The response of flow-dependent ecosystem services to climate change within the riverine landscape of the Koshi River Basin, Nepal

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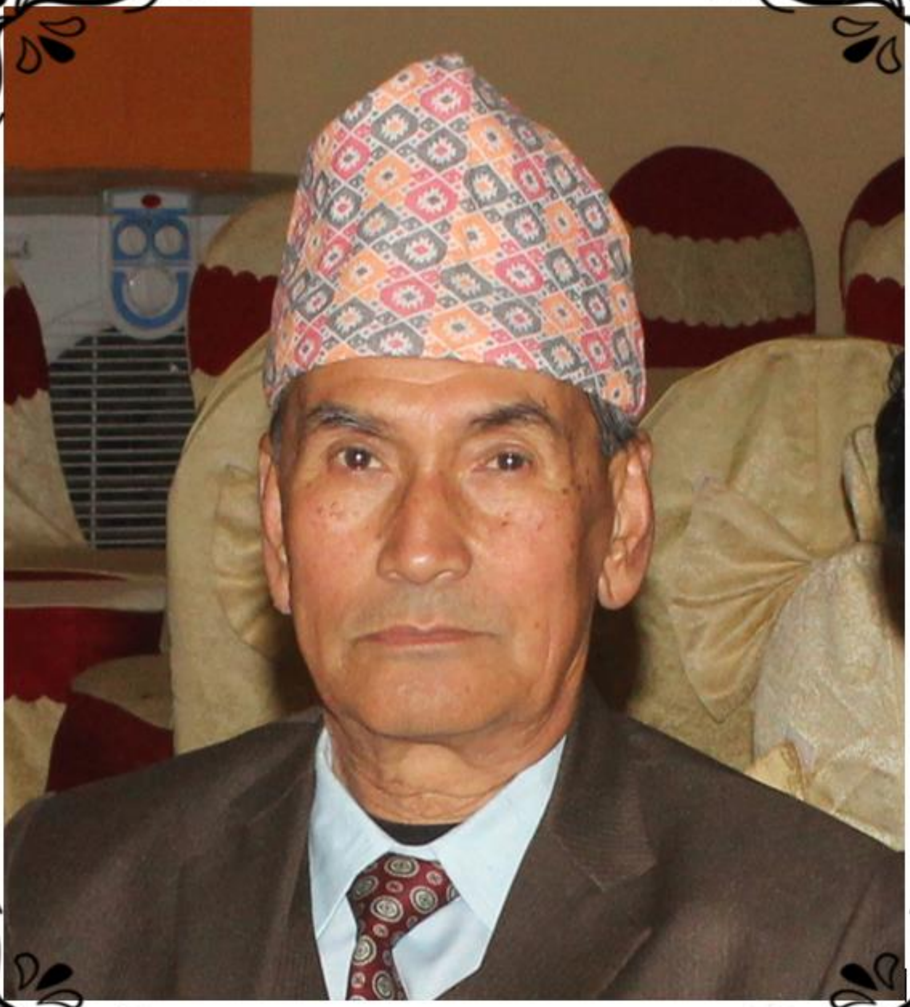
In Memory of My Beloved Father

Dan Ratna Bajracharya



who left us on the 5th of May 2022,

May his soul rest in peace.

Abstract

Riverine landscapes have been conceptualised as complex adaptive systems, characterised by many biophysical and social components, which interact at multiple scales. This complexity challenges traditional scientific methods because the multi-causal, multiple-scale character of riverine landscapes limits the usefulness of conventional reductionist falsification approaches, except at smaller scales and within limited domains. Identifying and understanding the various biophysical and social drivers of rivers, and their connections are challenging. Historically, most river science has been limited to relatively small-scale and location-specific studies conducted over small-time scales and the application of these studies to entire riverine landscapes is questionable as it infringes on the basic principles of hierarchy theory.

