), $\alpha = -\ln K_r$. The rate of the decay (α) has two broad components for spring flow which were the recession coefficients for the interflow (α_i) and the recession coefficients for the base flow (α_b). The process to calculate the recession coefficients involves the baseflow separation method in which the baseflow was extracted from the total discharge that provides the interflow component.

8.2.3 Springshed intervention: In order to increase the spring discharge, the springshed development approaches have been adopted to revive the Mathamali spring using the rainwater harvesting structures and plantations of native tree species. Before carrying out the intervention work, certain steps were adopted like the hydrogeological mapping of the springshed, the delineation of the mountain aquifer and the identification of the recharge area. If the slope of the area was greater than 50 % then there was no need for any physical structure because of the chances of landslides but if the slope was less than 50 % then the place was checked for stability. After the identification of the slopes in the area, artificial recharge works comprised of 14 staggered contour trenches and 5 percolation pits of different dimensions were constructed in the recharge zone of the springshed (Figure 8.2). Out of the 14 contour trenches, 9 trenches were freshly dug and 5 trenches were repaired.

Figure 8.2: Intervention work in the springshed a) Recharge area identification, b) Mapping for slope, c) Contour Trench and d) Percolation Pit

In the upper ridge of the springshed, construction of contour trenches and small recharge structures were completed as the area was more stable and the inclination was fairly less. The area was also planted with native tree species such as Banjh, Garhiwal etc to reduce the surface runoff, to prevent soil erosion and to increase the rate of infiltration. Below this region, the area was relatively slopy, therefore, percolation pits were constructed to facilitate the recharge to the spring. The dimensions of the contour trenches and the percolation pits were chosen based on the slope of the area and the suitability of the structure. Most of the contour trenches had a common dimension of 2m×0.6m×0.45m whereas the percolation pits were 0.9m×0.6m×0.45m.

***8.2.4 Hypothesis test with Analysis of variance (ANOVA)*:** The hypothesis P-value ≤ 0.05 testing is a technique to check if the relationship was valid or not for the consequences of the rainfall- springflow (Phillips, et al., 1988). A factor value of the coefficient of variation (s_w^2) between two different groups - the spring discharge and the rainfall was calculated by the equation 8.2:

$$s_w{}^2 = \frac{1}{I}\sum_{i=1}^{I}\sum_{j=1}^{ni}\left(\frac{(x_{ij}-\bar{x_\iota}{}^2)}{ni-1}\right) \qquad (8.2)$$

Where I is the group, whose mean values have to compare, n_i (i = 1,2 ,…..I). x_{ij} is the observation j in group i. Within the same group variance was calculated by the equation 8.3:

$$s_b{}^2 = n\sum_{i=1}^{I}\frac{(\bar{x_\iota}-\bar{x})^2}{I-1} \qquad (8.3)$$

Based on the data, variances were assumed to be equal, and were derived from separate but within the group. To test the null hypothesis, the ratio of S_b^2 and S_w^2 was compared. If the null hypothesis was not true, the means were not all equal, then S_b^2 will be greater than σ^2, and the population variance will be increased by the difference in the treatment.

8.3 RESULT AND DISCUSSION

8.3.1 Rainfall and spring discharge characteristics

The rainfall and the spring discharge in the Aglar watershed appear to be noteworthy annually and in the inter-seasonal variability (Figure 8.1). The annual variation in the rainfall for the Aglar watershed indicates that, there was a noteworthy fluctuation in the average annual rainfall. There was evidence which revealed that the decreasing rainfall trend in the region over the past 100 years has been changing (Mishra, 2017). However, there was a gentle increase in the rainfall received in the Aglar region during the past three years from 2015 to 2017. However, an average annual rainfall in Aglar during observed period (2014-2017) was measured to be less than 44 percent of that received in Mussoorie (average annual rainfall 2,000mm), clearly an orographic effect. This significant difference in the magnitude of the rainfall was also conveyed by the people of the local community of the region.

The average spring flow rate from the springshed varied before and after the intervention work. Before the intervention, it was 16.9±11.72 lpm (±SE) and after the intervention, it has changed to 41.63±31.64 lpm. During the monsoon months from June 15 to September 15, the minimum spring discharge was 3.25lpm before intervention but the minimum flow is around 25.51 lpm after the intervention. Soon after the intervention work maximum flow rate is noticed during the monsoon season with discharge rate of 146lpm which was earlier 80.07lpm in the monsoon month. During winters between January and February, the average discharge varied between 4.85 and 18.93 lpm. Thus, the springshed had the capacity to generate a maximum rainfall of 48.5% of the total volume during the monsoon as compared to (11.75%) during the winter. The rainfall and the soil moisture explained the discharge variations in this typical mountainous watershed in the lesser Himalaya with different land use and land cover (Nanda et al., 2018). John (2012) emphasized that for sustainable resource management, participation of the community and their attentiveness necessitates for more understanding of the other untouched evidences.

8.3.2 Spring discharge hydrological response

The discharge from the spring was mainly influenced by the rainfall amount and the rainfall intensity with soil and vegetation factors. In general, the more the amount of the rainfall, more recharge will take place and eventually have more outflow from the spring. The antecedent moisture present in the soil also plays a significant role in the recharge of the area and thus the discharge. In order to understand the Mathamali spring behaviour with rainfall, eight major rainfall events were selected. An event denotes a rainstorm with continuous rainfall above 50mm in a day within 24 hours. A total of 8 events were selected to understand the behaviour of the spring outflow with the rainfall. Events 1 to 5 were the events prior to the intervention in the springshed whereas Events 6 to 8 were the events after the intervention. The observed rainfall for Event 1 began at 00:20 hours on 14th February 2014, and ended at 21:00 hours on 15 th February 2014 with a cumulative rainfall of 94.53 mm. On 14th February 2014, the cumulative rainfall was 76.02 mm with the maximum intensity of 7.45 mm/h. The remaining rainfall occurred on the next day, the15th February 2014. During this event the total spring flow measured was 115940 litres with the peak spring flow at the rate of 6.76lpm. The time lag between the peak of the rainfall and the peak of the spring flow for this event was 72 hours. Prior to this event, there was no rainfall and the soil was in a dry state, thus the long-time gap for a peak response was due to the antecedent moisture present in the soil. The Event 6 that took place in the year 2017, just after the intervention work in the springshed, had similar soil antecedent moisture conditions but had a different response. The Event 6 began at 03:00 hours on 5th April 2017 and ended on the next day at 14:00 hours with a cumulative rainfall of 62.19mm and the maximum rainfall intensity that was measured was 7mm/hr at 15:00 hours on 5th April 2017. In a 24 hour duration, the total rainfall of 55.25mm occurred on the first day and 6.9 mm occurred on the next day. The total outflow measured was 207186.5 liters which was 1.8 times more than that of event 1. The peak of the spring flow occurred at 08:15 hours on 6th April 2017 and displayed a lag of only 17.4 hr. when compared to 72 hrs. for event 1, irrespective of almost the same rainfall intensity.

The event 2 has begun at 01:00 hours on 15th August 2014, and ended at 07:00 hours on 16th August 2014. It lasted for 30 hours with a cumulative rainfall of 125.6mm. A rainstorm occurred which allowed a maximum rainfall intensity of 31.61mm/h at 15:00 hours on 15th August 2014 with an average intensity of 8.37mm/h. The 24hr maximum rainfall on 15thAugust 2014 was 70.7 mm and on 16th August 2014, it was 55mm. The resultant outflow from the huge rainfall was 267685.8 liters. The maximum peak flow of 29.31 lpm occurred at 10:00 hours on 16th August 2014. The peak occurred after the storm and the lag time from the maximum rainfall was about 19 hrs. The event 5 which also had a huge cumulative rainfall of 108.6mm has begun at 11:00 hours on 2ndJuly 2016 and ended at 13:00 hours on 4th July 2016. There was a 19hr discontinuity in the rainfall between 11:00 hours on 2nd July 2016 to 06:00 hours on 3rd July 2016 which accounted for 98% of the total rainfall with a maximum intensity of 23.4mm/h at 17:00 hours on 2nd July 2016 and with an average rainfall intensity of 5.54mm/hr, after which the intensity had gradually weakened until the end of the rainfall. The total outflow from the spring was 120579.2 liters which was low when compared to the net rainfall received. The maximum peak flow occurred at 08:45 hours on 5th July 2016 and with a lag of 53.75 hr. During the event 2, the antecedent moisture of the soil was wet because of past short rainfall storm events and all of the cumulative infiltration was slower when compared to events 1 and 6 which resulted in less net recharge as all of the rainfall converted to surface runoff.

The rainfall event 3 began at midnight of 15th April 2015 but was insignificant to recharge the aquifer as it stopped raining after 2 minutes and then started raining again at 16:00 hours on the same day which lasted for two hours with a total of 55.25mm rainfall. The cumulative rainfall for event 6 was 62.2mm. The total volume of the spring flow that was measured was 261058 liters with a peak value of 13.05 lpm at 11:00 hours on 16th April 2015. Similarly the event 4 has distributed rainfall with a total cumulative rainfall of 55.4 and a maximum intensity of 18.54mm/hr at 17:00 hours on 26th July 2015. Table 8.1 summarized the characteristics of the rainfall events and the spring discharge outflow with the start and the end times.

Table 8.1: Rainfall- Spring Discharge event characteristics

Event No.	Duration (days)	Rainfall		Spring Discharge	
		Cumulative (mm)	Max Intensity (mm/h)	Cumulative (liter)	Peak discharge rate (lpm)
1	14-26, Feb - 2014 (13)	97.4	7.45	115940	6.76
2	15-27, Aug - 2014 (13)	125.67	31.6	2676859	29.31
3	15-19, Apr - 2015 (5)	62.19	37	261058	13.04
4	26-30, Jul - 2015 (5)	55	18.54	37457	34.77
5	2-11, Jul - 2016 (10)	108.6	23.4	120579	51.6
6	5-26, Apr- 2017 (22)	66.9	7	207186.5	45.5
7	23 Sep-8 Oct - 2017 (16)	75.6	15.4	458173	157.6
8	12-22, Dec - 2017 (11)	57.3	8.6	77004	33.4

The event 8 rainfall had almost a cumulative rainfall of 57.3mm with a maximum intensity of 8.6mm/hr but the total outflow from the spring was only 77005 liters. It was observed that the moisture of the soil was low and has initially absorbed all of the rainfall which resulted in a delay in the generation of the flow. A similar phenomenon was reported by Tian and Liu (2011). The transpiration from vegetation could be another factor that reduced the outflow from the spring. As vegetation could increase the opportunity for more evaporation and vegetation litter can further intercept the rainfall resulted in less recharge (Keesstra et al., 2016). The analysis of the spring flow from the event 7 indicated a major change as the total outflow was 458172.8 liters with a peak of 157.6 lpm and the lag between the maximum rainfall and the peak flow was 41hrs. The cumulative rainfall was only 75.6mm with a maximum intensity of 15.4mm/hr at 19:00 hours on 23rd September 2017. During this event, the event 8, the top soil layer did not display any runoff as all of the rainfall was infiltrated and has recharged the aquifer which eventually ended as spring flow. The different behaviour of all of the spring flow events corresponding to the rainfall displayed distinct interflow process. As the slope of the springshed was same for all of the events, the amount of the rainfall with intensity was a major factor responsible for recharge of the springshed. The intervention work as proved by events 8 and 6 lead to an increase in the total volume when compared to the other events with similar rainfall characteristics. The response of the springshed in terms of discharge to the rainfall events was not the same and varied according to the soil moisture, rainfall intensity and cumulative rainfall. From the observed daily discharge, there was a diurnal variation in the day and the night because of variation in the temperature. The diurnal hydrograph displayed the rising and the falling limbs with the maximum altitude in all of the days which had also signified the presence of conduit drainage system. The average flow of the Mathamali spring which is the only domestic water resource was 16.9lpm but soon after the intervention work in the springshed the average flow had increased by 2.6 fold. The presence of top forest cover in the recharge area allowed the land below to gradually store and gradually release. The alteration of the land cover may have unforeseen impacts on the water cycle which can in turn alter the spring discharge.

8.3.3 Recession Curve Analysis

The recession behaviour of the daily monitored spring discharge was studied for 12 different small recession events which included the events before and after the intervention work. The recession events were identified based on a portion of the hydrograph which extended from peak discharge to the low flow of the next rise continuously for at least 5 days. The summary of the analyzed recession behaviour towards different rainfall conditions was illustrated in Table 8.2

Table 8.2: Summary of recession events of Mathamali spring

			Discharge (lpm)		**Rainfall (mm)**		**Recession value**	
Event No.	**Date**	**Total Duration**	***Bigining***	***End***	***Total***	***Maximum***	***Slope***	***K (days)***
1	12-19 March-2014	8	7.27	5.31	43.9	21.93	0.05	22
2	14-20 May -2014	7	7.61	2.9	14.03	5.87	0.16	6
3	07-12 March-2015	6	7.54	6.69	163.71	79.05	0.02	42
4	23-28 September-2015	6	31.73	22.07	32.8	16.2	0.07	14
5	27Nov-02 December- 2015	6	21.8	14.74	5.4	4.6	0.08	13
6	23-28 April 2016	6	13.69	10.83	4	4	0.05	21
7	31August-5September-2016	6	69.85	41.2	21.4	12	0.11	9
8	8-13-Mrch-2017	6	29.83	20	44.25	29.4	0.08	13

9	31May-5 June -2017	6	33.41	20.85	31	16	0.09	11
10	09-14 September-2017	6	80.72	58.63	11.8	7.4	0.06	16
11	26-September-02October-2017	7	97.59	51.77	75.2	70	0.11	10
12	24-30 January-2018	7	21.13	12.92	22.6	22.4	0.08	12

The value of the recession slope varied from 0.02 – 0.16 before the intervention and from 0.06-0.11 after the intervention. During summer, the slope of the recession curve for events (2, 7, 9 and 11) was more when compared to the others due to increase in evaporation. The total volume of the spring from each recession event was calculated by the relation $V_t = \frac{Q_t}{\alpha}$, where α was the slope of the recession curve. The shape of a recession curve was governed by the rainfall amount and intensity along with the antecedent moisture condition. When the cumulative rainfall was more and occurred for a longer time with less intensity, the base of the hydrograph observed was more and vice versa as displayed in events (3 and 12). When the rainfall occurred during the wet conditions, as displayed in events (2, 4, 7, 10 and 11), the infiltrated water has raised the hydraulic head, built pressure and the movement of the subsurface flow became easier through fracture and cracks and lead to a high peak discharge. The decay of the recession curve for a short time as displayed in the events 2, and 11 indicated that there were more transmissivity properties of the aquifer during the dry condition of the soil as all of the soil pores were completely filled with the rainfall. The rapid decay of the spring from its peak discharge indicated limited storage capacity and more cut-offs with an additional permeability (Stevanovic, 2010). The flow of the subsurface below the top surface was restricted to only a few meters suggested electrical reflectometry measurements (Figure 8.3).

Findings from the recession curve analysis were consistent with the result of Wittenberg (1999) for storage discharge relationship. The average recession slope before the intervention was 0.08 which increased to 0.09 after the intervention indicating a minor effect on the rate of decay.

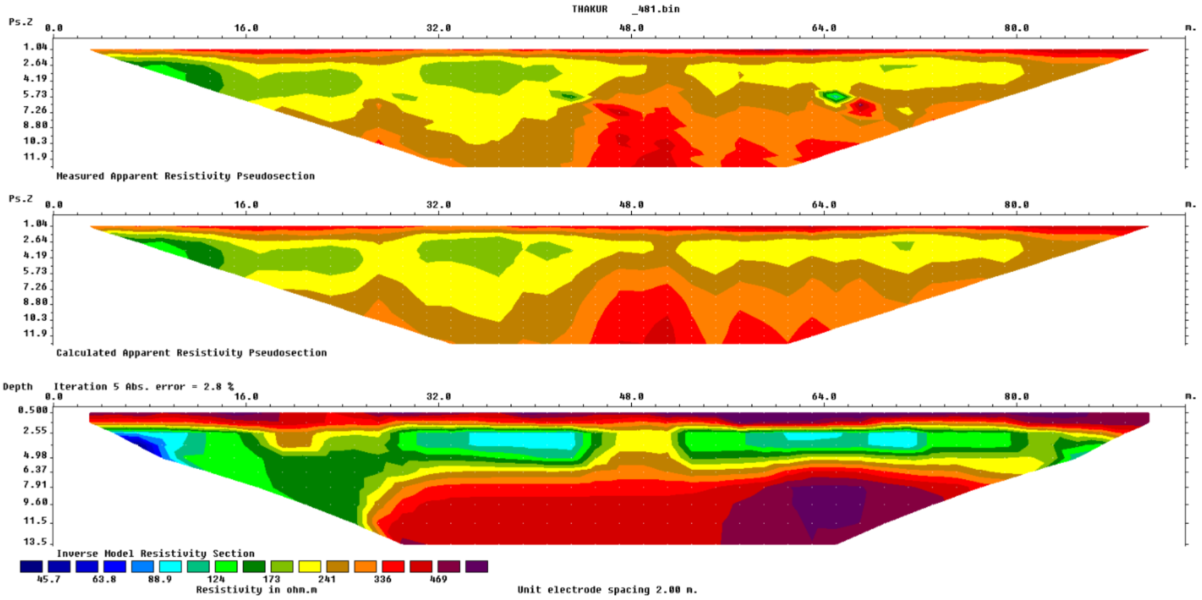


Figure 8.3: Electrical resistivity survey result

The perfect recession curve of an elongated period of more than a few months without rainfall was very rare in the Mathamali spring. Regular rainfall could cause small recession events which did not represent the impact of the intervention work. Therefore it was desired to investigate more recession events constituting different time span as far as possible which allowed to develop an average recession curve and the envelope of minima (Figure 8.4).

