Hydro-Environmental Impact of Climate and Land Use Change on Watersheds for Sustainable Development

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Edited by

T. I. Eldho and M. K. Jha

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This edited book includes the most up-to-date research findings on the topics of impact assessments of climate and land use change, modelling techniques, and case studies. The book may serve graduate students, expert engineers, scientists, and researchers who need a basic understanding of climate and land use change and its impacts on the hydrology, water resources and environment for their professional work and research studies.

The merit of this edited book lies in its well-balanced exposure of various aspects on climate change impact studies, land use change, mathematical modelling and field applications presented as case studies. Thus, it will not be surprising that this book will be of interest to a wide circle of graduate students, teachers, scientists, engineers, and practitioners.

The main highlights of this book include:

- Various aspects of hydrological and environmental processes.
- Comprehensive treatment on climate change and land use land cover changes and its impacts, illustrated with case studies.
- Recent modelling techniques for hydrological and environmental impact studies.
- Well balanced exposure to various case studies at different parts of the world.

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Part VI: Environmental Impacts on Sustainable Development of Watersheds

PREFACE

Sustainable development is the development of humans, eco-systems and nature that meets the needs of the present without compromising the possibilities of future generations to meet their own and future needs. Water is at the core of sustainable development and is critical for entire systems including socio-economic development, healthy ecosystems and for human survival itself. In this way, as watersheds are the scientific unit of water resources systems, it is important to understand the conditions of the watersheds with reference to hydrologic and environmental conditions with changing climate and land use.

In the last few decades, climate and land-use land-cover (LULC) changes have been identified as having the most critical impacts on water resources and the environment. Due to climate change, we face multiple challenges and its impacts, especially due to a changing and uncertain future climate, and a rapidly growing population that is driving increased social and economic development and urbanization. Climate change and land use impacts on water resources and environment can be better assessed on a river basin/watershed scale. Large number of studies are carried out in this regard, but a concise volume with causative factors and case studies have not yet been published.

The main aim of this edited book, "**Hydro-Environmental Impact of Climate and Land Use Change on Watersheds for Sustainable Development"**, is to discuss various aspects of climate and land-use changes and its impacts on water resources and environmental management on a watershed basis. There are 27 Chapters in the book and the chapters are arranged into six sections: **Hydro-Environmental Process and its modelling, LULC Impacts on Hydro-Environments, Climate Change Impacts on Hydro-Environments, Climate Change & LULC Impacts on Hydro-Environments, Extremes Events Impacts on Hydro-Environments, and Environmental Impacts on Sustainable Development of Watersheds.** The various sections in the book are focused on the technical aspects of climate and land-use change on a watershed scale, perspectives on water and environment management, skills and modelling of analyzing the complex issues, and on specific knowledge on issues in the future. Each topic is a contributed chapter

developed in logical progression with possible case studies and advancements in various areas.

In this edited book volume, we received contributions from leading researchers and professors from various parts of the world describing processes with examples of case studies. The book contains cutting edge assessments of climate and land-use changes and a number of cases studies from India, the USA, and other countries.

This edited book is intended for engineering and applied science graduate students, and faculties from introductory to the advanced level courses in hydrology, environmental science, climate science, water resources, and closely related fields. The book is also intended for professionals and the scientific community working in the areas of hydrology, water resources, climate science, and environmental science and geography.

(Prof. T. I. Eldho and Prof. M. K. Jha)

ACKNOWLEDGMENTS

Presently, all the world over, it is recognized that our climate system is drastically changing with both global and local anthropogenic impacts. On a global scale, the major impacts are due to an increase in greenhouse gas emissions and the related rise in global average temperatures. On a local scale, the impacts are mainly due to Land Use Land Cover Changes. With these changes, the totality of hydrological systems and the environment are affected on a watershed or river basin scale. As the major impacts on hydro-environment are on a watershed/river basin scale, we need to understand the impacts on a watershed scale. However, no major textbooks/edited volumes are available which consider the various issues on hydro-environment in a holistic way by considering various case studies. Thus, in this edited book project, we tried to explore the challenging research domain of Climate and LULC changes through a case study-based perspective.

We are sincerely thankful to Cambridge Scholars Publishing for allowing us to publish this edited volume on a contemporary research domain of "climate and land use change and its impacts on water resources and environmental management on a watershed basis". We would like to express our sincere gratitude to all the contributors for submitting the book chapters. We appreciate the contribution of authors who have dedicated their valuable time and efforts to writing the assigned manuscripts. The project follows a review process, where the identities of both the authors and reviewers are not disclosed to avoid any biased decision.