The study of ecosystem services in riverine landscapes is biased in scale. The majority of studies of flow-dependent ecosystem services are at a single scale, i.e. at a site or reach scale, and do not consider the entire river network. In addition, studies only evaluate one or two types of ecosystem services and the effect of climate change on these flow-dependent ecosystem services is limited.

The Koshi River Basin is the main river system of the greater Himalayan region and one of the most complex Himalayan rivers. It drains a region sensitive to climate change. The upper part of the basin stores substantial fresh water in the form of snow and glaciers. The system plays a key role in irrigation, household water for downstream areas, has a large potential for hydropower development, and supports ecosystem functioning. The Basin is home to more than 40 million people, of which 80 percent are dependent on the ecosystem services the system provides. The Basin is also home to sensitive and crucial ecosystems, with protected areas that support high levels of biodiversity – it is a hot spot of ecosystem services and functions as a vital corridor for various fauna.

This thesis uses multiple lines of evidence to understand the relationships between the physical template of the Koshi's riverine landscape, flow-dependent ecosystem services and the influence of climate change. The first study (Chapter 2) examines the congruence between the physical template and flow-dependent ecosystem services of the Koshi River Basin network. River characterization of the Basin shows a spatially heterogeneous river network and a high degree of congruency between the physical template of the river network and the abundance, use and value of flow-ecosystem services. The abundance and use of flow-dependent ecosystem services are heterogeneous among the various river zones identified within this river network. However, the potential value of ecosystem services is influenced not only by physical templates but also by the demography of the regional population.

The second study (Chapter 3) examines the potential effect of climate change on the flow regime of the Koshi River Basin. A hydrological model was developed to determine the potential changes to the flow regime of the Koshi Basin, under two climate scenarios over a 100-year period. Results show significant changes in the flow regime of all sub-basins in the Koshi due to climate change. Flow regime components were projected to increase in most sub-basins. However, flow regime changes vary among the six sub-basin studies and the rate of change varies over time. Changes to the frequency of high and extremely low flow events demonstrate the increase in hydrological extremes. Flow regime changes accelerate over the 100 years with the largest projected increases for Representative Concentration Pathway 8.5 scenarios.

The third (Chapter 4) study examines the response of the flow-dependent ecosystem services to climate change and the influence of lateral position in the riverine landscape on this response. Flow regime data from Chapter 2, along with the location of ecosystem services at three different lateral positions in the riverine landscape were used. A matrix of flow-dependent ecosystem service responses was constructed for the Sunkoshi River Basin. The distribution of the flow-dependent ecosystem services varied significantly between the river channel, riparian zone and floodplain sections of the riverine landscape. The potential change in the flow regime also differed by lateral position under the two climate scenarios. As a result, the response of ecosystem services to climate change in the Sunkoshi riverine landscape is predicted to vary under different climate change scenarios according to lateral position. Thus, the distribution and response of flow-dependent ecosystem services to climate change are not uniform in relation to the lateral position of the riverine landscape.

The fourth study (Chapter 5) examines the impact of climate change on flow-dependent ecosystem services based on the geomorphological organization of a river network. A river characterization schema, an inventory of ecosystem services among river zones, and flow regime data from Chapter 2 were used to construct a matrix of flow-dependent ecosystem services according to river zone. Results show the response of the flow-dependent ecosystem service to climate change will not be uniform within the Koshi River network. The responses varied most by river zones and lateral position but the nature of the response of ecosystem services to climate change was consistent among all sub-basins. The finding of this study highlights that the response of the flow-dependent ecosystem services to climate change is determined by the physical template of the river network. This study highlights the importance of scale and hierarchy to the response of ecosystem services in the riverine landscape.