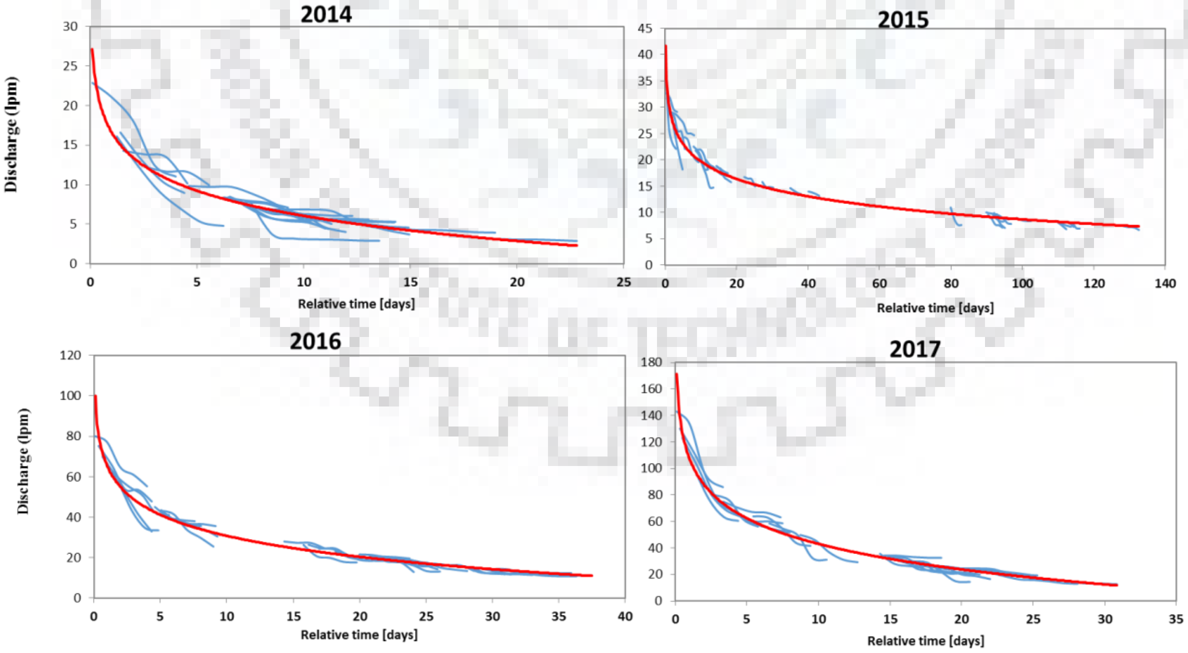


Figure 8.4: Master recession envelop by logarithmic function

The choice to produce an envelope curve by different functions - the logarithmic, the power, the exponential and the linear depended upon the accuracy desired. In the present analysis, the logarithmic function described the recession behavior well (Table 8.3) for the Mathamali spring for all of the years with a coefficient of determination of more than 0.88.

Table 8.3: Behaviour of recession envelop by different function

Regression Type	Function	Year				Year			
		2014	**2015**	**2016**	**2017**	**2014**	**2015**	**2016**	**2017**
		Regression equation constants				Coefficient of determination R^2			
Logarithmic	$Y = -\alpha ln(X)+b$	4.58,16.6	4.27, 30.68	15.01, 65.36	27.86, 107.23	0.88	0.95	0.95	0.96
Power	$Y = bX^{-\alpha}$	16.99, 0.50	32.63, 0.23	72.28, 0.398	119.8, 0.48	0.79	0.95	0.92	0.9
Exponential	$Y= be^{-\alpha X}$	15.52, 0.09	31.67, 0.05	66.57, 0.084	108.33, 0.099	0.79	0.97	0.96	0.95
Linear	$Y=-aX+b$	0.72, 14.98	0.90, 29.48	2.71, 59.16	4.75, 94.66	0.74	0.95	0.88	0.85

Analysis of the master recession curve (MRC) characterized an elongated period of individual recession events. The average daily spring flow was used to investigate the applicability of the number of recession coefficients to the formulated model which could later be used to predict the discharge during the lean period or the rainless time. Commonly, the Maillet equation is used to model the spring flow i.e. $Q_t = e^{-\alpha(t- t_0)}$, which is an exponential function. The Maillet equation which have only a single recession coefficient (α) was modified for two and three recession components and was calculated by the equations 8.4 and 8.5.

$$Q_t = \left[\sum_{t=1}^{N} Q_0{}^{e^{-\alpha_1 \times (t-0)}}\right] + \left[\sum_{t=N+1}^{N+M} Q_1{}^{e^{-\alpha_2 \times (t-N)}}\right] \tag{8.4}$$

$$Q_t = \left[\sum_{t=1}^{N} Q_0{}^{e^{-\alpha_1 \times (t-0)}}\right] + \left[\sum_{t=N+1}^{N+M} Q_1{}^{e^{-\alpha_2 \times (t-N)}}\right] + \left[\sum_{t=N+M+1}^{T} Q_2{}^{e^{-\alpha_3 \times (t-N+M)}}\right] \tag{8.5}$$

where, Q_0, Q_1, and Q_2 are the initial discharge values before the decay from one component to another and α_1, α_2, and α_3 are the slopes of the three recession components, time varies from t = 1 to T (Figure 8.5).

The decay of the flow from the Mathamali perennial contact and fracture type spring was well modelled by three exponent components rather than a single (α) coefficient. However, the recession curve coefficients of α_1, α_2, and α_3 has differed for each year as they depended on its peak flow and shape. The initial recession coefficients (α_1) characterized the turbulent drainage from fractures followed by an intermediate portion where the discharge was less turbulent, and redirected the impact of the rock matrix with the last component that ended with a gradual diminishing curve.

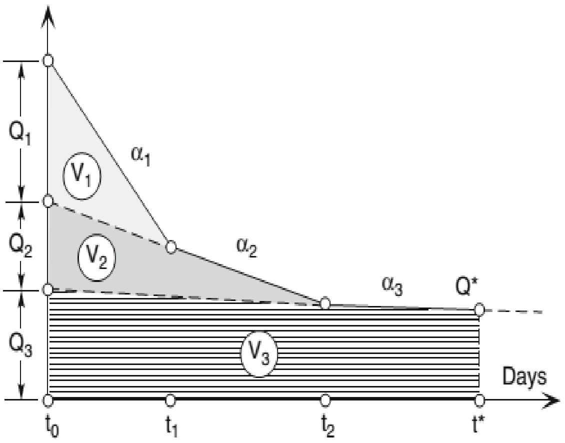


Figure 8.5: Schematic presentation of the recession with three component (Kresic, 2007)

Table 8.4 : Recession curve fitting by one, two and three coefficient

Year	*Fitting curve by*	*MRC Coefficient*	*Slope*	*Initial Discharge (lpm)*	*Final Discharge (lpm)*	*Duration (days)*	*Actual total discharge (litre)*	*Predicted total discharge (litre)*	*% Error from actual*
2014	*1 coefficient*	α_1	0.02	30.3	3.93	100	1216411	1827360	33.4
	2 coefficient	α_1	0.023	30.3	6.82	64		1703491	28.59
		α_2	0.018	7.53	3.93	36			
	3 coefficient	α_1	0.04	30.3	5.87	39		1217477	**0.09**
		α_2	0.01	7.13	4.46	44			
		α_3	0.008	3.93	3.93	17			
2015	*1 coefficient*	α_1	0.01	37.7	13.12	105	2529360	3487536	27.4
	2 coefficient	α_1	0.017	37.7	15.37	53		3024576	16.37
		α_2	0.006	18.25	13.12	52			
	3 coefficient	α_1	0.019	37.7	18.17	39		2992320	**15.49**
		α_2	0.027	21.8	14.85	13			
		α_3	0.006	18.25	13.12	53			
2016	*1 coefficient*	α_1	0.016	80.07	16.4	98	4811472	5586912	13
	2 coefficient	α_1	0.021	80.07	19.18	70		4935600	**2.5**
		α_2	0.006	19.54	16.4	28			
	3 coefficient	α_1	0.03	80.07	38.24	25		4625899	4.01
		α_2	0.013	39.26	19.2	54			
		α_3	0.008	19.2	16.4	19			
2017	*1 coefficient*	α_1	0.021	142.98	12.69	116	4867834	8832816	44.8
	2 coefficient	α_1	0.027	142.98	17.22	79		7653485	36.39
		α_2	0.024	29.87	12.69	37			
	3 coefficient	α_1	0.041	142.98	30.53	38		6218525	**21.72**
		α_2	0.025	30.8	14.68	35			
		α_3	0.005	15.73	12.69	43			

It was observed that after the intervention in the springshed the recession coefficients have increased to 0.041(α_1) and 0.025 (α_2) from an average of 0.03(α_1) and 0.017 (α_2). Whereas the last coefficient (α_3) that was responsible to maintain the flow for a longer period had increased from an average of 0.005 to 0.007 after the intervention. The post intervention work from the last one year indicated the increment in the net recharge, with 58% of the volume which was caused by the storage of water in the pits and the trenches. The relatively more coefficients of the spring, as reported by Padilla et al. (1994), might be because of different geological settings. The post intervention work in the year 2017 has increased the durations of decay by 16% to 116 days for 142.98lpm of peak flow to 12.69lpm of base flow when compared to the previous 100 days to recess from 30.3lpm to 3.93lpm in the year 2014 and 98 days to recess from 80.07lpm to 16.4lpm in the year 2016. The ratio of the recession coefficient (α_2/α_3) for pre intervention was 2.3 which increased to 5.0 after the intervention. The major change was due to the decrease in α_3 value from 0.007 to 0.005 which was related to the change in the effective porosity (Fiorillo, 2011). The lower value of α_3 suggested the low hydraulic conductivity which represented the slow depletion (Kumar and Sen, 2017). More volume was received during the post intervention work which indicated that the storage of water in the pits and trenches in the recharge zone, which later drained to the aquifer could enhance the holding capacity of the aquifer after the rainfall during the wet period rather than ending up as surface flow. In the changing rainfall pattern with the shrinking of monsoon time across the region and the Himalayas, promotion of this kind of intervention in the hills would increase the availability of water resource.

The percentage of duration in which the discharge was equaled or exceeded from the Mathamali spring after and before the intervention was calculated using the Weibull equation (Figure 8.6). The minimum average spring flow was 2.3 lpm which has increased 5 times to 11.5 lpm, whereas the average maximum flow has increased 1.8 times from 80.07 to 146.4. The total volume of water available from the spring after the intervention was 19901m^3, whereas the requirement was 3818m^3 (Kumar and Sen, 2017). The characteristic value for the spring using flow duration curve was 30.6 lpm before the intervention which also increased to 95 lpm after the intervention.

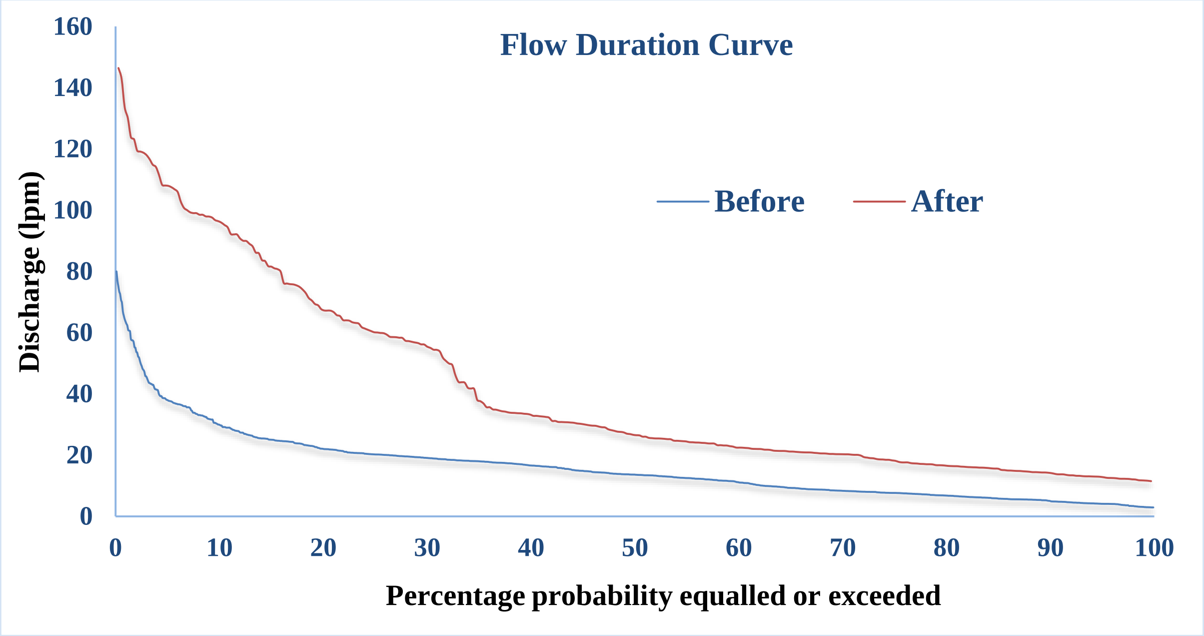


Figure 8.6: Flow duration curve for Mathamali spring

Findings from the flow duration curve revealed that on an average the Mathamali spring under the minimum flow conditions was able to meet the domestic water requirement if a storage tank of capacity of 1,000 m^3 (5×200) was constructed. Confirming the perceptions of the farmers and the local people regarding the decrease in the rainfall in the area, the major outcomes of the intervention in terms of volume could change the economy and the livelihood of the rural population. Although in a year (post intervention), it was hard to show the rate of the increment of the volume with the hydro-meteorological parameters. Therefore further measurement of the rainfall and the discharge along with the measurement of other hydro-geological parameters were necessary to develop this relationship.

8.3.4 Comparison of Mathamali spring with other type of springs

The analysis of the discharge data of the contact spring revealed that, during the monsoon season interflow, the baseflow decayed more rapidly at the rate of 0.04 day^{-1} and 0.78 day^{-1} respectively when compared to the pre and the post monsoon periods, therefore the recession hydrograph has a stiff slope. The results indicated that the permeability of the porous medium was comparatively high. If the number of the rainfall events during the monsoon season decreased, the daily spring discharge has reduced to a minimum. But during the pre and the post monsoon period, the permeability of the aquifer system decreased so the baseflow and the interflow component decayed slowly at the rate of 0.01 day^{-1} and 0.05-0.35 day^{-1} respectively which maintained the spring discharge for a longer period during the less rainfall condition. In case of the depression spring, the aquifer system was highly permeable during the pre-monsoon period so the baseflow recession (α_b) occurred at the rate of 0.03 day^{-1} which suggested that the baseflow component reduced to the minimum value after 33 days from the day of the peak discharge. But during the monsoon season, the permeability of the porous and the fractured system increased so the interflow decayed at a quicker rate but the aquifer system had the capacity to store and transmit water in the form of the baseflow which helped to maintain the spring discharge for a longer period. In the post monsoon season from October to December, the permeability of both the fractured rock system and the aquifer system was comparatively low so the interflow and the baseflow both had simultaneously contributed to maintain the spring discharge for a longer duration. In the contact-and-fracture spring system, the baseflow had played a considerable role to maintain the spring discharge throughout the entire year as the baseflow recession occured at the rate of 0.01 day^{-1} and maintained the flow during the lean period after 100 days from the peak discharge. During the pre-monsoon season, the permeability of porous and fractured rock system was very high which resulted in the decay of the interflow component at a faster rate of 1.02 (day^{-1}) and suggested that the interflow receded rapidly within 1 or 2 days after the day of the peak discharge. But during the Monsoon, may be due to the continuous and high intensive rainfall events, both the interflow and the baseflow simultaneously contributed and maintained the spring discharge.

8.3.5 ANOVA test

The present analysis required to test the association between the rainfall and the outflow from the Mathamali spring before and after the intervention work. It was noticed that there was a significant relationship between the daily spring discharge and the rainfall variability in the springshed before and after the intervention. Table 8.5 displayed the summary of the statistics for the rainfall and the spring discharge and the results of the ANOVA test for the three years from 2014-2017 duration and after the intervention in the springshed (2017).

Table 8.5: Summary of analysis of variance

Groups	*Count*	*Sum*	*Average*	*Variance*
Spring Discharge	1487	32401.99	21.79018	443.6818
Rainfall	1487	4483.704	3.015268	101.1304

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-Value*	*F crit*
Between Groups	262081.6	1	262081.6	962.099	0.000	3.84459
Within Groups	809591	2972	272.4061			
Total	1071673	2973				

Source of Variation	*SS*	*df*	*MS*	*F*	*P-Value*	*Fcrit*
Between Groups	110050.5	1	110050.5	222.7537	0.000	3.854264
Within Groups	359665.4	728	494.0458			
Total	469715.9	729				

Table 8.5 provides a clue that if F > Fcrit (962.099 > 3.84459 and 222.7537 > 3.854264) suggesting that one can reject the null hypothesis of no relationship between the rainfall and the spring discharge. The means of the rainfall and the spring discharge were not equal. The rejected results of the hypothesis testing of the relationship between the rainfall variability and the spring discharge indicated that the rainfall variability affect the behaviour of the spring discharge in a way that the low rainfall diminished the spring recharge with time and as there was high rainfall more springs were produced within the springshed. There was a time lag between the rainfall and the spring discharge due to the differences in the time taken for the rainfall to penetrate into the top soil surface and the slow rate of the subsurface flow towards the springs. The Mathamali spring in the Aglar watershed dried which lead to the decline of the base-flow which in turn has reduced the availability of water for both domestic and livestock purposes. The results of the analysis could be treated as a preliminary test to establish benchmarks for sustainable development of the springshed.