We are thankful to IIT Bombay and North Carolina A&T University for the support in making this Edited Volume possible. The authors are thankful to their families for giving moral support during this work. The first author, T.I. Eldho, acknowledges the contributions of his former and current students Dr. Rakesh Sinha, Dr. S. Sreedevi, Dr. Gaurav Misuriya and Ms. Sanjukta Das. Co-author, M.K. Jha, acknowledges the contributions from his former graduate students and collaborators across the USA.

(Prof. Eldho T.I. & Prof. M. K. Jha)

EDITORS PROFILE

Dr. Eldho T.I., Professor, Department of Civil Engineering, IIT Bombay, Mumbai, India.

Dr Eldho is a Professor & Former Head and Chair of the Department of Civil Engineering, IIT Bombay. He has more than 30 years of experience in the area of water resources and environmental engineering as a Scientist, Professor and Consultant. He works in the areas of Watershed Management, Fluid Mechanics, Turbulence, Hydraulics Coastal Hydrodynamics, and Climate Change Impact on Water Resources, CFD, Groundwater Flow, and Contaminant transport. He got his Ph.D. from IIT Bombay in 1995 and worked as Postdoctoral Fellow at the Institute for Hydromechanics, University of Karlsruhe (currently Karlsruhe Institute of Technology), Germany, from 1996 to 1998. From 1998 to 1999, he worked as a Water Resources Modeler and Consultant at Mott MacDonald Company Cambridge UK. Later Dr. Eldho worked as a Senior Research Fellow at Hydrotech Research Institute, National Taiwan University, Taipei from 1999 to 2000. In 2000, Dr. Eldho returned to India and joined at Department of Civil Engineering, IIT Kharagpur as a Faculty. Further, Dr. Eldho joined IIT Bombay as a Faculty in 2001 and continued his teaching, research, and professional career. He has developed the Hydraulics Laboratory of IIT Bombay with many sophisticated pieces of equipment and facilities. During the past 23 years at IIT Bombay, Dr. Eldho has guided 35 Ph.Ds., 10 Postdoctoral Fellows and 60 master's theses. He has published more than 220 research papers in reputed international and national journals, and more than 375 papers in various international and national conferences. He has developed and offered 25 courses and a number of short-term courses for college teachers and working professionals. Dr. Eldho has delivered more than 200 invited lectures at various institutions in India and abroad. He has also developed two popular video courses on "Fluid Mechanics" and "Watershed Management". Prof. Eldho serves as an Editor/Associate Editor and Editorial Board Member for a number of Indian and international journals and has worked as a reviewer for more than 50 national and international journals in the recent past. He is also a research proposal

reviewer for many research organizations and delivered several invited/ keynote lectures at various national and international organizations and conferences. Dr. Eldho has co-authored two popular textbooks and contributed 20 book chapters in various edited books. Dr. Eldho has worked as a consultant for many state and central government organizations, municipal corporations, and companies in the areas of hydraulics, fluid mechanics, flood studies, sump model studies, hydraulic designs etc. And completed more than 100 consultancy projects and more than 10 sponsored projects with agencies such as ISRO, DST, and various ministries of state and central governments. Dr. Eldho is a recipient of many prestigious awards including Eminent Water Resources Scientist, constituted by the Indian Water Resources Society in 2018.

Dr. Manoj K. Jha, Professor, Department of Civil Engineering, North Carolina A&T State University, USA and Visiting Professor IIT Bombay

Dr. Manoj K. Jha is a Professor of Civil engineering at the Department of Civil, Architectural, and Environmental Engineering, North Carolina A&T State University, USA. He is also currently a Visiting Professor at the Civil Engineering Department, IIT Bombay, India. Dr. Jha has over 20 years of experience in the areas of hydrology to water quality, water management strategies, and impact assessment studies on water resources. Specific research areas include surface and subsurface hydrology, field and watershed multi-scale hydrologic and water quality modelling, water resources engineering and management, impact assessment studies of climate change and land use changes, evaluation of BMPs for sediment and nutrients fate and transport, and extreme hydrological events (floods and droughts) studies. He has developed and applied various field to watershed scale models to extend the boundaries of our knowledge and understand impacts of land use and climate change on hydrology, water availability, water quality. His research accomplishments include substantial extramural funding, student support and mentoring, and many peer-reviewed journal publications and conference presentations. Dr. Jha is highly engaged in service activities, including as a member of ASCE, AWWA, ASABE organizations, and editorial board and review committees. He is a registered professional engineer (PE). He currently serves on a federal advisory board for the USPEA for climate change studies.