This thesis highlights the importance of the physical template in the production of flow-dependent ecosystem services across the riverine landscape and recognises that the heterogeneity of the physical template influences the response of ecosystem services in the riverine landscape to climate change within river networks. The Koshi River Basin does not support a simple clinal gradient river model, its river network is heterogeneous in terms of the

arrangement of its physical template. Given the congruency between the physical template and ecosystem services, ecosystem services are also heterogeneous within the river network. Moreover, the response of ecosystem services to climate change within a river network is also not uniform and varies according to the lateral and longitudinal position of the river network. This thesis is the first to study the importance of the physical template for ecosystem services in a large Himalayan river basin. Furthermore, this study shows that the distribution and response of flow-dependent ecosystem services are complex and respond in a complex way to flow regime changes arising from climate change. In particular, this complex response depends upon lateral and longitudinal positions within the river system. Moreover, the relationship between flow and ecosystem services may change over time.

This research has enabled the construction of a social-ecological systems framework to understand the abundance, use and value of ecosystem services within entire river networks. The framework unpacks the complex interplay of biophysical and social components within riverine landscapes as well as understanding the role of controllers for the production of ecosystem services and their use and social value in the riverine landscape coupling the human dimension. Overall, this framework illustrates the riverine landscape as a complex adaptive system.

Overall, this thesis contributes to our understanding of riverine landscapes as a complex adaptive system. Complex adaptive systems are a mechanism to understand riverine landscapes as social-ecological systems. Ecosystem services are an ideal indicator to consider interactions between the environment and humans in a social-ecological system through a lens of complex adaptive systems. Finally, this thesis improves knowledge of the interaction among physical templates, ecosystem services and people at a large scale in a systematic way, and demonstrates how the riverine ecosystem services may respond to climate change.

Certification

I certify that the ideas, experimental work, results, analyses, software and conclusions reported in this thesis are entirely my own effort, except where otherwise acknowledged. I also certify that the work is original and has not been previously submitted for any other award, except where otherwise acknowledged.

[redacted]	10th April 2023
Candidate Name	Date

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Finally, I would like to dedicate this thesis to my beloved father “Dan Ratna Bajracharya” who left us on the 5th of May 2022. May his soul rest in peace.

Preface

This thesis is by publication and the research carried out during my PhD candidature in the Department of Geography and Planning, University of New England. This thesis contains published work and/or work prepared for publication, all of which have been co-authored. The pronoun "we" used in this research chapter reflects the co-author's contributions. The bibliographical details of the work and where it appears in the thesis are outlined as follows.

Chapter 2 has been published by *Annals of the American Association of Geographers*: Bajracharya, S.R., Thoms, M.C., Parsons, M. (2023). "**The heterogeneity of ecosystem services across the riverine landscape of the Koshi River Basin, Nepal**." http://www.tandfonline.com/(Doi: 10.1080/24694452.2023.2187338)

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Table of Contents

Chapter 5: The role of geomorphological organization in the response of flow-dependant ecosystem services to climate change in river networks 251

List of Tables

List of Figures

Glossary of abbreviations

ANOSIM = Analysis of Similarity

APHRODITE = Asian Precipitation – Highly Resolved Observed Data Integration Toward Evaluation of Water Resource