8.4 CONCLUSION AND RECOMMENDATIONS

Springs are the backbone of the mountain community and drying up and leading to reduction of base-flow is threat and a concern for the community living in hills. As perceived by the residents from the location of the study, the spring flow has decreased significantly, affecting the issues of drinking water, ecological health and water quality. The study was conducted to understand the drying of the springs and the availability of water during the dry periods. Rainfall is the only source to recharge the springshed. The lack of conservation practices and degradation of the land are some of the main causes of reduction in the recharge and for spring outflow. Understanding of recession of the hydrograph and compromising different rainfall conditions helped to understand the hydrological behaviour of the aquifer and provided some clues about the storage- discharge relationship. The recession analysis gave an idea about the rate of decay in different spring systems and helped to estimate the number of days after which the discharge occurs in an extreme situation in the absence of successive rainfall. For the contact spring, the recession coefficients were in the range of 0.01 to 0.04 day^{-1} for the baseflow and 0.05 to 0.78 day^{-1} for the interflow, whereas for the depression spring, the recession coefficients were in the range of 0.01 to 0.03 day^{-1} for the baseflow and 0.28 to 0.76 day^{-1} for the interflow. In case of the Mathamali spring which is a contact-and-fracture type spring system, the baseflow decayed at a constant rate of 0.01 day^{-1} which signified the permeability of the aquifer system and was expected to likely remain constant all through the year. The interflow coefficients were in the range of 0.16 to 1.02 day^{-1}.

The average spring flow rate from the springshed has increased from 16.9lpm to 41.63lpm with the intervention. It was suggested that the integration of farmer's participation and springshed intervention practices were needed to revive the springs. The post intervention work during the last one year indicated the increment in the net recharge with 58% of volume The flow duration analysis of the daily flow suggested that, the characteristic value for the Mathamali spring was 30.6 lpm before the intervention which has increased to 95 lpm after the intervention. Even during the minimum flow conditions the spring would be able to meet the domestic water requirement if a storage tank of capacity of 1,000 m^3 is constructed. From the master recession curve analysis it was concluded that the fitting of the recession curves by three-exponential recession coefficient forecasted that the spring discharge in the recession period neared 90% accuracy when compared to the one recession coefficient at 70% and the two recession coefficient at 16%. The ratio of the recession coefficient (α_2/α_3) was 2.3 which increased to 5.0 after the intervention due to the decrease in the value of α_3 from 0.007 to 0.005 which was related to the change in the effective porosity and was responsible for the discharge rate. In the ANOVA analysis, the springflow volume variability did not completely describe, although it was statistically significant and rejected the null hypothesis of no relationship between the rainfall and the spring discharge. The complete advantage of the intervention effort in the springshed could be recognized after 3 to 5 years with regular cleaning of the pits and the trenches, which could be filled with medium aggregates and dry leaves. The present study, just after a year of the intervention, indicated only adequate changes that took place and needed to be supplemented through long monitoring, which is being continued at present and with advanced studies such as isotopic analysis that are being planned for the near future. Finally at the end of this, the authors have some recommendations to secure life of the rural community in the Himalaya Mountains.

1) Strengthen the basic civic education through execution of awareness campaign focusing on the spring water conservation and discuss the strategies to control the negative actions, for example, cultivation on the steep slopes.

2) Request concerned government authority to design policies and guidelines that adhere with the Forest Act, Water Act and other recommendations suggested by the world environmental organizations (WEO).
3) To work in collaboration with the active NGO’s, Forest department, local representatives, environmental and hydro-geologists to leverage the spring water, thus building a community capacity for water sustainability.
4) Detailed isotopic analysis and follow up on remote sensing data analysis to calculate the rate of forest deprivation and land cover changes over the years.
5) Detailed analysis of the soil and water quality to suggest the best cropping systems for the up liftment of the socio- economic status of the residents of the area.

CHAPTER 9

CONCLUSIONS AND FUTURE RECOMMENDATIONS

9.1 Overview

As we all understand that, water is the key element to support life, however its improper use and unscientific harnessing cause various issues. Already few nations around the globe are confronting an extreme water emergency and in which recent example is of Cape Town in South Africa. The issue of water scarcity is aggravated due to enormous rural and industrial expansion along with the aimless overexploitation of surface and groundwater resources for irrigation and agriculture and hydropower generation. Irrigation occupies upper priority as it accounts for 70% followed by the industries (20%) and rest 10% accounts for domestic use. The ongoing and continuous water resources and hydrological issues (limited gauging concern and data sharing) in light of climate change and other anthropogenic impacts, attracts concern for data issue that has influenced and keeps on influencing poor individuals over the Himalayan and other mountainous region to access water for livelihood and food security. The present study in dissertation introduces about the issues of water in Himalaya and outline the background and research gap with the necessity of the study in rural mountainous area.

Thus, the short-and-long term uninterrupted monitoring of surface and sub-surface flows along with the meteorological parameters i.e. rainfall, temperature, are a prerequisite for understanding the key driven processes and sustainable watershed management at local or regional level in mountainous region. However, in the Himalaya and many other part of country, these hydro-meteorological gauging systems remain very limited and often not available. Even in the case of available gauging location, these are hardly satisfactorily maintained and it has been noticed that several gauging locations have declined over the past few years. As a consequence, this dissertation focused on the development of hydro-meteorological monitoring system in Aglar watershed (305km^2) located in the Lesser Himalaya. The objective of establishing this network of hydro meteorological gauging was to observe high resolution data to understand the rainfall response on stream flow under different land use and to understand the dynamic behavior of the sub-surface flow which is the main domestic water supply source. Appropriate quantification of surface and sub-surface flows and understanding of the hydrological processes helps in developing rainwater controlling approaches which will relief the livelihoods of rural mountainous people.

The specific objectives of the present study were as follows:

1. To develop an Aglar experimental watershed with intensive instrumentation and data collection to understand the hydrological responses.
2. To develop rating curve and assessment of associated uncertainty and correlate it with morphometry of watershed.
3. To investigate the sub-surface flow dynamic behavior and modeling of recession curve.
4. To quantify the crop water requirement and develop micro watershed irrigation using spring system.
5. To understand the impact of spring intervention on spring yield.

Summary of conclusions on different aspects of the objectives and major contribution of this research work are presented below.

9.2 Analysis and interpretation from hydro-meteorological data

Hydro-meteorological data monitoring in the Lesser Himalaya and its analysis plays an imperative role, and delivers valuable facts and information. In the present case the analysis are restricted to rainfall, discharge from two different rivers located in different land use land cover and analysis make available following conclusions.

9.2.1 Rainfall Characteristics

Rainfall was measured by calibrated recording rain gauge logger and archives the time of occurrence of individually rainfall with time that gives accurate measurement of rainfall intensity. The average annual rainfall of the Tehri region was 1029mm whereas the annual rainfall in year 2016 and 2017 was more than the average rainfall of the region, however the annual rainfall was less in year 2014 and 2015. Annually the highest number of rainy days (71) was noticed in year 2017 followed by 2015 (62), 2014 (60) and 2016 (57). The analysed seasonal rainfall revealed that an average of 726.7mm of rainfall occurred during the monsoon period whereas in summer and winter it was 223.3mm, 111.9mm respectively and during post monsoon very less amount 3.4mm or negligible rainfall occurs. The highest percentage of total rainy days is observed in the month of July (36.4%) followed by August (32.4%), June (18.8%) and September (12.4%). During the early month of September (1-20) the watershed remains dry all the time and probability of occurring rainfall is very less as compared to July (11-20). It is advised to store the excess rain occurred during July (11-20) and stored water can for later use to meet their requirements.

9.2.2 *Discharge behavior in Aglar and Paligaad sub-watershed*

Automatic recording water level were used as equipment to measure water levels which later were converted to flow via rating curves. The discharge in the rivers were measured by salt dilution method which is commonly suitable in the mountainous catchment. In beginning of the water year flow is increasing since May and reaching the first peak in the month of June which increasing continuously between July to August, when the more rainfall occurs after which discharge starts decreasing between September and January due to less or no rainfall condition. The mean of daily recorded river flow is 0.98 m^3/s for Paligaad and 0.58 m^3/s for Aglar, shows that Aglar River is a comparatively small river in term of total volume yield. Seasonal variation of river discharge reveals that about 70.0% of discharge is during the rainy season and very low percentage of river discharge was found in winter (10.5%) and summer (11.6%) season.

9.2.3 *Rainfall runoff response under different land cover*

The catchments show differences in the land use land cover (LULC) pattern, the Paligaad consists of 55.1% of the catchment’s area with forest and 27.3% with agriculture cover whereas Aglar have 42.7 % area under forest and 16.7% as agricultural land, this different forest coverage and agricultural land together with the soil have different impact on hydrological responses. To understand the hydrological responses, rainfall-runoff (RR) events were selected on the basis of “increases in discharge because of rainfall over a 10mm in a day and discharge surpassing the preceding discharge by at least 10%” which gave 15 RR events (7 for Aglar and 8 for Paligaad) during April 2014–October 2016. Runoff responses from Aglar and Paligaad sub-watersheds towards rainfall, demonstrated the nonlinear behavior suggesting that total discharge for the watershed are not only dependent on rainfall amount and its intensity but also on base flow and soil antecedent moisture conditions.

A rainfall of 13.72mm in summer (May) resulted in a 1.66mm and 4.72mm of direct runoff in Aglar and Paligaad watershed respectively, while rainfall of the 33.40mm (two times higher) happening in winter (February) were generate only 1.55mm and 3.39mm of direct runoff in Aglar and Paligaad sub-watershed, suggesting that portion of the total rainfall was used for recharging of the soil moisture reserves. Further RR responses suggests that when the watershed turn out to be wet during the rainy season, the quick response in discharge (Paligaad > Aglar) increases, possibly the antecedent condition and slope of the watershed plays an essential role. During the water deficit time period evapotranspiration (mm) is dominant over the rainfall, and rainfall during this time is few mm results in low generation of total flow from the watershed, because an extensive amount of the rainfall is lost as evaporation from the open surface and transpiration from plant and trees and very less portion of rainfall is used to supply the soil water demand. The reasonably low value of runoff coefficient in Aglar as compared to Paligaad could be associated to the low water transmit ability of soils and high soil infiltration capacity. Finally it is concluded that Paligaad shows flashy response towards the rainfall whereas Aglar exhibit a wide range of dampening runoff response for different rainfall characteristics which prove the hypothesis of more fracture and cracks in the aquifer of Paligaad sub-watershed.

9.2.4 *Flow duration curve*

Flow duration curve (FDC) involving the frequency of observed flow data over a specified period. The flow duration curve of Aglar in comparison to Paligaad shows higher “high flows”, representing more frequent extreme conditions, being coupled with lower “low flows”, representing less base-flow contribution. The less variability in the lower tail (35 %–100 % exceedance) of the duration curve in the both watershed may be because of base-flow contribution to the total river flow suggests a valuable means for studying the effect of geology on the ground water contribution to the river. The upper portion of duration curve, which represents the high flow conditions shows high variability in case of Paligaad as compared to Aglar. The flatter seasonal duration curve of Aglar as compared to Paligaad, characterizing more uniform river flow, suggesting that the total seasonal flow will be spread more evenly over the season, provides sustainable flow for a longer period, and less extreme flow conditions.

9.3 Rating curve development and uncertainty analysis

Understanding of dynamic nature of river flow at mountains are full of challenges, cannot be accurately succeeded without knowing in what quantity it is available and causes many errors while measuring the river discharge and gauge height which becomes very challenging to stochastic nature of discharge preciously and likely foreseeable water resources availability. A linear trend line between ‘log Q’ (Y-axis) and ‘log (h)’ (X-axis) was well fitted in Matlab to obtain the stage-discharge relationship for three rivers (Aglar, Balganga and Paligaad). The developed relationship between stage and discharge were similar for Aglar and Paligaad which have relatively less relief ratio (0.002 and 0.004) as compared to Balganga which has relief ratio (0.007). The stage-discharge relationship for the Balganga where flow is usually low as compared to Aglar and Paligaad are frequently influenced by section control. High flow in the Paligaad is influenced by channel control whereas Aglar is influenced by combination of both section and channel control. With the limited stage-discharge observation, it is very difficult to identify a particular cause for the variability in future.

The uncertainty was analysed using maximum likelihood method in stage discharge relationship and it was estimated to 11.9% in Aglar, 28% in Balganga and 43% in Paligaad. Because of flashy nature of Paligaad river as compared to Balganga and Aglar so the favorable discharge measurement consists of only a few measurements, and the error is as much as 43%. Our conclusion from the uncertainty analysis is that uncertainty in stage-discharge relation will be more where less data (pair of Q, H) is observed for rating curve generation during the high flows. Also in case of the Paligaad, 95% uncertainty prediction interval (bound) is much wider for larger values of stage measurement as compared to Aglar and Balganga. A weighting factor concept is developed to understand the influence of watershed geomorphology on uncertainty and the geomorphological parameters such as area of watershed, drainage density, relief ratio, form factor and elongation ratio. The higher value of weighing factor (0.37) for Paligaad as compared to Aglar (0.27) and Balganga (0.35), more will be the uncertainty, suggests more error in Paligaad as compared to Balgange and less in case of Aglar. This concept supports the degree of the uncertainty in discharge estimation and it could be further reduced by more field instrumentation, developing new methods based on data, technologies and techniques for high flow measurements and winter river flow monitoring.

9.4 Spring discharge dynamics using recession curve analysis

Himalayan springs are one of the important sources of domestic water supply in this region. Monitoring and modelling of the spring system helps to understand the dynamic nature as well as seasonal variability in spring discharge. With this aim a fracture-and contact-type spring (Mathamali) located in the Aglar watershed has been instrumented for continuous discharge data collection. The recession curve for different events were analysed and suggests that the decay of spring during the rainless time, nonlinear least square and newly developed combined power law fits the recession curve better than the exponential and hyperbola which many literatures pursued. Least square method best fit for wet period events with RMSE (0.07-0.22) and NSE (0.90-1) whereas combined power law best fit for dry period events with RMSE (0.07-0.56) and NSE (0.97-1). Maximum value of recession slope for the studied spring is 0.06 which is more as compared to the Ranichauri spring (0.02) located in same district but in different geological location. The long decay from spring is analyzed using master recession curve (MRC), which support the use of three exponential coefficients over the use of single and double exponential coefficient. It is observed that these recession parameters not only depend on initial spring discharge but also depends on other hydro geological parameters.

Storage-discharge relationship of Mathamali spring using relation $-dQ/dt = aQ^b$, confirms the dynamic nature of spring. Different values of "a" for different considered events indicates different physio-climatic process which governs the sub-surface flow. Investigated monthly cumulative spring discharge during the monsoon period (July-September) is about 73% of the total spring discharge. Flow duration curve of the spring flow revels that daily spring flow is 72% more than required domestic water i.e. 28% less than required domestic water demand indicating water scarcity during dry seasons. Further analyses of FDC reveals that 90 percentile of observed discharge data is less than 30.6 lpm which can be taken as the characteristic value for minimum spring flow. Spring recession curve analysis and methodology to fit the decay behavior can also be used for long and short term planning to address the water resource issues in Aglar watershed and for comparing the spring characteristics at other mountainous watershed.

9.5 Spring potential for sustainable agriculture

In the mountainous regions, limited land with uncertain water availability (surface and sub-surface) pose a major threat to the livelihood. The observed discharge of Mathamali spring revealed that the average annual availability of spring water is 7149.5m^3. The volume of spring water varies with the season and reached maximum volume (1063.8m^3) in the month of October and minimum volume (293.2m^3) in February. Resident of the area grows majorly 10 crops i.e Potato, Onion, Garlic, Rice, Beans, Tomato, Cabbage, Capsicum, Radish, and Peas. The FAO PM method has been used to calculate crop water requirement for major crops that are grown in the study area and found that crop evapotranspiration is higher (946-1062mm) for crops with extended duration (165-180days) as compared to (92.91mm) for short duration (60days) crops. Farmers can harness the total volume of spring and rainfall

($21119.4m^3$) which goes directly to the river, to irrigate their small land holdings. The spring discharge analysis revealed that the average annual availability of spring discharge in this watershed is $7149.5m^3$ and have an option to use the water for agriculture in an optimized way. The economy of this region is mainly dependent on agriculture which is the main user of water. Understanding of rainfall and spring variability plays a crucial role in developing artificial structure for storage of excess of spring and rainfall, which can be used later for irrigation.

If excess spring discharge during monsoon can be stored by constructing a tank of $1000m^3$ and utilizing it for irrigation during the required period will increase the net benefit from agriculture. The estimated net crop yield is 335.84 quintal with benefit to cost (B/C) ratio of 2.54 by utilizing the stored water. It has been found that system of rice intensification (SRI) produces 49% higher yield with 14% less water increases water productivity by adopting SRI techniques. The crop yields from the field can be further increased by applying the water through drip irrigation. Sensitivity analysis divulges that the increase in the total yield by 30% can increase the revenue of farmers by 217% more than their input costs. Judicious use of these available natural resources require long term planning and accurate database, planning and management, and risks and benefits of agriculture.