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PART I:

HYDRO-ENVIRONMENTAL PROCESS AND ITS MODELLING

CHAPTER 1

SUSTAINABLE DEVELOPMENT OF WATERSHEDS - AN OVERVIEW OF HYDRO-ENVIRONMENTAL IMPACTS & MODELING

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Abstract

As per the United Nations reports, sustainable development is the development of humans, ecosystems, and nature to meet the present demands without compromising the necessities of future generations. Water is the core of sustainable development and is crucial for the entire system including socio-economic development, healthy ecosystems, and for human survival itself. That way, as watersheds are the scientific unit of the water resources system, it is important to understand the conditions of the watersheds with reference to hydrologic and environmental conditions with changing climate and land use. In this chapter, various issues of watersheds within the perspectives of water resources and environmental problems are discussed. In recent times, two important issues that affect the sustainable development of watersheds are Land Use / Land Cover (LULC) changes and climate change impacts due to various anthropogenic issues induced on the earth and its atmosphere. We need to understand these issues in terms of hydrology and environmental impacts. Here we discuss some of these issues in brief to understand the sustainable watershed developmental issues.

Keywords: Watershed; Sustainable development; Hydrology; Environmental system.

Introduction

According to United Nations Reports (UN, 1987), sustainable development of any resource is required for its sustenance for future generations. As water is a limited resource, water resource sustainability is the development of humans, ecosystems, and nature addressing the present requirements without adversely impacting the needs of future generations and the ecological system. As the watershed is the scientific unit of a water resources system, its development with reference to hydrologic and environmental conditions with changing climate and land use is very important. Sustainable development of watersheds is vital for reducing the global burden of disease and improving the health, welfare, and productivity of populations and nature as a whole. Due to the anthropogenic impacts of industrial development of the past century, the watersheds/river basins are at the heart of adaptation to climate and land use changes, serving as the crucial link between the climate system, human society, and the environment. While looking into the perspectives of sustainable development of watersheds with the changes in climate and land use and its impacts, two important aspects to be examined include the hydrological and environmental impacts on the system.

On a watershed/river basin scale, hydrology deals with the study of the spatial and temporal distribution and movement of water within the watershed. In hydrology, we deal with the occurrence, movement, distribution, management and storage of water within the watershed (Mishra and Singh, 2003). Due to the complex nature of the hydrological processes within a watershed/river basin and their variation with time and space, hydrological modeling is essential to analyze the impacts of climate and land use changes. On a watershed scale, hydrologic modeling deals with processes of rainfall, runoff, percolation, evapotranspiration, storage, etc. Through hydrological modeling on a watershed scale, we can do water resources assessments, flood and drought analyses and planning and management of a watershed/river basin, leading to sustainable development. From an environmental perspective, sustainable watershed development deals with various issues of water quality, land use, soil degradation, various pollution problems within the system, and the overall environmental health of the watershed and its aquatic and ecological systems.

In this introductory chapter, the main focus is on the various issues of sustainable development of watersheds, hydrological systems, and their modeling, environmental systems and their modeling, and related managemental issues on a watershed/river basin scale. Further, the hydrological and environmental effects of climate and Land Use / Land Cover changes are discussed briefly. Also, various hydrological modeling tools and environmental impact assessment models used for hydro-environmental impact assessment are briefly illustrated.

Watersheds and sustainable development

Watershed and its characterization

A watershed (Fig. 1.1) is a geographical area that is drained to a common outlet on a river or a stream (Murty 1994). A watershed can also be a river basin and is considered as the basic hydrological and physical-biological unit to carry out the various climate and land use changes impact studies (Sheng 1990).