AR5 = IPCC 5th Assessment Report

Arc Hydro = Arc Hydro ArcGIS tool

ASTER = Advanced Spaceborne Thermal Emission and Reflection Radiometer

CBS = Central Bureau of Statistics

cf = Confirmed from

CMIP5 = Coupled Model Intercomparison Project Phase 5

CSB 17 = Central sub-basin 7

DEM= Digital Elevation Model

DHM = Department of Hydrology and Meteorology

ES= Ecosystem Service

ESB 16 = Eastern sub-basin 16

Fp = Floodplain

FPC = Flood Pulse Concept

FPZ = Functional process zone

FPZ1 = High Himalayan River

FPZ2 = Meandering River

FPZ3 = Braided River

FPZ4 = High Elevation Floodplain River

FPZ5 = Low Elevation Floodplain River

GCM = General Circulation Model

GIS = Geographical Information System

HKH = Hindu-Kush Himalaya

HRU = Hydrological response unit

ICIMOD = International Centre for Integrated Mountain Development

IHA = Indicators of Hydrological Alteration

InVEST = Integrated Valuation of Ecosystem Services and Trade-Offs

IPCC = Intergovernmental Panel on Climate Change

KRB = Koshi River Basin

MEA = Millennium Ecosystem Assessment

NSB 2 = Northern sub-basin 2

NSE = Nash-Sutcliffe efficiency

PBIAS = Percentage Bias

PGIS = Participatory Geographical Information System

R^2 = Coefficient of determination

Rc = River channel

RCC = River Continuum Concept

RCP = Representative Concentration Pathway

RCP4.5 = It is a scenario that assumes the increased radiative forcing will stabilize at 8.5 W/m^2 in 2100

RCP8.5 = It is a scenario that assumes the increased radiative forcing will stabilize at 8.5 W/m^2 in 2100

RES = Riverine Ecosystem Synthesis

RESonate = Automated hydrogeomorphic data extraction toolbox in ArcGIS

RL = Riverine Landscape

RLU = Riverine Landscape Unit

Rz = Riparian zone

SDC = Serial Discontinuity Concept

SEC = Social-Ecology System

SESB 27 = Southeastern sub-basin 27

SIMPER = SIMilarity PERcentage analysis

SRTM = Shuttle Radar Topography Mission

SWAT = Soil and Water Assessment Tool

SWAT-CUP = SWATCalibration and Uncertainty Programs

SWSD 18 = Southwestern sub-basin 18

TEEB = The Economics of Ecosystems and Biodiversity

VDC = Village Development Committee

WSB 8 = Western sub-basin 8

Chapter 1: Rivers, people, ecosystem services, and the influence of climate change

Rivers, people, river flow and ecosystem services at the riverine landscape in Sunkoshi River.

1.1. Background

Rivers are important to humans and have played a fundamental role in the development of society for centuries. Early human settlements were often established in areas where fresh surface water was abundant and reliable, such as adjacent to perennial rivers (Brierley, 2018). For example, the emergence of early industrial civilizations occurred on the floodplains of three river valleys - the Nile, Tigris-Euphrates and Indus. Since this time, riverine landscapes have served as areas for human settlement, built infrastructure, and intensive agricultural production (Böck et al., 2018). Most major cities of the world are close to rivers, as they provide essential societal needs for instance water for household use, transportation, and fertile land for agriculture. Interactions between biophysical, socio-economic, political and cultural factors that shape social relations to rivers vary in space and time. Different forms of co-evolution between people and rivers occur in different areas over different time scales, as rivers played different roles at different stages of human history (Sivapalan et al., 2021). The type of riverine landscape, its position and environmental setting, as well as the influence and response of different natural and human stressors, define the socio-economic and cultural context of the interactions between people and riverine landscapes.

Human–environment relationships have long been a topic of study and a cornerstone of geography (cf. Marsh 1865; Turner, 2015). The central importance of rivers to society is based on the resources these landscapes and their associated ecosystems provide to humans. Riverine landscapes provide an array of ecosystem services that are of benefit to human well-being. These services include freshwater, food, building materials, medicinal products, foliage for livestock and wildlife. These landscapes and associated ecosystems also provide critical habitats for many aquatic plants, fishes, reptiles, birds and mammals, and represent a corridor for many migratory animals. In addition, freshwater ecosystems within riverine landscapes are now becoming tourist attractions area, thus providing recreation services to many. The ecosystem services provided by the riverine landscape have been valued in monetary terms, highlighting the economic importance of the benefits nature provides. Sharma et al., (2015) calculated the economic benefits generated by ecosystem services from wetlands in the Koshi Tappu Wildlife Reserve, Nepal, to be worth US$ 16 million per year. The economic value of ecosystem services provided by rivers and their floodplains, globally, has been estimated to exceed US$25,681 ha^{-1} (Costanza et al., 2014). Moreover, approximately 25 percent of global terrestrial ecosystem services are provided by floodplains (Tockner and Stanford, 2002). Humans have further optimized the capture of services of river systems through modifying them. For example, the construction of dams to generate hydropower illustrates how humans may increase the provisioning of ecosystem services with multiple benefits to people. Other examples include irrigation of floodplain surfaces, flood control, drinking water, recreation and transportation.