9.6 Rejuvenation of spring: coping with water insecurity

It has been reported that adopting the springshed development methodology can increase the discharge and maintain flow for longer duration during lean periods. The major challenges faced in adopting this approach is to identify the recharge areas precisely and incentivizing farmer's fields and finding community participation and financing. The springshed intervention practices were implemented after three years of monitoring i.e in early April, 2017 to increase spring discharge. The intervention comprises of artificial recharge works of 14 staggered contour trenches and 5 percolation pits of different dimensions in the recharge zone of springshed. The measured average flow before the intervention was 16.9lpm but soon after the intervention work the average flow increased by 2.6 fold.

Post intervention work of last one year shows the increment in net recharge, and volume. FDC analysis of daily flow suggested that, the characteristic value for the Mathamali spring was 30.6lpm before intervention which has increased to 95lpm after intervention and even in the minimum flow conditions spring is able to meet domestic water requirement if we construct the storage tank of capacity of 1,000 m^3. The ratio of recession coefficient (α_2/α_3)

was 2.3 which increased to 5.0 (46%) after the intervention because of decrease in the value of α_3 from 0.007 to 0.005 which is related to change in the effective porosity and is responsible for the net discharge rate. The present result is just after a year of intervention, shows only adequate changes that took place and need to supplemented through separately long monitoring (which is continuing) and advanced studies such as isotopic analysis (planned for near future work).

9.7 Key messages

In the Lesser Himalaya, there are major gaps in the knowledge of hydrological processes occurs and data related issues which raised many unanswered queries (land cover impact on discharge, rainfall influence on discharge etc.). The present work solved few data issues concern in lesser Himalaya and answers few queries that were not attempted so far after setting of an experimental watershed. Author personally feels that in remote and rural location of the Himalaya, field incentive and public-government organizations need to establish to train local stakeholders. From the present study the following key messages have been drawn:

- Prior to hydro-meteorological instrumentation in the field, identification and prioritization of watershed should be acknowledged which resolve the water resources issues, helps in hydrological study and provide the opportunities for the development of further instrumentation and management strategies.
- To assess the influence of climate changes and other anthropogenic effect on surface and sub-surface flow, requires reliable instrumentation which can withstand for longer duration may be periods of centuries.
- Gauging location is decided using topography, LULC, soil condition, and other field constraints to cognizant the planning and decision for sustainable management.
- Advance techniques and instruments to be used that can cover the discharge measurement during the extreme conditions in the river so that error in stage-discharge relationship can be minimized.
- We have an important understanding of the rainfall runoff processes in the Aglar and Paligaad, efforts are required to develop conceptual or physical model that requires short data (less than 5 years) and are essentially based on rainfall and other meteorological variables with morphometric characteristics of the watershed.

- Agriculture is dominating user of water in this region, whereas unpredictable rainfall together with the increase in temperature are threats for their food securities. Thus there is a requirement for a detailed assessment of available natural resources (springs) to ascertain best management practices and comprehend their both positive and negative impression on agriculture, and to identify how these springs can be reinforced to meet smallholder and marginal farmers water requirements.

9.8 Major research contributions

The main research contribution in the present dissertation work is summarized as follows:

- An experimental watershed has been developed on the Aglar river to understand the hydrological response of sub-watersheds under different land cover using the high frequency hydrological data.
- All the rainfall, surface and sub-surface flow data analysed and used in this dissertation are primary.
- Uncertainty analysis have been performed on the developed rating curve which is not in traditional practice and linked the uncertainty with the morphometric characteristics of watershed by introducing the weighing factor concept.
- Developed model for spring recession curve using combined power and exponential law.
- Development of spring water resource and implementation of water harvesting structure for spring discharge enhancement.

9.9 Scope for future research in the Aglar watershed

- Continue monitoring effort and further strengthening of more instrumentation with more river gauging, sediment sampling and installation of piezometers to understand the geological factors influencing the surface and sub-surface flow.
- Improvement in developed rating curve and reduce the uncertainty in developed rating curve which are because of varying river bed material and effects of ongoing construction in the upper portion of the watershed.
- Event and sub-hourly based hydrological modeling to provide the general explanation of hydrological processes in the upper Aglar and Paligaad sub-watersheds. Investigation at watershed response and interaction between the

upstream and downstream would provide valuable information on how the watershed slope and its configuration behave.

- Detailed isotopic analysis and follow ups on remote sensing data analysis for carrying out the rate of forest deprivation and land cover changes over the years.
- Further work is required to quantify the spring volume after two and three years to assess the intervention potential for local level and further analysis needed to verify the present results.

BIBLIOGRAPHY

1. ACWADAM (2009) Field-based capacity building in geohydrology based catchment area planning for spring water management under the Himmotthan initiative. ACWADAM technical report.
2. Adrian R.J., Westerweel J., (2011). Particle image velocimetry (Vol. 30). Cambridge University Press, Cambridge
3. Agarwal A., Agarwal N. K., and Rathi V. K., (2015). Water stress on springs of Lesser Himalayan region. British J. Appl. Sci. Technol, 9 (3), pp. 243-255.
4. Agarwal C.S., (1998). Study of drainage pattern through aerial data in Naugarh area of Varanasi district, U.P, Journal of Indian Society of Remote Sensing. 26 pp. 169-175.
5. Agrawal N. K., Anirudh K., Leikanger I. CP., Sherpa, J. D., Dhrupad C., and Pantha R. H. (2016). Action for mountain adaptation: solutions beyond the boundaries of science, policy, and practice. ICIMOD Working Paper, (2016/4).
6. Agrawal S., Sanyal P., Sarkar A., Jaiswal M. K., and Dutta K., (2012). Variability of Indian monsoonal rainfall over the past 100 year and its implication for C3–C4 vegetational change. Quaternary Research, 77(1), pp. 159-170.
7. Ahmed A.U., Hill R.V., Smith L.C., Wiesmann D.M., Frankenberger T., Gulati K., Quabili W., Yohannes Y., (2007). The World's Most Deprived: Characteristics and Causes of Extreme Poverty and Hunger. IFPRI, Washington, DC.
8. Akan A. O. and Yen B. C., (1981). Mathematical model of shallow water flow over porous media, J. Hydraul. Div., ASCE, 107 (4), pp. 479-494.
9. Alaouze CM (1989) Reservoir releases to uses with different reliability requirements. J Am Water Resour Assoc. 25(6): 1163-1168.
10. Allen R.G., Pereira L.S., Raes D., Smith M., (1998). Crop Evapotranspiration - Guidelines for Computing Crop Water Requirements. FAO Irrigation and Drainage Paper 56.
11. Alpert P., Ben-Gai T., Baharad A., Benjamini Y., Yekutieli D., Colacino M., Diodato L., Ramis C., Homar V., Romero R., Michaelides, S., and Manes, A.: The paradoxical increase of Mediterranean extreme daily rainfall in spite of decrease in total values, Geophys. Res. Lett., 29, pp. 1–31, DOI: 10.1029/2001GL013554, 2002.
12. Amerasinghe U., Shah T., Turral H., Anand B.K., (2007). India's water future to 2025-2050: Business-as-usual scenario and deviations. Vol. 123. IWMI.
13. Amit H, Lyakhovsky V, Katz A, Starinsky A and Burg A (2002) Interpretation of spring recession curves. Ground Water. 40(5):543-551

14. Andermann C., Longuevergne L., Bonnet S., Crave A., Davy P., and Gloaguen R., (2012). Impact of transient groundwater storage on the discharge of Himalayan rivers. Nature Geosciences, 5 (2), ngeo1356.
15. Andermann C., Longuevergne L., Bonnet S., Crave A., Davy P., and Gloaguen, R. (2012). Impact of transient groundwater storage on the discharge of Himalayan rivers. Nature Geosciences, 5 (2), ngeo1356.
16. Anderson MG, Burt TP (1980) Interpretation of recession flow. J Hydrol. 46(1-2): 89-101.
17. Angelini P, Walter D (1977) The problem of modeling limestone springs: the case of Bagnara (North Apennines, Italy). Ground Water 35(4): 612-618.
18. Aryal K., Chettri N., Lepcha R., Bhuchar S., Kandel P., Karki S., Phuntsho K. and Ning W. (2017). Participatory ecosystem-based planning and management: A resource manual for mid-level technicians and development workers. ICIMOD Manual 2017/4. Kathmandu: ICIMOD
19. Askri B., Bouhlila R., Job J.O., (2010). Development and application of a conceptual hydrologic model to predict soil salinity within modern Tunisian oases. J Hydrol. 380:45–61.
20. Athira, P., K. P. Sudheer, R. Cibin, and I. Chaubey. (2016) Predictions in ungauged basins: an approach for regionalization of hydrological models considering the probability distribution of model parameters. Stochastic environmental research and risk assessment 30(4): 1131-1149.
21. Atkinson T. C., (1977). Diffuse flow and conduit flow in limestone terrain in the Mendip Hills, Somerset (Great Britain). Journal of hydrology, 35(1-2), pp. 93-110.
22. Baedke S. J. and Krothe N. C. (2001). Derivation of effective hydraulic parameters of a karst aquifer from discharge hydrograph analysis. Water resources research, 37(1), pp. 13-19.
23. Baedke SJ, Krothe NC (2001) Derivation of effective hydraulic parameters of a karst aquifer from discharge hydrograph analysis. Water Resour Res. 37(1): 13-19.
24. Baffaut C., Sadler E.J., Ghidey F., (2015). Long-term agroecosystem research in the central Mississippi river basin: Goodwater creek experimental watershed flow data. J. Environ. Quality 44(1):18–27.
25. Bagyaraj M., Gurugnanam B., (2011). Significance of morphometric studies, soil characteristics, erosion phenomena and landform processes using remote sensing and GIS for Kodaikanal Hills. J Environ Earth Sci 3, pp. 221–233.

26. Bakalowicz M (2005) Karst groundwater: a challenge for new resources. Hydrogeol J. 13(1):148–160.
27. Baldassarre D. G. and Montanari, A., (2009). Uncertainty in river discharge observations: a quantitative analysis, Hydrol. Earth Syst. Sci., 13, 913–921, DOI: 10.5194/hess-13-913-2009.
28. Barnes BS (1939) The structure of discharge recession curve. Trans Am Geophys Union. 20(4): 721–725.
29. Barros A. P. and Colello J. D., (2001). surface roughness for shallow overland flow on crushed stone surfaces, J. Hydraul. Eng.,ASCE, 127 (1), pp. 38-52.
30. Barrows C.J. (1998) River basin development planning and management: A critical review. World Dev. 26 (1), pp. 171–186.
31. Bartelmus P., (1997). Measuring sustainability: Data linkage and integration.
32. Bates B.C., Kundzewicz Z.W., Wu S, Palutikof J.P. (eds) (2008). Climate change and water technical paper of the Intergovernmental Panelon Climate Change IPCC Secretariat, Geneva.
33. Bates C. G., and Henry A. J., (1928). Forest and streamflow experiment at Wagon Wheel Gap, Colorado. Mon. Weather Rev. 56, pp.79-97.
34. Beavis S.G., Roberts J., Ellis D.J., (2010). Water-dependent ecosystems: the ecological consequences of irrigation infrastructure refurbishment. Waterlines Report Series No 33.
35. Beniston M (2003) Climatic change in mountain regions: A review of possible impacts. Clim Change.**59**(1) 5–31.
36. Beven K. and Binley A., (1992). The future of distributed models: Model calibration and uncertainty prediction. Hydrological Processes, 6, pp. 279-298.
37. Bharati L., Gurung P., Jayakody P., Smakhtin V., and Bhattarai U., (2014). The projected impact of climate change on water availability and development in the Koshi Basin, Nepal. Mountain Research and Development, 34(2), pp. 118-130.
38. Birk S., Ecke F., (2014). The potential of remote sensing in ecological status assessment of coloured lakes using aquatic plants. Ecol Indicators 46:398–406.
39. Birkhead A. L. and James C. S. (1998). Synthesis of Rating Curves from Local Stage and Remote Discharge Monitoring using Nonlinear Muskingum Routing. Journal of Hydrology, 205: 52.
40. BIS (1993) Indian Standard Code of Basic Requirements for Water Supply, Drainage and Sanitation. IS 1172. 4th revision. New Delhi, India.

41. Biswas S., Sudhakar S., Desai V.R., (1999). Prioritisation of subwatersheds based on morphometric analysis of drainage basin-a remote sensing and GIS approach. J. Indian Soc. Remot. Sens. 27 pp. 155–166.
42. Blaney H.F. and Criddle W.B., (1950). Determining water requirement in irrigated area from climatological and irrigation data. USDA Agr. SCS-TP 96.
43. Blume T, Zehe E and Bronstert A (2007) Rainfall—runoff response, event-based runoff coefficients and hydrograph separation. Hydro Sci J. 52(5):843-862
44. Boiten W., (2000). Hydrometry, Francis and Taylor publishers, 242 p.
45. Boldt J.A., Oberg K.A., (2015). Validation of streamflow measurements made with M9 and RiverRay acoustic Doppler current profilers. J. Hydraul. Eng.: 04015054.
46. Boman B. and Shukla S. (2009). Water measurement for agricultural irrigation and drainage systems. Agricultural and Biological Engineering Department, Florida Cooperative Extension Service, University of Florida.
47. Bonacci O (1993) Karst spring hydrographs as indicators of karst aquifers. Hydro Sci J 38(1): 51-62.
48. Bonacci O., Buzjak N., Roje-Bonacci T., (2015). Changes in hydrological regime caused by human intervention in karst: A case of the Rumin. Springs. Hydrol. Sci. J. DOI:10.1080/02626667.2015. 1111518.
49. Boussinesq J (1904) Theoretical research on the flow sheets of water seeped into the soil and on the flow of springs. Pure Math and Appl J.10:5–78.
50. Bradshaw C. J. A., Sodhi N. S., Peh K. S. H., and Brook B. W., (2007). Global evidence that deforestation amplifies flood risk and severity in the developing world, Global Change Biol., 13, pp. 1–17, DOI: 10.1111/j.1365-2486.2007.01446.x.
51. Bras R.L., Cordova J.R., (1981). Intra-seasonal water allocation in deficit irrigation. Water Resour. Res. 17(4), pp. 866–874.
52. Brauman K.A., Freyberg D.L., Daily, G.C., (2012). Potential evapotranspiration from forest and pasture in the tropics: a case study in Kona, Hawaii. J Hydrol. 440–441:52–61.
53. Brutsaert W (2005) Hydrology: an introduction. Cambridge University Press. UK.
54. Brutsaert W, Nieber JL (1977) Regionalized drought flow hydrographs from a mature glaciated plateau. Water Resour Res. 13(3):637–643.
55. Buechler S., Sen D., Khandekar N., and Scott C. A., (2016). Re-linking governance of energy with livelihoods and irrigation in Uttarakhand, India. Water, 8 (10), 437.
56. Burman R.D., (1976). Intercontinental comparison of evaporation estimates. J. Irrig. Drain Eng. 102(1), pp. 109–118.

57. Chandramouli C., (2011). Registrar General Census of India 2011.Provisional Population Totals. New Delhi. Government of India.
58. Chaudhary P., Rai S., Wangdi S., Mao A., Rehman N., Chettri S., and Bawa K. S., (2011). Consistency of local perceptions of climate change in the Kangchenjunga Himalaya landscape. Current Science, pp. 504-513.
59. Chauhan M., (2010). A perspective on watershed development in the Central Himalayan State of Uttarakhand, India. International Journal of Ecology and Environmental Sciences, 36 (4), pp. 253-269.
60. Chauhan M.S., Kumar V., Dikshit P.K.S., Dwivedi S.B. (2014). Comparison of discharge data using ADCP and current meter. Int. J. Adv. Earth Sci. 3(2):81–86.
61. Chauhan, M. S., Dikshit, P. K. S., and Dwivedi, S. B. (2015). Modeling of Discharge Distribution in Bend of Ganga River at Varanasi. Computational Water, Energy, and Environmental Engineering, 4(03), 25.
62. Chaulagain N (2006) Impacts of Climate Change on Water Resources of Nepal: The Physical and Socioeconomic. Conference Series: Earth and Env Sci. 6(29):292029.
63. Chen C.Y., Yu F.C., (2011). Morphometric analysis of debris flows and their source areas using GIS. Geomorphology 129 pp. 387–397.
64. Cheng Q (2008) A combined power-law and exponential model for streamflow recessions. J Hydrol. 352(1):157-167.
65. Chini C. M., and Stillwell A. S., (2016). Where Are All the Data? The Case for a Comprehensive Water and Wastewater Utility Database. DOI: 10.1061/(ASCE)WR.1943-5452.0000739.
66. Chow VT (1964) Handbook of applied hydrology. New York, U.S.A. McGraw Hill Inc.
67. Christiansen J.E., (1966). Estimating pan evaporation and evapotranspiration from climatic data. ASCE, J Irrigation and Drainage Specific Conf., Reston, VA., 193–231.
68. Christopher F. S., Jeffrey T. C. and Stephen M. W., (2010). The Continuous Slope-Area Method for Computing Event Hydrographs, Scientific Investigations Report, U. S. Geological Survey.
69. Church M. (1973). Some tracer techniques for stream-flow measurements. Tech. Bull. Br. Geornorphol. Res. Group.
70. Claessens L., Hopkinson C., Rastetter E., and Vallino J., (2006). Effect of historical changes in land use and climate on the water budget of an urbanizing watershed, Water Resour. Res., 42, W03426, DOI: 10.1029/2005WR004131.
71. Clark C., (1987). Deforestation and floods, Environ. Conserv., 14 (1), pp. 67–69.