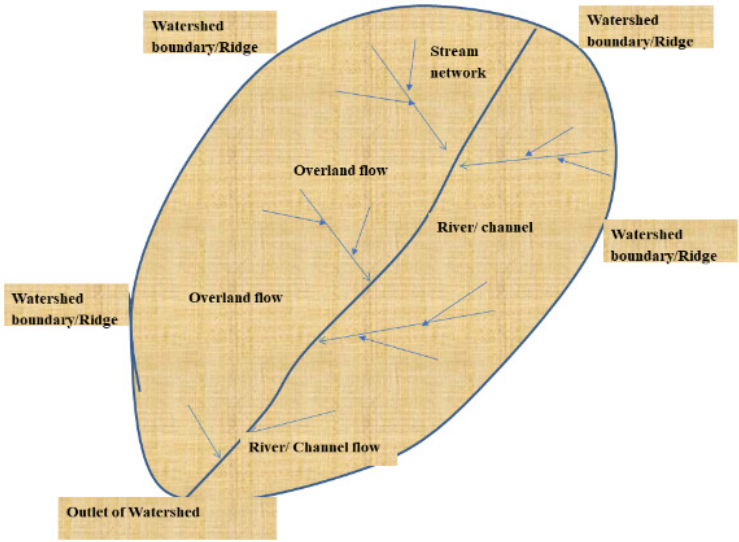

Figure 1-1 A general representation of a watershed/river basin

When considering a watershed, due to its geographical and physical complexities, to understand various hydro-environmental impacts, watershed modeling is essential. As shown in Fig. 1.1, a watershed is bounded by ridges and water falling in it is drained to a single outlet (Murty 1994; Singh 2000).

We can characterize watersheds based on the geology and geophysical conditions, topographic features, and other parameters. The other parameters that can be used to characterize watersheds include (Murty 1994; NCIWRDP 1999):

- Physiography such as slope, land type, altitude, and other physical features.
- Shape (e.g., broad, or narrow) and morphometric parameters (e.g., bifurcation ratio, drainage density, and stream order (Figure 1.2).
- Size of the watershed.
- Geology and soils of the watershed.
- Hydrogeology of the watershed.
- Climate parameters (e.g., wind, precipitation, humidity, temperature, evaporation, etc.)
- Hydrology of watershed.
- Land use and land cover (LULC).
- Drainage of watershed.
- Socioeconomic factors.

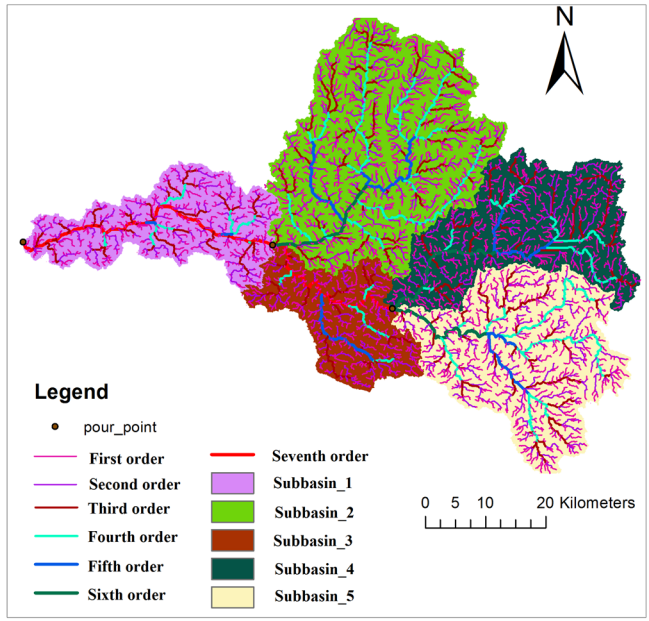

Figure 1-2 A watershed/ river basin with subbasins and geomorphological features.

Hydro-environment system and sustainable development of watershed

As per the United Nations sustainable development goals (SDG), "Securing Sustainable Water for All" is an overarching goal. Some of the major areas of sustainable development of water include sectors such as agriculture, industry and energy, domestic sectors, cities, and ecosystems. Water scarcity is a major challenge to the sustainable development in any society due to which an efficient and equitable management of water is essential. For SDG, water plays a vital role in strengthening the resilience of social, economic, and environmental systems with respect to the rapid and unpredictable variations including climate changes and land use variations.

As the basic scientific unit, a watershed is not only a hydrological unit, but also a socio-political-ecological entity, that is significant in determining social, food, and economic security, and facilitates life support services to the population (Wani et al. 2008). As far as overall sustainable development is concerned, conservation of soil and water conservation are the fundamental steps of the watershed management program. In an integrated approach, watersheds are crucial to an overall social, environmental, and economic well-being (Fig. 1.3).