72. Clarke J.J., (1966). Morphometry from map, essays in geomorphology. Elsevier Publishing Company, New York, pp 235–274.
73. Clarke R.T., (1999). Uncertainty in the estimation of mean annual flood due to rating-curve in definition. Journal of Hydrology 222 (1– 4): 185–190.
74. Comina C., Lasagna M., De Luca D.A., Sambuelli L., (2014). Geophysical methods to support correct water sampling locations for salt dilution gauging. Hydrol Earth Syst Sci 18(8):3195–3203.
75. Cruz R.V., Harasawa H., Lal M., Wu S., Anokhin Y., Punsalmaa B., Honda Y., Safari M., Li C., and Huu Ninh N., (2007). Asia. Climate Change 2007: Impacts, Adaptation and Vulnerability. In ML Parry, OF Canziani, JP Palutikof, PJ Van Der Linden, CE Hanson (Eds.) Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK. pp. 469-506.
76. Cynthia F. Malvicini, Tammo S. Steenhuis, M. Todd Walter, J.-Yves Parlange, Michael F. Walter (2005) ‘Evaluation of spring flow in the uplands of Matalom, Leyte, Philippines’. Advance in Water Resource. 28(10), 1083-1090.
77. Dastanen G., (1970). Review of work done on water requirement of crops in India, Navabharatprakasn, Poona, India.
78. Dataflow Systems Pty Ltd. (2008) PCSoftware and Technical Handbook for Odyssey Data Recorders. Christchurch, New Zealand. 29-40.
79. Datta AR, Bolisetti T, Balachandar R (2012) Automated linear and nonlinear reservoir approaches for estimating annual baseflow. J. Hydrol. Eng. 17:554–564.
80. Day, T. J., (1976). On the precision of salt dilution gauging, Journal of Hydrology, 31, 293–306.
81. De Walle D. R., Swistock B. R., Johnson T. E., and McGuire K. J., (2000). Potential effects of climate change and urbanization on mean annual streamflow in the United States, Water Resour. Res., 36 (9), pp. 2655 –2664, DOI: 10.1029/2000WR900134.
82. Deju R., (1971). Regional hydrology fundamentals. Gordon and Breach Science Publishers, Newark.
83. Dewandel B., Lachassagne P., Bakalowicz M., Weng P. H., and Al-Malki A. (2003). Evaluation of aquifer thickness by analysing recession hydrographs. Application to the Oman ophiolite hard-rock aquifer. Journal of hydrology, 274(1-4), pp. 248-269.
84. Dickinson, W. T. 1967. “Accuracy of Discharge Determinations.” Hydrology Paper No. 20 Fort Collins, Colorado: Colorado State University.

85. Dingman SL (1978) Synthesis of flow-duration curves for unregulated streams in New Hampshire. J Am Water Resour Assoc. 14(6):1481-1502.
86. Dixon, H. (2010). Managing national hydrometric data: from data to information. Global Change: Facing Risks and Threats to Water Resources, 451-458.
87. Dixon, H., Hannaford, J., and Fry, M. J. (2013). The effective management of national hydrometric data: experiences from the United Kingdom. Hydrological sciences Journal, 58(7), 1383-1399.
88. Domeneghetti A., Castellarin A. and Brath A., (2012). Assessing rating-curve uncertainty and its effects on hydraulic model calibration. Hydrology and Earth System Sciences. 16:1191-202.
89. Doorenbos, J., Pruitt, W.O., (1977). Guidelines to Crop water requirements. Irrigation and Drainage Paper No. 24 (revised), FAO, Rome, Italy, 144.
90. Dudeja, D., Bartarya, S. K., and Biyani, A. K. (2011). Hydrochemical and water quality assessment of groundwater in Doon Valley of Outer Himalaya, Uttarakhand, India. Environmental monitoring and assessment, 181(1-4), 183-204.
91. Dunne T. and Leopold L.B., (1978). Water in Environmental Planning, W.H. Freeman and Co., New York, New York.
92. Eckhardt, K. (2005). How to construct recursive digital filters for baseflow separation. Hydrological Processes, *19*(2), 507-515.
93. Engelman R., Lekoy P., (1993). Sustaining water, population and the future, in Population action international. Washington DC.
94. Entekhabi D., Asrar G. R., Betts A. K., Beven K. J., Bras R. L., Duffy C. J., Dunne T., Koster R. D., Lettenmaier D. P., McLaughlin D. B., Shuttleworth W. J., van Genuchten M. T., Wei M. Y., and Wood E. F.. (1999). An agenda for land surface hydrology research and a call for the second international hydrological decade. Bull. Amer. Meteor. Soc. 80, pp. 2043–2058.
95. Eriksson M., Jianchu X., Shrestha A.B., Vaidya R.A., Nepal S. and Sandstrom K., (2009). The Changing Himalayas Impact of climate change on waterresources and livelihoods in the greater Himalaya. International Centre forIntegrated Mountain Development (ICIMOD). Kathmandu.
96. Falkenmark M., (1986). Fresh water—time for a modified approach. Ambio. 15 (4), pp. 192–200.

97. Fauchereau N., Trzaska S., Rouault M., Richard Y. (2003). Rainfall Variability and Changes in Southern Africa during the 20th Century in the Global Warming Context. Nat. Hazards 29, pp. 139–154.
98. Femeena, P.V., Sudheer, K.P., Cibin R., and Chaubey I. (2018) Spatial optimization of cropping pattern for sustainable food and biofuel production with minimal downstream pollution." Journal of environmental management, 212: 198-209.
99. Fenton J. D. and Keller R. J. (2001). The calculation of stream-flow from measurements of stage, Technical Report 01/6, Cooperative Research Centre for Catchment Hydrology, Melbourne.Bartels, R., 1982. The Rank Version of von Neumann’s Ratio Test for Randomness. J. Am. Stat. Assoc. 77, 40–46.
100. Fereres E., Orgaz F., Gonzalez-Dugo V (2011). Reflections on food security under water scarcity. J. Exp. Botany, 62 pp. 4079–4086.
101. Fetter CW (1988) Applied Hydrogeology. Columbus. OhioMerrill Publishing Company.
102. Fiorillo F (2009) Spring hydrographs as indicators of droughts in a karst environment. J Hydrol. 373:290-301.
103. Fiorillo F, Esposito L, Guadagno F (2007) Analyses and forecast of the water resource in an ultra-centenarian spring discharge series from Serino (Southern Italy). J Hydrol. 336(1):125–138.
104. Fiorillo F, Wilson RC (2004) Rainfall induced debris flows in pyroclastic deposits, Campania (southern Italy). Eng Geol 75(3):263-289.
105. Flener C., Wang Y., Laamanen L., Kasvi E., Vesakoski J.M., Alho P., (2015). Empirical modeling of spatial 3d flow characteristics using a remote-controlled ADCP system: monitoring a spring flood. Water 7(1):217–247.
106. Ford, Derek, Williams P (1989) Karst Geomorphology and Hydrology. London, Unwin Hyman, 601 pp.
107. Gajbhiye S., Mishra S.K., Pandey A., (2013). Prioritization of shakkar river catchment through morphometric analysis using remote sensing and GIS techniques. J. Emerg. Technol. Mech. Sci. Eng. 4(2):129–142.
108. Gampe D. and Ludwig R., (2017). Evaluation of Gridded Precipitation Data Products for Hydrological Applications in Complex Topography. Hydrology, 4(4): 53.
109. Garg N.K., Dadhich S.M., (2014). Integrated non-linear model for optimal cropping pattern and irrigation scheduling under deficit irrigation. Agric Water Manag 140 1–13.

110. Georgiou P.E., Papamichai D.M., (2008). Optimization model of an irrigation reservoir for water allocation and crop planning under various weather conditions. J. Irrig. Sci. 26: 487–504.
111. Gilman K (1977) Dilution gauging on the recession limb: 1. Constant rate injection method. Hydro Sci J. 22(3):353-369.
112. Gleick P .H. (2002). The World Water: 2002.2003. A biennial report on freshwater resources. Island Press, Washington, D.C. 2.
113. Gleick P. H. (2000). The World Water: 2000.2001. A biennial report on freshwater Resources, Island Press, Washington, D.C. 315.
114. GoS, Government of Sikkim. (2014). Dhara Vikas Handbook. Gangtok, India: Rural Management and Development Department, Government of Sikkim.
115. Grassini P., Indaco G.V., Pereira M.L., Hall A.J., Trapani N., (2007). Responses to short-term waterlogging during grain filling in sunflower. Field Crops Res 101(3): 352–363.
116. Gregory K. J. and Walling D. E., (1973). Drainage basins forms and processes: A geomorphological approach. Arnold, London.
117. Gupta V. Nautiyal H. Kumar V. Jamir I. and Tandon R. S., (2016). Landslide hazards around Uttarkashi township, Garhwal Himalaya, after the tragic flash flood in June 2013. Natural Hazards, 80 (3): 1689-1707.
118. Guven A. and Aytek A., (2009). New approach for stage-discharge relationship:Gene-expression programming. J. Hydrologic Eng., 14(8): 812-820.
119. Hajkowicz S, Collins K (2007) A review of multiple criteria analysis for water resource planning and management. Water Resour Manag. 21:1553–1566.
120. Hammer G.L., Hansen J.W., Phillips J.G., Mjelde J.W., Hill H., Love A., Potgieter A., (2001). Advances in application of climate prediction in agriculture. Agric Syst. 70: 515–553.
121. Hansen DP, Ye W, Jakeman AJ, Cooke R, Sharma P (1996) Analysis of the effect of rainfall and streamflow data quality and catchment dynamics on streamflow prediction using the rainfall-runoff model IHACRES. Environmental Software. 11(1-3):193-202.
122. Hargreaves G.H. and Samani. A., (1982). Estimating potential evapotranspiration, Proc. ASCE. Jr. Irri. and drai., 108 (IR-3), pp. 225-230.
123. Hargreaves G.H., (1956) Irrigation requirement based on climatic data. Paper 1105, Proc. ASCE. Jr. Irri. and drai., 82 (IR-3), 1-10.

124.Hasan M. A. and Pradhanang S. M., (2017). Estimation of flow regime for a spatially varied Himalayan watershed using improved multi-site calibration of the Soil and Water Assessment Tool (SWAT) model. Environmental Earth Sciences, 76 (23), pp. 787.

125.Hauet A., Creutin J.D., Belleudy P., (2008). Sensitivity study of largescale particle image velocimetry measurement of river discharge using numerical simulation. J. Hydrol. 349(1):178–190.

126.Hellegers P., Immerzeel W., Droogers P., (2013). Economic Concepts to Address Future Water Supply-Demand Imbalances in Iran, Morocco and Saudi Arabia. J. Hydrol. 502 pp. 62–67.

127.Henderson, F.M. (1966). Open channel flow. The Macmillan Company, New York.

128.Hergarten S, Birk S (2007) A fractal approach to the recession of spring hydrographs. Geophys. Res. Lett. 34, L11401.

129.Herschy R.W., (1999). Hydrometry, Principles and Practices, Second edition, Wiley, 376

130.Herschy R.W., (2002). The uncertainty in a current meter measurement. Flow Measurement and Instrumentation, 13 (7) pp. 281–284.

131.Herschy R.W., (2008). Streamflow measurement, 3rd edn. Taylor and Francis, USA.

132.Hess T., (2005). Crop Water Requirements, Water and Agriculture, Water for Agriculture, WCA info NE. http:// silsoe.cranfield.ac.uk/iwe/dailyet.htm.

133.Hilgersom K.P., Luxemburg W.M.J., (2012). Technical note: how image processing facilitates the rising bubble technique for discharge measurement. Hydrol Earth Syst Sci 16:345–356.

134.Hornbeck J. W., Bailey S. W., Buso D. C., and Shanley J. B., (1997). Streamwater chemistry and nutrient budgets for forested watersheds in New England: Variability and management implications. Forest Ecology and Management 93 (1-2), pp. 73-89.

135.Horton R.E., (1932). Drainage basin characteristics. Tran. Amer. Geo. Uni. 13(1): 350-361.

136.Horton R.E., (1945). Erosional development of streams and their drainage basins; hydrophysical approach to quantitative morphology. Bull. Geol. Soc. Am. 56: 275–370.

137.Hough J., (1986). Management Alternatives for Increasing Dry Season Base Flow in The Miombo Woodlands of Southern Africa. Ambio 15 (6): 341-346.

138.Houghton-Carr H., Fry M., and Wallingford, U. K., (2006). The decline of hydrological data collection for development of integrated water resource management tools in Southern Africa. IAHS publication, 308, 51.

139. Hu Q., Feifei P., Xuebiao P., Liting H., Xiaoxiao W., Pengyu Y., Pei W., Zhihua P., (2017). Dry-wet variations and cause analysis in Northeast China at multi-time scales. Theor. and App. Climat. pp. 1-12.
140. Huang Y., Chen X., Li Y. P., et al. (2012). A simulation-based two-stage interval-stochastic programming model for water resources management in Kaidu-Kongqi watershed, China. Journal of Arid Land, 4 (4): 390–398.
141. Hudson J.A., (2004). The impact of sediment on open channel flow measurement in selected UK experimental basins. J. Flow Measure. Instrum. 15(1): 49–58
142. Hundecha Y. and Bardossy A., (2004). Modeling of the effect of land use changes on the runoff generation of a river basin through parameter regionalization of a watershed model, J. Hydrol., 292, pp. 281–295, DOI:10.1016/j.jhydrol.2004.01.002.
143. ICIMOD W. and GBPIHED R. (2015). MoFSC. Kangchenjunga landscape conservation and development initiative, feasibility assessment report regional synthesis.
144. IIRS (1989) Geohydromorphology, Soil, and Vegetation landuse mapping of Aglar watershed (U.P.) using remote sensing techniques.
145. ISO 1100-2 (2010). Hydrometry - Measurement of Liquid Flow in Open Channels Part 2: Determination of the Stage-Discharge Relationship, 28 pp., Int. Organ. for Stand., Geneva, Switzerland.
146. Jacob CE (1943) Correlation of ground-water levels and precipitation on Long Island, New York. Trans AGU. 24(2):564-573.
147. Jacobsen T., Adams R.M., (1958). Salt and silt in ancient Mesopotamian agriculture. Science 128(3384), pp. 1251–1258.
148. Jain S.K., (2012). India's water balance and evapotranspiration. Current sci. 102(7), pp. 964-967.
149. Jain, P.K. and Gideon S. (1985). Evapotranspiration model for semiarid regions. Jr. Irri. and drai., ASCE, 3 (4), pp. 369-379.
150. Jalbert J., Mathevet T., and Favre A. C., (2011). Temporal Uncertainty Estimation of Discharges from Rating Curves using a Variographic Analysis, Journal of Hydrology, 397: 83.
151. James A.J. (2003), Institutional Challenges for Water Resources Management: India and South Africa. Water, Households and Rural Livelihoods working Paper 7.
152. James LD, Thompson WO (1970) Least squares estimation of constants in a linear recession model. Water Resour Res. 6(4):1062-1069.

153. Janga R., Nagesh K., (2006). Optimal reservoir operation using multi objective evolutionary algorithm. Water Resour. Manage. 20(6), pp. 861–878.

154. Janga R., Nagesh K., (2008). Evolving strategies for crop planning and operation of irrigation reservoir system using multi-objective differential evolution. Irri Sci 26(2) pp. 177-190.

155. Jensen M.E., Burman R.D., and Allen R.G., (1990). Evapotranspiration and irrigation water requirements. ASCE Manuals and Reports on Engineering Practices No.70, ASCE, New York, pp. 360.

156. John G. M., (2012). Mainstreaming sustainable land management in agro-pastoral production system in Kenya pages pp. 36-57.

157. Jones J.A., Achterman G.L., Augustine L.A., Creed I.F., Folliott P.F., MacDonald L., Wemple B.C., (2009). Hydrologic effects of a changing forested landscape – challenges for the hydrological sciences. Hydrol. Process. 23, pp. 2699-2704.

158. Kale, R. V., and Sahoo, B. (2011). Green-Ampt infiltration models for varied field conditions: A revisit. Water resources management, 25(14), 3505.

159. Kale, R. V.; Goyal, V. C. (2013). Recession flow analysis for assessment of springs. India Water Week, 2013 on theme Efficient Water Management: Challenges and Opportunities. Vigyan Bhawan New Delhi.

160. Kang M. S., Chen R. S., Zhang Z. H., et al. (2008). Some problems facing hydrological and ecological researches in the mountain watershed at the upper stream of an inland river basin. Advances in Earth Science, 23 (7) pp. 675–681.

161. Kang M., Park S.W., (2014). Combined simulation-optimization model for assessing irrigation water supply capacities of reservoirs. J. Irrig. Drain Eng. 140(5):04014005.

162. Keesstra S., Pereira P., Novara A., Brevik E. C., Azorin-Molina C., Parras-Alcántara L., and Cerda A., (2016). Effects of soil management techniques on soil water erosion in apricot orchards. Science of the Total Environment, 551, pp. 357-366.

163. Kevin S., (2012). Developing Rating Curves for Bedrock Step-Pool Rivers using Sparse Data. Proceedings of The National Conference On Undergraduate Research (NCUR) 2012 Weber State University, Ogden Utah March 29 – 31, 2012.

164. Khanal S., Ambinakudige S., Rodgers J., (2013). A GIS analysis of the spatial relation between evapotranspiration and pan evaporation in the United States. Water Internat 38(3):353-360.

165. Khandelwal D.D., Anil K.G., Vishal C., (2015.) Observations of rainfall in Garhwal Himalaya, India during 2008–2013 and its correlation with TRMM data. Current Sci 108(6): 1146.

166. Kipkemboi, J. (2005). Utilization of wetlands through integration of finger ponds into riparian farming systems in East Africa, PhD thesis, UNESCO-IHE Institute for Water Education, Delft, The Netherlands.

167. Kitlasten W., Fogg G.E., (2015). Hydrogeology of a groundwater sustained montane peatland: Grass Lake. Calif. Wetl. Ecol. Manag. 23(5):827–843.

168. Klemes V. (1988). Hydrology of mountainous areas, IAHS publications. Wallingford

169. Knisel WG (1963) Baseflow recession analysis for comparison of drainage basin and geology. J Geophys Res. 68(12):3649-3653.

170. Kovacs A, Perrochet P, Kiraly L, Jeannin P (2005) A quantitative method for characterisation of karst aquifers based on the spring hydrograph analysis. J Hydrol. 303:152–164.

171. Krakauer NY, Temimi M (2011) Stream recession curves and storage variability in small watersheds. Hydrol Earth Syst Sci. 15(7):2377–2389.

172. Kresic N (1997) Quantitative Solutions in Hydrogeology and Groundwater Modeling: Boca Raton. CRC Lewis Publishers, p 461.

173. Kresic N., (2007). Hydrogeology and Groundwater Modeling, Second ed. CRC Press/Taylor and Francis, Boca Raton, FL.

174. Kresic N., (2010). Types and classifications of springs. In Groundwater Hydrology of Springs (pp. 31-85).

175. Kreye, R., Wei, M. and Reksten, D (1996) ‘Defining source area of water supply springs”. Hydrology Branch, Ministry of Environment, Land and Parks.

176. Kronvang B., Bruhn A. J., (1996). Choice of sampling strategy and estimation method for calculating nitrogen and phosphorus transport in small lowland streams. Hydrol. Process., 10, pp. 1483-1501.

177. Kuczera G. and Parent E. (1998). Monte Carlo assessment of parameter uncertainty in conceptual catchment models: the Metropolis algorithm. Journal of Hydrology, 211, pp. 69-85.

178. Kumar V. and Sen S., (2017). Evaluation of spring discharge dynamics using recession curve analysis: a case study in data-scarce region, Lesser Himalayas, India. Sustainable Water Resources Management, pp. 1-19. DOI: 10.1007/s40899-017-0138-z.

179. Kumar Y., (2005). Micro-Hydropower Potential in Uttaranchal. In M.L. Dewan and Jagdish Bahadur (Eds.), Uttaranchal: Vision and Action Programme. Concept Publishing Company, New Delhi, pp. 102-109.

180. Kundzewicz Z.W., Mata L.J., Arnell N.W., Doll P., Kabat P., B. Jiménez, K.A. Miller, Oki T., Sen Z. and Shiklomanov I.A., (2007). Freshwater resources and their management. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Parry M.L., O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (eds.), Cambridge University Press, Cambridge, UK, pp. 173-210.

181. Lamba, J., Way, T. R., Srivastava, P., Sen, S., Wood, C. W., and Yoo, K. H. (2012). Surface transport of nutrients from surface-broadcast and subsurface-banded broiler litter. Transactions of the ASABE, *55*(3), 995-1002.

182. Lamba, Jasmeet, Puneet Srivastava, Thomas R. Way, Sumit Sen, C. Wood, and Kyung H. Yoo. (2013). Nutrient loss in leachate and surface runoff from surface-broadcast and subsurface-banded broiler litter. Journal of environmental quality 42, no. 5 (2013): 1574-1582.

183. Laurance W. F., (2007). Forests and floods, Nature, 449, pp. 409–410.

184. Laurenson BE (1961) A study of hydrograph recession curves of an experimental catchment. J Inst Eng Aust. 33:253-258.

185. Le C., Renard J., Bonnifait B. L., Branger F. and Boursicaud L. R., (2014). Combining hydraulic knowledge and uncertain gaugings in the estimation of hydrometric rating curves: A Bayesian approach, Journal of Hydrology, 509, 573–587.

186. Lehmann N., Finger R., Klein T., Calanca P., Walter A., (2013). Adapting crop management practices to climate change: modeling optimal solutions at the field scale. Agri. Syst. 117 pp. 55–65.

187. Leonard J, Mietton M, Najib H, and Gourbesville P., (2000). Rating curve modelling with Manning’s equation to manage instability and improve extrapolation. Hydrological Sciences Journal. 45(5): 739– 750.

188. Li L., Gochis, D. J. Sobolowski S. and Mesquita M. D., (2017). Evaluating the present annual water budget of a Himalayan headwater river basin using a high-resolution atmosphere-hydrology model. Journal of Geophysical Research: Atmospheres, 122 (9), pp. 4786-4807.

189. Ling H. B. et al., (2012). Surface runoff processes and sustainable utilization of water resources in Manas River Basin, Xinjiang, China. Journal of Arid Land, 4 (3) pp. 271–280.

190. Liniger H.P., Weingartner R., and Grosjean M., (1998). Mountains of the world: water towers for the 21st century. Report for the UN Commission on Sustainable Development, CSD session. Strategic Approaches to Freshwater Management, Paul Haupt Verlag, Bern. pp. 32.
191. Liu H.X., Shao Q.M., Kang C. (2014). Flow characteristics and cavitation effect of the submerged water jet discharged from a central-body nozzle. World J. Eng. Tech. 2:281–288.
192. Mahamuni, K., Upasani, D. and Kulkarni, H. (2009) "Field Based Capacity Building in Geohydrology Based Catchment Area Planning for Spring Water Management Under the Himmotthan Initiative." ACWADAM Technical Report HIMM/tech1/2009.
193. Maikhuri R. K., Nautiyal A., Jha N. K., Rawat L. S., Maletha A., Phondani P. C., BahugunaY. M. and Bhatt, G. C., (2017). Socio-ecological vulnerability: Assessment and coping strategy to environmental disaster in Kedarnath valley, Uttarakhand, Indian Himalayan Region. International Journal of Disaster Risk Reduction, 25: 111-124.
194. Maillet ET (1905) Essais d'hydraulique souterraine and fluviale. A. Hermann.
195. Martin E.C., (2006). Measuring water flow in surface irrigation ditches and gated pipe. Cooperative Extension Pub No AZ1329 Arizona Water Series No 31.
196. Mas J. F., (1999). Monitoring land-cover changes: A comparison of change detection techniques, International Journal of Remote Sensing, 20 (1): 139–152.
197. Maskey S., Guinot V. and Price R.K., (2004). Treatment of precipitation uncertainty in rainfall runoff modelling: a fuzzy set approach. Advances in Water Resources, 27: 889-898.
198. McDonnell J.J., (2003). Where does the water go when it rains? Moving beyond the variable source area concept of rainfall-runoff response. Hydrol. Process. 17: 1869–1875.
199. McMillan H., Freer J., Pappenberger F., Krueger T., and Clark M., (2010). Impacts of uncertain river flow data on rainfall-runoff model calibration and discharge predictions, Hydrol. Process, 24: 1270–1284, DOI:10.1002/hyp.7587.
200. Mehta R., Jain S.K., (2009). Optimal operation of a multi-purpose reservoir using neuro-fuzzy technique. Water Resour. Manag. 23(3): 509-529.
201. Melching C.S., (1992). An improved first-order reliability approach for assessing uncertainties in hydrological modelling. Journal of Hydrology, 132: 157-177.
202. Mero F, (1963) Application of the groundwater depletion curves in analyzing and forecasting spring discharges influenced by well fields. Symposium on surface waters, General assembly of Berkeley of IUGG, IAHS Publication 63:107-117.

203. Merz, R., & Blöschl, G. (2009). A regional analysis of event runoff coefficients with respect to climate and catchment characteristics in Austria. Water Resources Research, 45(1).

204. Michael A.M., (1999). Irrigation Theory and Practice, Vikas Publishing House, New Delhi, India. pp 530-539.

205. Middleton N, Thomas D (1997) World Atlas of Desertification. 2nd Ed. London.

206. Miller J. D., Immerzeel W. W., and Rees G., (2012). Climate change impacts on glacier hydrology and river discharge in the Hindu Kush–Himalayas: a synthesis of the scientific basis. Mountain Research and Development, 32(4): 461-467.

207. Miller PC, Poole DK, Miller PM (1983) The influence of annual precipitation, topography, and vegetative cover on soil moisture and summer drought in Southern California. Oecologia. 56:385–391.

208. Miller V.C., (1953). A Quantitative geomorphic study of drainage basin characteristics on the clinch mountain area. Columbia University, Department of Geology, ONR, New York.

209. Milly PCD (1993) An analytic solution of the stochastic storage problem applicable to soil-water, Water Resour. Res. 29(11): 3755-3758.

210. Mishra A., (2017). Changing Temperature and Rainfall Patterns of Uttarakhand. Int. J. Environ. Sci. Nat. Res.; 7(4): 555716.

211. Mitchell WD (1957) Flow duration curves of Illinois streams. Illinois Department of Public Works and Buildings, Division of Waterways.

212. Mittal S. Tripathi G. and Sethi D., (2008). Development strategy for the hill districts of Uttarakhand. Indian Council for Research on International Economic Relations.

213. Moeletsi M., Walker S., (2013). Agroclimatological suitability mapping for dry land maize production in Lesotho. Theor. Appl. Climatol. 114: 227–236.

214. Montanari A., Baldassarre Di G., (2009). Uncertainty in river discharge observations: a quantitative analysis. Hydrology and Earth System Sciences 13(6): 913–921.

215. Montanari, A. and Brath, A., (2004). A stochastic approach for assessing the uncertainty of rainfall-runoff simulations. Water Resources Research, 40, W01106.

216. Montanari, A., (2007). What do we mean by ‘uncertainty’? The need for a consistent wording about uncertainty assessment in hydrology. Hydrological Processes, 21(6), 841-845.

217. Moore R.D., (2004). Introduction to salt dilution gauging for streamflow measurement-part 2. Constant-rate Inject 8(1):11–15

218. Moradi-Jalal M., Haddad O.B., Marino M.A., Karney B.W., (2007). Reservoir operation in assigning optimal multi-crop irrigation areas. Agric Water Manag 90, pp. 149–159.

219. Moriasi DN, Arnold JG, Van Liew MW, Bingner RL, Harmel RD and Veith TL (2007) Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans ASABE. 50(3):885-900.

220. Mujumdar P.P., Ramesh T.S.V., (1998). A short-term reservoir operation model for multicrop irrigation. Hydrol Sci J 43(3), pp. 479–494.

221. Nagesh K.D., Raju K.S., Ashok B., (2006). Optimal reservoir operation for irrigation of multiple crops using genetic algorithms. J. Irrig. Drain Eng. 132 pp. 123–129.

222. Naik S. D. and Das S.N., (1995). Watershed Prioritization of Dhansiri Catchment, Brahmaputra Basin, using Remote Sensing Techniques, Project Report RSAM/RSAG/WSP/95/1

223. Najafi M.R., Moradkhani H., Piechota T.C. (2012). Ensemble streamflow prediction: climate signal weighting methods vs climate forecast system reanalysis. J Hydrol 442:105–116.

224. Nanda A., Sen S., Jirwan V., Sharma A., and Kumar V., (2018). Understanding Plot-Scale Hydrology of Lesser Himalayan Watershed-A Field Study and HYDRUS-2D Modeling Approach. Hydrological Processes. doi:10.1002/hyp.11499.

225. Nandargi S and Dhar ON. Hydrometeorological Study of the Himalayan Region. Austin J Earth Sci. 2015;2(1): 1010. ISSN:2380-0771.

226. Nash JE, Sutcliffe JV (1970) River flow forecasting through conceptual models, Part I - A discussion of principles. J Hydrol. 10(3):282–290.

227. Nathan RJ, McMahon TA (1990) Evaluation of automated techniques for base flow and recession analyses. Water Resour Res. 26(7):1465-1473.

228. National Research Council (NRC). (1991). Opportunities in the Hydrologic Sciences. Washington, DC: National Academy Press.

229. Naudiyal N. and Schmerbeck J. (2017). The changing Himalayan landscape: pine-oak forest dynamics and the supply of ecosystem services. Journal of forestry research, 28 (3): 431-443.

230. Nautiyal M.D., (1994). Morphometric analysis of a drainage basin using aerial photographs: a case study of Khairkuli Basin, District Dehradun, UP. Journal of the Indian Society of Remote Sensing, 22(4): 251-261.

231. Nayar, Vibhu, and Kavitha Natarajan. "Quantitative Morphometric analysis of Kosasthalaiyar sub basin (Chennai basin) using remote sensing (SRTM) data and GIS techniques." International Journal of Geomatics and Geosciences 4, no. 1 (2013): 89.
232. Negi G. C. and Joshi V., (2004). Rainfall and spring discharge patterns in two small drainage catchments in the Western Himalayan Mountains, India. Environmentalist, 24(1): 19-28.
233. Negi GCS and Joshi V (1996) Geo-hydrology of springs in a mountain watershed: The need for problem solving research. Current Sci. 71(10): 772–776.
234. Nepal S. and Shrestha A. B., (2015). Impact of climate change on the hydrological regime of the Indus, Ganges and Brahmaputra river basins: a review of the literature. International journal of water resources development, 31(2): 201-218.
235. Nepal S., Flugel W. A., Krause P., Fink M., and Fischer, C., (2017). Assessment of spatial transferability of process-based hydrological model parameters in two neighbouring catchments in the Himalayan Region. Hydrological Processes, 31(16): 2812-2826.
236. Newman B.D., Wilcox B.P., Archer S.R., Breshears D.D., Dahm C.N., Duffy C.J., McDowell N.G., Phillips F.M., Scanlon B.R., Vivoni E.R., (2006). Ecohydrology of water-limited environments: A scientific vision, Water Res. 42. DOI: 10.1029/2005WR004141.
237. Nookaratnam K., Srivastava Y.K., Venkateswarao V., Amminedu E., Murthy K.S.R., (2005). Check dam positioning by prioritization of micro watersheds using SYI model and morphometric analysis—Remote sensing and GIS perspective. J. Indian Soc. Remote Sens. 33(1): 25–28.
238. Olen B. and Wu J., (2015). Impacts of Water Scarcity and Climate on Land Use for Irrigated Agriculture in the US West Coast. In 2015 AAEA & WAEA Joint Annual Meeting, July 26-28, San Francisco, California (No. 205719). Agricultural and Applied Economics Association & Western Agricultural Economics Association.
239. Oyebande, L. (2001). Water problems in Africa—how can the sciences help?. Hydrological Sciences Journal, 46(6), 947-962.
240. Padilla A, Pulido-Bosh, Mangin A (1994) Relative importance of base flow and quick flow from hydrographs of karst spring. Ground Water. 32(2): 267–277.
241. Palazzoli I., Maskey S., Uhlenbrook S., Nana E., Bocchiola D., (2015). Impact of prospective climate change on water resources and crop yields in the Indrawati, Nepal. Agric. Syst. 133 pp. 143–157.

242. Pandey A., Behra S., Pandey R. P. and Singh R. P., (2011). Application of GIS for watershed prioritization and management. A Case Study. International Journal of Environmental Sciences Development and Monitoring, 2(1): 25-42.

243. Pant D.N. and Roy, P.S. (1990). Vegetation and landuse analysis of Aglar Watershed using Satellite Remote Sensing Technique. Journal of the Indian Society of Remote Sensing, 18(4): 1–14.

244. Pappenberger F., Matgen P., Beven K. J., Henry J. B., Pfister L. and De Fraipont P., (2006). Influence of uncertain boundary conditions and model structure on flood inundation predictions, Adv. Water Resour., 29: 1430–1449.

245. Pappenberger F., Matgen P., Beven K.J., Henry J.B., Pfister L., Fraipont de P., (2006). Influence of uncertain boundary conditions and model structure on flood inundation predictions. Advances in Water Resources 29(10): 1430– 1449.

246. Paul, D. K., (1997). Rain-fed farming system development in India: retrospect and prospect, in: Katyal, J, C., Farrington, J., Research for rain-fed farming, Overseas Development Institute, London.

247. Paul, S. K., Bartarya, S. K., Piyoosh Rautela, and Mahajan A. K.. (2000) Catastrophic mass movement of 1998 monsoons at Malpa in Kali Valley, Kumaun Himalaya (India). Geomorphology 35(3-4):169-180.

248. Peleg, Nadav, and Haim Gvirtzman (2010) Groundwater flow modeling of two-levels perched karstic leaking aquifers as a tool for estimating recharge and hydraulic parameters. J Hydrol. 388(1): 13-27.

249. Pelletier P., (1988). Uncertainties in the single determination of river discharge: a literature review. Canadian Journal of Civil Engineering 15(5): 834– 850.

250. Pellikka P. K., Lotjonen M., Siljander M., and Lens L., (2009). Airborne remote sensing of spatiotemporal change (1955–2004) in indigenous and exotic forest cover in the Taita Hills, Kenya. International Journal of Applied Earth Observation and Geo information, 11(4) pp. 221-232.

251. Penman. H.L., (1948). Natural evaporation from open water, bare soil and grass. Proc. Royal soc. of London, Series A: 193: 120-146.

252. Pereira L.S., Allen R.G., Smith M., Raes D., (2015). Crop evapotranspiration estimation with FAO 56: Past and future. Agric Water Manage 147: 4–20.

253. Perumal M., Moramarco T., Sahoo B., and Barbetta S. (2010). On the Practical Applicability of the VPMS Routing Method for Rating Curve Development at Ungauged River Sites. Water Resources Research, 46.