On a country scale, healthy watersheds facilitate various critical ecosystem services including healthy ecological systems, availability of sufficient quantity and quality water, soil stabilization, carbon storage, and wildlife movement corridors, etc. Urban development and agricultural operations endanger the watershed health (Fig. 1.3). Due to the urbanization process, vegetation is replaced by impervious surfaces such as buildings, roads, parking lots, etc. It can increase the impermeable area and frequency and volume of stormwater runoff which causes the transport of more pollutants such as sediments, bacteria, and nutrients into waterways and even flooding problems. Industrial activities can also have an adverse impact on watersheds. On a watershed scale, the entry of these pollutants into rivers/channels causes various environmental and economical problems. Sediment and excessive nutrients cause many problems such as deposition, water quality issues, problems with aquatic systems, etc. Climate change also impacts watershed health, which in turn results in more rain, thereby increasing the potential of stormwater runoff to carry pollutants into rivers/channels. Reducing the carbon footprint also aids in protecting watersheds.

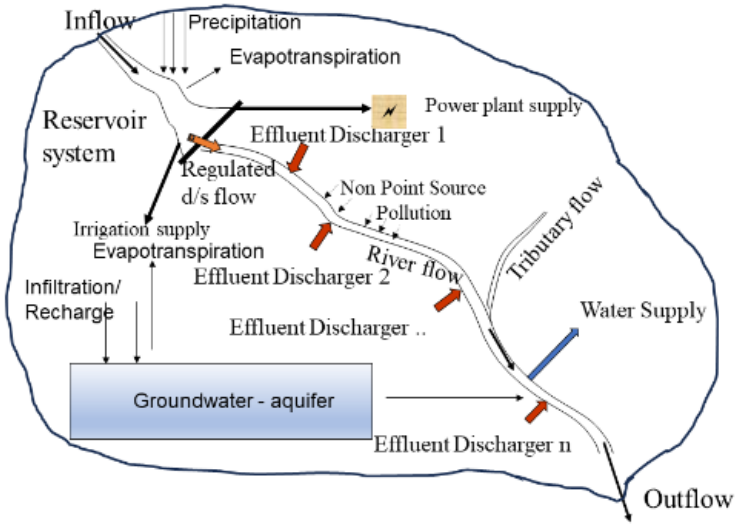

Figure 1-3 A general representation of a watershed with various hydro-environmental system features

In the last few decades, overall, the globe, water, and environmental sustainability are challenged by climate and LULC changes caused by anthropogenic activities. Climate and LULC changes significantly affect the hydrological processes, water resources, and environmental systems. The changes in hydrological and hydrodynamic processes lead to complex river pollution problems affecting the overall water quality of the area. Further, watersheds impact the global carbon cycle in terms of deforestation/afforestation and other related issues. For environmental sustainability, a general understanding of the watershed ecosystem with the carbon cycling dynamics is important.

Climate and LULC changes and impacts on watershed

Globally, in the last few decades, climate change has been one of the major challenges affecting the world and the flora and fauna by a high scale increase in vulnerability with varying intensity (Hansen and Cramer, 2015; Stocker et al., 2013). In the last few decades, the warming climate has had a prevalent impact on the hydrologic cycle and the total environmental system (Oki and Kanae, 2006). The hydrology of a watershed is not only influenced by the climate and its changes, but also by the various geophysical features (such as soil, vegetation, and geology). There is a decisive role played by the storage and discharge characteristics of the basin. For a watershed or a river basin, the inter and intra-annual variabilities in the climate and LULC play a significant role in spatiotemporal modulations in the flow regimes. Other than the natural factors, anthropogenic interventions in land and water (for energy, food, and other needs) from the local watershed scale to regional scales have significant impacts on the hydrological and environmental fluxes (Jaramillo and Destouni, 2015). The identification and attribution of changes in watersheds, river basins, or regional hydrology to global climate change and distinguishing that from the regional anthropogenic interventions is extremely complex and challenging (Maina et al., 2013; Sterling et al., 2013). Further, the various uncertainties in input and validation datasets (climate, vegetation, runoff, etc.), hydro-climate models, methods of assessments, and future climate-forcing scenarios affect hydrologic projections and the reliability of climate change and environmental assessments.