254. Perumal M., Moramarco T., Sahoo B., and Barbetta S., (2007). A Methodology for Discharge Estimation and Rating Curve Development at Ungauged River Sites. Water Resources Research, 43.
255. Petersen O. A., Soot A, Reitan T., (2009). Bayesian rating curve inference as a streamflow data quality assessment tool. Water Resources Management 23(9): 1835– 1842.
256. Petras I, (1986) An approach to the mathematical expression of recession curves. Water S.A.12(3):145-150.
257. Phillips P.C. and Perron P. (1988). Testing for a unit root in time series regression. Biometrika, 75(2): 335-346.
258. Portal I.W., (2010). Meteorological datasets. www.indiawaterportal.org/metdata
259. Postel S.L., (2003). Securing water for people, crops, and ecosystems: new mindset and new priorities. Nat Resour. Forum 27: 89–98.
260. Pumo D., Viola F., and Noto L. V., (2010) Climate changes' effects on vegetation water stress in Mediterranean areas, Ecohydrology, 3: 166–176.
261. Quilbe R., Rousseau M. A. N., Savary S., and Garbouj M. S., (2008). Hydrological responses of a watershed to historical land use evolution and future land use scenarios under climate change conditions, Hydrol. Earth Syst. Sci., 12: 101–110.
262. Radulovic, M., Radojevic, D., Devic, D. and Blecic, M., (2008). Discharge calculation of the spring using salt dilution method – application site Bolje Sestre Spring (Montenegro), available at: http: //balwois.com/balwois/administration/full_paper/ffp-1257.pdf (last access: 24 July 2013), 25 2008.
263. Rahman M.M., Arya D.S. Goel N.K., (2010). Limitation of 90 m SRTM DEM in drainage network delineation using D8 method: A case study in a flat terrain of Bangladesh. Appl. Geomat. 2: 49–58.
264. Rai S. C. and Sharma E., (1998). Comparative assessment of runoff characteristics under different land use patterns within a Himalayan watershed. Hydrological processes, 12 (13): 2235-2248.
265. Rai S. C., Sharma E. and Sundriyal R. C., (1994). Conservation in the Sikkim Himalaya: traditional knowledge and land-use of the Mamlay watershed. Environmental Conservation, 21(1): 30-34.
266. Raju K.S., Nagesh K.D. (2004). Irrigation planning using genetic algorithms. Water Res Manag 182: 163–176.

267. Rantz S.E., (1982). Measurement and computation of stream-flow, Volume 2, Computation of discharge, volume Water-Supply Paper 2175. U. S. Geological Survey, Washington.

268. Rasul G., (2010). The role of the Himalayan mountain systems in food security and agricultural sustainability in South Asia.

269. Rawat P. K. Tiwari P. C. and Pant C. C., (2011). Climate change accelerating hydrological hazards and risks in Himalaya: a case study through remote sensing and GIS modeling. International Journal of Geomatics and Geosciences, 1(4): 678.

270. Riggs HC (1964) The base-flow recession curve as an indicator of ground water, International Association of Scientific Hydrology Publication (IASH). 63:352-363.

271. Rijsberman F. R., (2006). Water scarcity: fact or fiction? Agricultural water management, 80 (1-3): 5-22.

272. Rockstrom J., Steffen W., Noone K., Persson A., Chapin F.S., Lambin E.F., (2009). A safe operating space for humanity. Nature 461(7263): 472–475.

273. Rodda J.C. (1994). Mountains – A Hydrological Paradox or Paradise?, Beitragezur Hydrologie der Schweiz, B. e. Birmensdorf ed., pp. 41-51.

274. Rodda, J. C., and Dixon, H. (2012). Rainfall measurement revisited. Weather, 67(5), 131-136.

275. Roncoli C., Orlove B., Kabugo M., Waiswa M., (2011). Cultural styles of participation in farmers' discussions of seasonal climate forecasts in Uganda. Agric Hum Values 28 pp. 123–138.

276. Rosgen, D. L., (1996). A classification of natural rivers: reply to the comments by Miller J.R. and Ritter Catena J.B., 27(3-4): 301-307.

277. Russo SL, Amanzio G, Ghione R, De Maio M (2015) Recession hydrographs and time series analysis of springs monitoring data: application on porous and shallow aquifers in mountain areas (Aosta Valley). Environ Earth Sci. 73(11):7415-7434.

278. Sahin V. and Hall M. J., (1996). The effects of afforestation and deforestation on water yields. Journal of hydrology, 178(1-4), pp .293-309.

279. Sahoo G. B. and Ray C., (2006). Flow Forecasting for a Hawaii Stream using Rating Curves and Neural Networks, Journal of Hydrology, 317: 63.

280. Sarker M.A.R, Khorshed A., Gow J., (2012). Exploring the relationship between climate change and rice yield in Bangladesh: an analysis of time series data. Agric Syst 112: 11–16.

281. Saurral R. I., V. R. Barros, and Lettenmaier D. P., (2008). Land use impact on the Uruguay River discharge, Geophys. Res. Lett., 35, L12401, DOI: 10.1029/2008GL033707.

282. Scanlon B. R., Keese K. E., Flint A. L., Flint L. E., Gaye C. B., Edmunds W. M., and Simmers I., (2006). Global synthesis of groundwater recharge in semiarid and arid regions, Hydrol. Processes, 20, 3335 –3370.

283. Schindler D.W., (2001). The cumulative effects of climate warming and human stresses on Canadian freshwaters in the new millennium. Can. J. Fish. Aquat. Sc. , 58: 18-29.

284. Schmidt A.R., (2002). Analysis of stage-discharge relations for open-channel flows and their associated uncertainties. PhD thesis, University of Illinois, Urbana-Champaign.

285. Schreier H., (2005). Challenges in Mountain Watershed Management. In Global Change and Mountain Regions (pp. 617-625). Springer, Netherlands.

286. Schumn S.A., (1956). Evolution of drainage systems and slopes in badland, at Perth Amboy, New Jersey. The Geological Society of America, 67, pp. 597–646

287. Sefe F.T.K., (1996). A study of the stage-discharge relationship of the Okavango River at Mohembo, Botswana. Hydrological Sciences Journal, 41(1): 97-116.

288. Sen S, Srivastava P, Dane JH, Yoo KH and Shaw JN (2010) Spatial–temporal variability and hydrologic connectivity of runoff generation areas in a North Alabama pasture—implications for phosphorus transport. Hydrol Process. 24(3): 342-356

289. Seyhan E., (1976). Calculation of runoff from basin physiography (crbp).

290. Sharma A. R., (2015). Climate change and community perceptions in the Khudi Watershed, Lamjung, Nepal. Hydro Nepal: Journal of Water, Energy and Environment, 17: 49-54.

291. Sharma B., Nepal S., Gyawali D., Pokharel G.S., Wahid S., Mukherji A., Acharya S. and Shrestha A.B., (2016). Springs, storage towers, and water conservation in the midhills of Nepal. International Centre for Integrated Mountain Development.

292. Sharma S.K., Rajput, G.S., Tignath, S., Pandey, R.P., (2010). Morphometric analysis of and prioritization of watershed using GIS. J. Indian Water Res. Soc., 30 (2): 33–39.

293. Shieh C., Jan C., Tsai Y., (1996). A numerical simulation of debris flow and its application. Nat Hazards 13(1): 39–54.

294. Shiklomanov A. I., Lammers R. B., and Vorosmarty C. J., (2002). Widespread decline in hydrological monitoring threatens pan-Arctic research. Eos, Transactions American Geophysical Union, 83 (2), 13-17.

295. Shivhare, N., Rahul, A. K., Omar, P. J., Chauhan, M. S., Gaur, S., Dikshit, P. K. S., and Dwivedi, S. B. (2017). Identification of critical soil erosion prone areas and prioritization of micro-watersheds using geo informatics techniques. Ecological Engineering.
296. Shoemaker WB, Kuniansky EL, Birk S, Bauer S and Swain ED (2008) Documentation of a conduit flow process (CFP) for MODFLOW-2005.
297. Shope C.L., Bartsch S., Kim K., Kim B., Tenhunen J., Peiffer S., Park J., Ok S.Y., Fleckenstein J., Koellner T., (2013). A weighted, multimethod approach for accurate basin-wide streamflow estimation in an ungauged watershed. J Hydrol 494:72–82.
298. Shrestha R.R., Bardossy A., Nestmann F., (2007). Analysis and propagation of uncertainties due to the stage-discharge relationship: a fuzzy set approach. Hydrological Sciences Journal. 52(4): 595– 610.
299. Singh KP (1971) Model flow duration and streamflow variability. Water Resour Res. 7(4):1031-1036.
300. Singh R., Helmers M.J., Crumpton W.G., Lemke D.W., (2007). Predicting effects of drainage water management in Iowa's subsurface drained landscapes. Agric Water Manag 92(3): 162-170.
301. Singh S. P., and Thadani R., (2015). Complexities and controversies in Himalayan research: A call for collaboration and rigor for better data. Mountain Research and Development, 35 (4): 401-409.
302. Smakhtin VU (2001) Low flow hydrology: a review. J Hydrol. 240(3):147-186.
303. Smil V., (2001). Feeding the world: A challenge for the twenty-first century. MIT press.
304. Smith K.G., (1950) Standards for grading texture of erosional topography. Am J Sci 248: 655–668
305. Smith M. (1992). CROPWAT – a computer program for irrigation planning and management. FAO Irrigation and Drainage Paper, No. 46, Rome, Italy. 125 pp.
306. Solyom PB and Tucker GE (2004) Effect of limited storm duration on landscape evolution, drainage basin geometry, and hydrograph shapes. J Geophys Res. 109 (F3).
307. Sophocleous M (2002) Interactions between groundwater and surface water: the state of the science. Hydrogeol J. 10(1): 52-67.
308. Srivastava V.K. and Maitra D., (1995). Study of drainage pattern of Raniganj Coalfield (Burdwan District) as observed on Landsat-TM/IRS LISS II imagery, Journal of Indian Society of Remote Sensing, 23: 225-235.
309. Stevanovic Z, Milanovic S, Ristic V., (2010). Supportive methods for assessing effective porosity and regulating karst aquifers. Acta Carsol. 39(2): 301–311.

310.Strahler A.N., (1957). Quantitative analysis of watershed geomorphology. Trans Amer. Geo. Uni., 38: 913-920.

311.Strahler A.N., (1964). Quantitative Geomophology of Drainage Basins and Channel Networks, in Handbook of Applied Hydrology, E. Chow VT, Editor. McGraw Hill, New York. p. 4-11.

312.Subramanya K., (2006). Engineering Hydrology. Tata McGraw-Hill, New Delhi.

313.Sudheer K.P., Gosain A.K., Mohana R.D., Saheb S.M., (2002). Modelling evaporation using an artificial neural network algorithm. Hyd Process 16(16) pp. 3189-3202.

314.Sujono J, Shikasho S, Hiramatsu K, (2004) A comparison of techniques for hydrograph recession analysis. Hydrol Process. 18, 403–413.

315.Sun, G. and Liu, Y., 2013. Forest influences on climate and water resources at the landscape to regional scale. In Landscape Ecology for Sustainable Environment and Culture(pp. 309-334). Springer, Dordrecht.

316.Szilagyi J., Balint G., Gauzer B., and Bartha P., (2005). Flow Routing with Unknown Rating Curves using a State-Space Reservoir-Cascade-Type Formulation, Journal of Hydrology, 311:219.

317.Tague C, Grant G (2004) A geological framework for interpreting the low-flow regimes of Cascade streams, Willamette River Basin, Oregon. Water Resour Res. 40(4).

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

319.Tamchos S. and Kaul V., (2015). Increasing hydrological hazards in the Himalayas: defence lies in integrated scientific preparedness. Current Science, 108 (5), 764.

320.Tarafdar S (2013) Understanding the dynamics of high and low spring flow: a key to managing the water resources in a small urbanized hillslope of lesser Himalaya, India. Environ Earth Sci. 70:2107–2114

321.Teegavarapu R.S.V., Simonovic S.P., (2002). Optimal operation of reservoir systems using simulated annealing. Water Resour. Manage. 16(5): 401–428.

322.Thakur A.K., Mohanty R.K., Patil D.U., Kumar A., (2014). Impact of water management on yield and water productivity with system of rice intensification and conventional transplanting system in rice. Paddy Water Environ 12(4): 413-424.

323.Thorntawaite C.W., (1948). An approach towards a national classification of climate. Geo. Rev. 38: 55-94.

324. Tian D. and Liu D., (2011). A new integrated surface and subsurface flows model and its verification. Applied mathematical modelling, 35(7): 3574-3586.
325. Timilsina-Parajuli L., Timilsina Y. and Parajuli, R., (2014). Climate change and community forestry in Nepal: Local people's perception. American Journal of Environmental Protection, 2(1) 1-6.
326. Tiwari P. C., and Joshi B., (2012,a). Rainfall variability and its impacts on water resources and rural health in Kumaon Himalaya, India. Impact of Climate Change on Water and Health, 286.
327. Tiwari P.C., Joshi, B., (2012). Environmental changes and sustainable development of water resources in the Himalayan headwaters of India. Water Resour. Manag. 26, pp. 883–907.
328. Toebes C, Morrissey WB, Shorter R, Hendy M (1969) Base-flow-recession curves. In: Handbook of Hydrological Procedures. Proc. 8, Ministry of Works, Wellington, New Zealand.
329. Toebes C, Strang DD (1994) On recession curves-1: Recession Equations. J Hydrol. 3(2): 2-15.
330. Tung Y.K., (1996). Uncertainty and reliability analysis. In: L.W. Mays (ed.), Water Resources Handbook, McGraw-Hill, New York, NY, USA, p.p. 7.1-7.65.
331. Uhlenbrook S., Didszun J. and Wenninger J., (2008). Sources areas and mixing of runoff components at the hillslope scale – a multi-technical approach. Hydrological Sciences Journal, 53 (4).
332. UN (United Nations) (2011). Challenges and opportunities for water in the transition to a green economy international UN-water conference water in the green economy in practice: towards Rio? 20, 3–5 October 2011.
333. UNESCO-WWAP (2006) Water: A Shared Responsibility. The United Nations World Water Development Report 2. New York, NY.
334. Vadillo J. A., Dunne T., (1978). Field studies of hillslope flow processes. In: Hillslope Hydrology. Ed. MJ Kirkby, pp. 227-293.
335. Vaidya R. A., (2015). Governance and management of local water storage in the Hindu Kush Himalayas. International Journal of Water Resources Development, 31 (2), pp. 253-268.
336. Valdiya K. S., (1980). The two intra crustal boundary thrusts of the Himalaya. Tectonophysics 66 (4) pp. 323-348.

337. Valdiya K.S., Bartarya S.K., (1991) Hydrological studies of springs in the catchment of the Gaula River, Kumaun Lesser Himalaya, India. Mt Res Dev. 11(3):239-258

338. Varela-Ortega C., Blanco-Gutierrez I., Swartz C.H., Downing T.E., (2011). Balancing groundwater conservation and rural livelihoods under water and climate uncertainties: an integrated hydro-economic modeling framework. Glob. Env. Change 21(2): 604–619.

339. Vashisht AK, Bam B (2013) Formulating the spring discharge-function for the recession period by analyzing its recession curve: A case study of the Ranichauri spring (India). J Earth Syst Sci. 122(5):1313-1323.

340. Vashisht AK, Sharma HC (2007) Study on hydrological behavior of a natural spring. Current. Sci. 93:837-840.

341. Vashisht, A. K. (2012). Current status of the traditional watermills of the Himalayan region and the need of technical improvements for increasing their energy efficiency. Applied energy, 98, 307-315.

342. Vedula S., Nagesh K.D., (1996). An integrated model for optimal reservoir operation for irrigation of multiple crops. Water Resour. Res. 32(4) pp. 1101–1108.

343. Vema, Vamsikrishna, K. P. Sudheer, and I. Chaubey. (2017) Development of a hydrological model for simulation of runoff from catchments unbounded by ridge lines. Journal of Hydrology. 551: 423-439.

344. Venetis C., (1970). A note on the estimation of the parameters in logarithmic stage-discharge relationships with estimates of their error. International Association of Scientific Hydrology. Bulletin 15, 105 p.

345. Verry E. S., (1986). Forest harvesting and water: the Lake States experience. Water Resources Bulletin, 22 (6), pp. 1039-1047.

346. Vicente-Serrano S.M., Azorin-Molina C., Sanchez-Lorenzo A., Revuelto J., (2014). Sensitivity of reference evapotranspiration to changes in meteorological parameters in Spain (1961-2011). Water Resour. Res. 50(11) pp. 8458–8480.

347. Vinogradov Y. B., Semenova O. M., and Vinogradova T. A., (2011). An approach to the scaling problem in hydrological modelling: the deterministic modelling hydrological system. Hydrological processes, 25 (7), pp. 1055-1073.

348. Vishal K., Van R., Hadenb B.A., Joycea D.R., Purkeya L.E., Jackson C., (2013). Irrigation demand and supply, given projections of climate and land-use change, in Yolo County, California. Agric Water Manage 117 pp. 70–82.

349. Viviroli D., Durr H. H., Messerli B, Meybeck M., and Weingartner R., (2007). Mountains of the world, water towers for humanity: Typology, mapping, and global significance, Water Resources Research, 43.

350. Vogel RM, Kroll CN (1992) Regional geohydrologic-geomorphic relationships for the estimation of low-flow statistics. Water Resour Res. 28(9):2451-2458.

351. Von Zabeltitz C., (2011). Crop Water Requirement and Water Use Efficiency. In Integrated Greenhouse Systems for Mild Climates (313-319). Springer Berlin Heidelberg

352. Vorosmarty C.J., McIntyre P.B., Gessner M.O., Dudgeon D., Prusevich A., Green P., Glidden S., Bunn E., Sullivan C.A., Reidy L.C., Davies, P.M., (2010). Global threats to human water security and river biodiversity. Nature 467, pp. 555–561.

353. Wada Y.T., Gleeson, Esnault L., (2014) Wedge approach to water stress. Nature Geoscience 7(9): 615–617.

354. Wagener, T., M. Sivapalan, and B. McGlynn (2008). Catchment classifica-tion and services—Toward a new paradigm for catchment hydrologydriven by societal needs, in Encyclopedia of Hydrological Sciences,edited by M. G. Anderson, John Wiley, Chichester, U. K

355. Ward D.P., Hamilton S.K., Jardine T.D., Pettit N.E., Tews E.K., Olley J.M., Bunn S.E., (2013). Assessing the seasonal dynamics of inundation, turbidity, and aquatic vegetation in the Australian wet–dry tropics using optical remote sensing. Ecohydro. 6(2):312–323.

356. Watson C.C., Holmes R.R. Jr, Biedenharn D.S., (2013). Mississippi river streamflow measurement techniques at St. Louis, Missouri. J. Hydraul. Eng. 139(10):1062–1070.

357. Wedgbrow C.S., Wilby R.L., Fox H.R. and O'Hare G. (2002). Prospects for seasonal forecasting of summer drought and low River flow anomalies in England and Wales. International Journal of Climatology, 22: 219–36.

358. Weingartner R., Barben, M., Spreafico M., (2003). Floods in mountain areas – an overview based on examples from Switzerland, Journal of Hydrology, 282:10-24.

359. Wenninger J., Uhlenbrook S., Lorentz S. and Leibundgut C., (2008). Identification of runoff generation processes using combined hydrometric, tracer and geophysical methods in a headwater catchment in South Africa. J of Hyd. Sci., 53 (1): 65-80.

360. Westerberg I. K., Guerrero J-L, Younger P.M., Beven K.J., Seibert J., Halldin S., Freer J.E. and Xu C-Y., (2011). Calibration of hydrological models using flow duration curves. Hydrology and Earth System sciences, 152205–2227.

361. White WB (1988) Geomorphology and Hydrology of karst terrains. New York.

362. White, K. L., and Chaubey, I. (2005). Sensitivity analysis, calibration, and validations for a multisite and multivariable SWAT model. JAWRA Journal of the American Water Resources Association, 41(5), 1077-1089.

363. White, K. L., and Srivastava, P. (2007). Hydrologic components of watershed-scale models. Transactions of the ASABE, *50*(5), 1695-1703.

364. Wijesekera N. T. S., and Perera L. R. H., (2012). Key Issues of Data and Data Checking for Hydrological Analyses-Case Study of Rainfall Data in the Attanagalu Oya Basin of Sri Lanka. Engineer: Journal of the Institution of Engineers, Sri Lanka, 45 (2).

365. Wittenberg H (1999) Baseflow recession and recharge as nonlinear storage processes. Hydrol Process. 13(5):715–726.

366. WMO (1994). Guide to Hydrological Practices, 5th Edition, World Meteorological Organization No. 168, Geneva.

367. Wood A.W. and Lettenmaier D.P., (2006). A test bed for new seasonal hydrologic forecasting approaches in the western U.S., Bulletin of the American Meteorological Society 87, pp. 1699-1712, DOI: 10.1175/BAMS-87-12-1699.

368. World Meteorological Organization (2010). Manual on stream gauging. Volume II—Computation of discharge, WMO 1044, 195 p.

369. Yen B.C., and Gonzalez J.A., (1994). Determination of Boneyard Creek Flow Capacity by Hydraulic Performance Graph, Research Report No. 219, Department of Civil Engineering, Univ. of Illinois at Urbana-Champaign.

370. Yoon S. S. and Lee B., (2017). Effects of Using High-Density Rain Gauge Networks and Weather Radar Data on Urban Hydrological Analyses. Water, 9 (12), 931.

371. Youngs EG (1985) Characterization of hydrograph recession of land drains. J Hydrol. 82:17-25.

372. Yu P, Yang T, Liu CA (2002) Regional model of low flow for Southern Taiwan. Hydrol Process. 16(10):2017-2034.

373. Zavoianu I., (1985). Morphometry of drainage basins. Elsevier, Amsterdam.

374. Zende, A.M., Nagarajan, R., Atal, K.R., (2013). Prioritization of sub-watersheds in semi-arid region, western Maharashtra, India using geographical information system. Amer. J. Eng. Res., 2(10), pp. 128-135.

375. Zheng H., Chen F., Ouyang Z., Tu N., Xu W., Wang X., Miao H., Li X., Tian Y. (2008). Impacts of Reforestation Approaches on Run-Off Control in the Hilly Red Soil Region of Southern China. Journal of Hydrology, 356, pp. 174-184.

376. Zotarelli, L., Dukes, M. D., Romero, C. C., Migliaccio, K. W., and Morgan, K. T. (2010). Step by step calculation of the Penman-Monteith Evapotranspiration (FAO-56 Method). Institute of Food and Agricultural Sciences. University of Florida.

LIST OF PUBLICATIONS

Book Chapter (1)

1. Analysis of Spring Discharge in the Lesser Himalayas: A Case Study of Mathamali Spring, Aglar Watershed, Uttarakhand. **,** Springer, DOI **10.1007/978-981-10-5711-3_23**

Papers (4)

2. Vikram K and Sumit S., "Evaluation of Spring Discharge Dynamics Using Recession Curve Analysis: A Case Study in Data Scare Region, Lesser Himalayas, India". *Sustainable water resource management* (Springer). DOI ***10.1007/s40899-017-0138-z***
3. Vikram K and Sumit S, "Assessment of Spring Potential for Sustainable Agriculture: A Case Study in Lesser Himalayas", *Water resource management*, Springer (under review)
4. Vikram K and Sumit S, "Prioritization of Aglar sub watersheds using morphometry analysis". *Journal of Earth System Science*, Springer, (under review)
5. Vikram K, Sumit S, Santosh P and Debashish S., "Rejuvenation of Spring in Garhwal Mountain: Assessment of water resource and coping with water insecurity", *International Journal of Water Resources Development*, Taylor & Francis (under review)

Conferences (6)

6. Vikram K. and Sumit S., "*Optimal crop planning under the constraint of area and water demand using multi-objective programming*", American Society of Agricultural and Biological Engineers (ASABE-18), October 03-06 Oct 2018, Hyderabad, India.
7. Vikram K. and Sumit S., "*Estimation of Uncertainties in Stage-Discharge Curve for an Experimental Himalayan Watershed*", AGU Fall Meeting Abstracts, 2016.
8. Vikram K and Sumit S, "*Morphometric Analysis of lesser Himalaya: a case study of Aglar watershed*", HYDRO International – 2016, 08-10 Dec. 2016, Pune – India.
9. Vikram K and Sumit S, "*Analysis of Spring Discharge in the Lesser Himalaya: A Case Study of Mathamali Spring, Aglar Watershed, Uttarakhand*" International Conference on Water, Environment, Energy and Society, (ICWEES-2016), 15-18 March 2016, Bhopal
10. Sumit S and Vikram K, "*Developing an Instrumented Watershed in the West Himalayas, India: Need and Challenges for Hydrological Sciences*", ASABE-15, 26-29, July -2015, U.S.A.
11. Sumit S, Vikram K and Raushan K, "*Static and Dynamic Response of Hydrologic Characteristics on Spring Discharge in the Tehri Garhwal region of Uttrakhand*". 2014, Dehradun.

Working papers (2)

12. Vikram K. and Sumit S., “Rating Curve Development and Uncertainty Analysis in Garhwal Himalaya Stream”, (to be communicate in ISH Journal of Hydraulic Engineering).
13. Vikram K. and Sumit S., “Hydrological Response Under Different Land Cover” (to be communicate in Journal of Flow Measurement and Instrumentation).

Appendix I

Summary of Hydro-meteorological parameters monitored at Aglar watershed

S. No	Hyd-Met Parameter	Location	Measurement since	Total Duration (Months)*	Present Status
1	Spring Discharge	Mathamali	01-Feb-14	52	Continue
2	Rainfall	Mathamali	16-Nov-13	55	Continue
		Mundani	29-Nov-13	54	Continue
		Mathamali Plot	10-Dec-14	53	Continue
		Mundani Plot	10-Dec-14	53	Continue
3	AWS	Near Mathamali R/G	01-Sep-15	33	Continue
4	River Flow	Mathamali	26-Oct-13	53	Dis-continue
		Upper Aglar	12-Apr-14	49	Continue
		Shivalaya	21-Jun-15	35	Dis-continue
		Paligaad	12-Apr-14	49	Continue
		Balganga	07-Jun-14	47	Continue
5	Hydraulic Conductivity	Aglar Watershed	02-Dec-13	-	-

* Duration indicated are till May, 2018

Appendix II

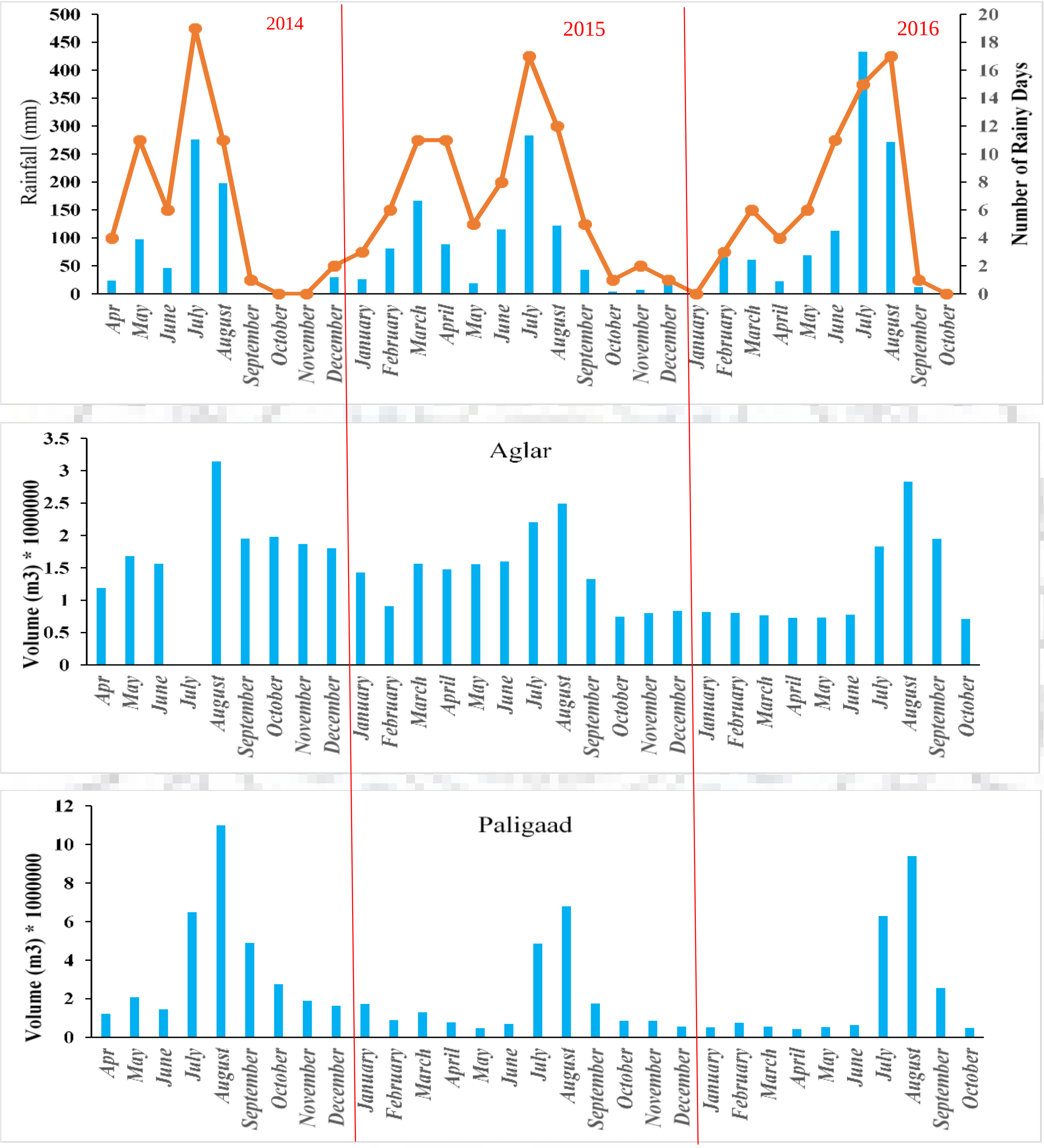
Comparison of different methods used for river flow estimation

Method		Cost effectiveness	Accuracy	Time effectiveness	References	Remarks
Direct measurement method	Timed volume method	Inexpensive	High	Efficient	Najafi et al. (2012), Shope et al. (2013)	Rivers with low flow
Velocity-area methods	Float method	Inexpensive	Low	Efficient	Hilgersom and Luxemburg (2012), Watson et al. (2013)	For small rivers
	Dilution gauging method	Inexpensive	Low	Efficient	Moore (2004), Comina et al. (2014)	Difficult to apply and tracer can influence the environment
	Trajectory method	Inexpensive	High	Inefficient	Boman and Shukla (2009)	Applied only to rivers where flow can be diverted into a pipe
	Current meters method	Expensive	High	Efficient	Boldt and Oberg (2015)	Used only for short term study
	Acoustic Doppler current profiler method	Expensive	High	Efficient	Flener et al. (2015)	Used where all the flow can be diverted into a pipe
		Expensive	High	Efficient	Herschy (2008)	Accuracy of the result get affected by the size of the river

Formed construction methods	Weirs method	Expensive	High	Inefficient	Hudson (2004), Martin (2006)	Construction of weirs and hydraulic structure may alter the local habitat
	Flume method	Expensive	High	Inefficient	Baffaut et al. (2015)	
Non-contact measurement methods	Remote sensing method	Expensive	Low	Efficient	Ward et al. (2013)	Covers larger areas in less time
	Particle image velocimetry	Expensive	High	Efficient	Hauet et al. (2008)	Covers larger areas but estimates need to be validated and not suitable for mountains

Appendix III

Rainfall and flow volume during different years



Top: Monthly total rainfall (mm) and line indicates number of rainy days.
Middle: monthly volume (m^3) from Upper Aglar sub watershed.
Bottom: monthly volume (m^3) from Paligaad sub watershed

Appendix - IV

Questionnaire

1. **General Information of sampled village/MWS**

Village Name:	Climate:Dry/ Wet/……….
Source of domestic and irrigation:	Location (Lat. & Long.)
Annual Average Rainfall: mm	Average Temperature: ……………..°C
Major Crops:	

2. **Land Distribution**

Sl. No.	Land Category	Total area (ha)
1	Personal	
2	Common Property	
3	Others	

3. **Demographic Details:**

Sl. No.	Caste	Population			Total Households (nos.)			
		Male	Female	Total	Landless	Marginal (<1.0ha)	Small (1.0 – 2.0 ha)	Large (>2.0 ha)
1	SC							
2	ST							
3	OBC							
4	Others							

4. **Major Crops**

Sl. No.	Crops	Kharif			Rabi			Summer		
		Area (ha)	Production (‘000 kg)	Productivity (kg/ha)	Area (ha)	Production (‘000 kg)	Productivity (kg/ha)	Area (ha)	Production (‘000 kg)	Productivity (kg/ha)
Rainfed/ Irrigated										
	Cereals									
	Pulses									
	Vegetables									
	Cash Crops									

5. Hydrological Details

Sl. No.	Particulars/ Indicators	::	Benchmark
a)	Rainfall (Intensity, no. of rainy days)	::	
b)	Stream Flow (cum/sec)	::	
c)	Ground Water Level (metre)	::	
d)	Status of spring water	::	
e)	Drinking Water availability	::	

6. Agriculture:

Sl. No.	Particulars/ Indicators	Benchmark	Sl. No.	Particulars/ Indicators	Benchmark
1	Forest land as % of total agri. Land		8	**Improvement in productivity (Agriculture)**	
2	Total cropped area in Agriculture			(i) Cereals	
3	Demonstration of new technology			(ii) Pulses	
4	No. of farmers undergone training			(iii) Oil seeds	
5	**Cropping intensity**			(iv) Cash Crop	
6	**Increase in area (Agriculture)**			(v) Fodder	
	(i) Cereals				
	(ii) Pulses/Vegetables				
	(iii)Fodder				
	(iv)Cash Crop				
	(v) Pasture Land				
7	**Improvement in productivity (Agriculture)**				
	(i) Cereals				
	(ii) Pulses/Vegetables				
	(iii)Fodder				
	(iv)Cash Crop				
	(v) Pasture Land				

7. Economic, Financial, Process, and Group participation

Sl. No.	Particulars/ Indicators	Benchmark	Sl. No.	Particulars/ Indicators	Benchmark
	Economic Indicators		**Financial Indicators**		
1	Total Income		1	Finance/credit linkages (SHGs etc.) (nos.)	
2	No. of families recorded positive change in income (Rs.)		2	Watershed development Fund - Utilization	
3	Distress migration		3	Maintenance mechanism	
	Process Monitoring			**Formation of Institutions**	
1	Status of area and stream treatment		1	No. of SHGs etc.	
2	No. of social audits		2	Awareness of participation in Watershed Committee (%)	
3	Gram Sabha participation in planning & management of watershed		3	Involvement of beneficiaries (%)	

Thanks for your valuable information