On a watershed or river basin scale, climate and LULC changes are the key factors influencing the changes in hydrological processes. The changes can be in terms of evapotranspiration (ET), infiltration rate (Rientjes *et*

al. 2011), soil moisture, base flow, and runoff (Sinha and Eldho 2018) The climate variability effects the rainfall, humidity (Wang *et al*. 2008), routing time, peak flow, and runoff volume (Prowse *et al*. 2006). The consequences can be in terms of flooding, water scarcity, or droughts. Hence, the interpretation of the impacts of LULC and climate changes is essential for water resources and environmental management at the watershed/ river basin scale. In many parts of the world, the population explosion, rapid socioeconomic growth and deficit of sufficient water resources may lead to water scarcity (Wagner *et al*. 2013, 2016).

Hydrology of watershed and modeling

In river basin/watershed hydrology, we try to understand the hydrologic processes and their responses (Singh and Woolhiser, 2002). For an effective assessment of the water resources of a river basin/watershed, we need to evaluate various hydrological processes and their responses. Generally, the precipitation occurring in a watershed are categorized into abstractions and surface runoff (Fig. 1.4). The important abstractions include evaporation, transpiration, interception, infiltration, surface/ subsurface storages (Eldho and Kulkarni, 2017). One of the important processes that affects the watershed hydrology is evaporation/transpiration, which is the sum of the loss of water due to direct evaporation from vegetation and land surface and the water transpired by vegetation (Linsley et al., 1958). Within a watershed, depending on various hydroclimatic conditions, the evapotranspiration may vary, and it can be sometimes more than 50% of the precipitation (Singh, 1989). Another important abstraction is infiltration which can be defined as the percolation of water into the soil through the land surface. Within a watershed, soil characteristics and pattern of precipitation influence the infiltration (Singh, 1988; Chow et al., 1988). The lateral movement of water through the soil layers is known as subsurface flow or interflow (Linsley et al., 1958). Interception can be considered in terms of water detained by vegetation and other ground objects. Further abstraction can be stored in depressions and landforms, known as depression storage.

The surface runoff in a watershed is the precipitation component that flows through the surface after various abstractions. The surface runoff can be overland flow or channel flow and finally moves to the watershed outlet without being stored for a long time (Black, 1991). Overland flow is the precipitation that flows over the land surface after infiltration and other abstractions. Within a watershed, depending on the drainage network, the overland flow combines with the various stream networks to form a channel

flow (Linsley et al., 1958). The various hydrologic processes from precipitation to runoff are very important in the water resources evaluation of a watershed.

Within a watershed, various watershed/hydrologic models can be used to evaluate the hydrologic processes. The hydrological/watershed models can be categorized as empirical models, black box models, lumped models, and physically distributed models. In the recent past, various watershed models are developed by hydrologists and engineers. Some of the widely used watershed models are discussed as follows (Eldho and Kulkarni, 2017).

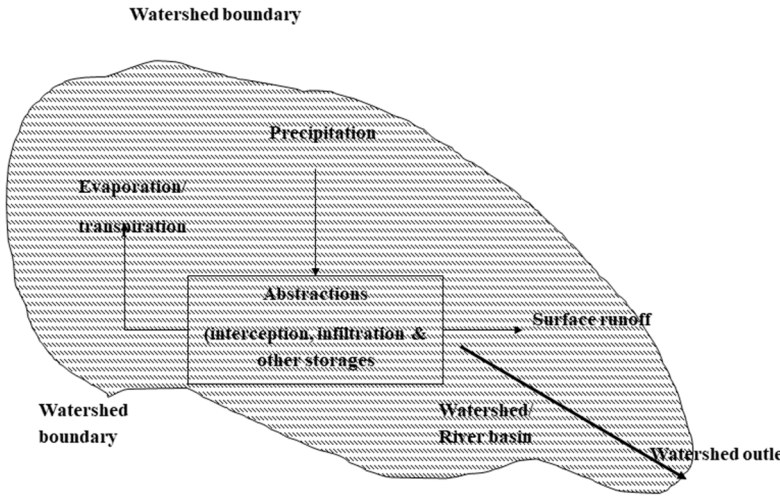

Figure 1-4 Various hydrological processes within a watershed/river basin

i) ***Black Box / Empirical Models***: For watershed/river basin level modelling and runoff estimation, so many empirical models are developed using the field observations or principles like the Rational method (Runoff in a catchment = Coefficient of runoff x precipitation intensity x area of the watershed). These models do not give insights into the hydrological process taking place in the watersheds and accuracy depends on the data and calibration (Singh, 1988).

ii) ***Watershed-based Water Balance Model***: It is a simple model developed based on mass balance or lumped storage representations, that is: change in storage = rainfall – runoff –