The Himalayas are a region of enhanced biodiversity and ecosystem services (Chettri et al., 2008). It has been identified as a region important for global conservation (Brooks et al., 2006) because it is endowed with rich natural resources; housing endemic flora and fauna communities and supplying valuable ecosystem services to regional people (Schild, 2008; Kandel et al., 2018). The Himalayas cover an area of over 4.3 million km^2 and includes the countries of Nepal and Bhutan and parts of Afghanistan, Bangladesh, China, India, Myanmar, and Pakistan. The region is commonly referred to as the ‘Third Pole and the water tower of Asia’ (Behrman, 2010). It contains a significant amount of frozen water outside of the Polar Regions and is the source of 10 major river systems (Figure 1.1) that collectively provide water resources to over half of the world’s biodiversity hotspots, fresh drinking water, hydropower and irrigation for 1.9 billion people or approximately 23 percent of the world’s population (Wester et al., 2019). Furthermore, about 10 percent of the world’s population depend directly on these mountain resources for their livelihoods and well-being while an estimated 40 percent depend indirectly on these resources for goods such as food, timber, hydroelectricity and medicine and a wide range of services such as fresh air and water, climate regulation, carbon storage, and the maintenance of aesthetic, cultural, and spiritual values (Schild, 2008; Kandel et al., 2018). The supply of ecosystem services in the Himalayas has a vital role in the well-being and sustainable livelihood of people within the region and beyond. It is a region where the coupling between humans and rivers is strongly evident. Living surrounding the riverine landscape deepened the communities connected with the riverine landscape. The water for household use, fertile land for agriculture, means of transport and cultural linkage are the services provided by the riverine landscapes.

Figure 1. 1. The Hindu-Kush Himalaya (HKH) region source of 10 major river systems in Asia.

The river ecosystems of the Himalayas provide vital resources in the form of provisioning, regulating, cultural and supporting services. Water is perhaps the most critical ecosystem service provided by this mountain region, particularly in terms of its supply to more densely populated downstream areas. The importance of the Himalayas as sources of freshwater has justified their label as the "water towers" of the world. It is estimated that at least half of the world's population depends on water originating from mountain headwaters of the Himalayas (Egan and Price, 2017). Despite the contribution of mountain ecosystems of the Himalayas to global communities, they are marginalised regions (Schild and Sharma, 2011) because of limited research, knowledge and data. These mountain regions have been referred to as a global '*White Spot*' (Schild, 2008) in terms of environmental knowledge. For instance, studies of rivers draining mountain regions and their benefits to communities are concentrated in the USA, Europe, and China (Wang et al., 2021). Furthermore, enhanced anthropogenic climate variations have emerged as a prominent driver of global change, especially in the Himalayas (Schild and Sharma, 2011). The potential impacts of climate change on the riverine landscapes of mountain environments and their associated ecosystems will increase pressure on these landscapes to provide ecosystem services. Climate change will increase extreme events (flood and drought), erratic and intensive rainfall will trigger landslides in mountains (Bajracharya et al., 2018). However, the full extent of the impact remains unclear, because data collection from these remote regions is challenging and knowledge and understanding of how the mountain ecosystem services may respond to climate change is limited. There is a need for further research into the effects of climate change on rivers at the roof of the world.

Riverine landscapes have been conceptualised as complex systems, characterised by many biophysical and social components that interact at multiple scales (Thoms and Sheldon, 2019). This complexity challenges traditional scientific methods because the multi-causal, multiple-scale character of riverine landscapes limits the usefulness of the conventional reductionist falsification approach, except when considered at very small scales and within limited domains (Thoms, 2005). Identifying and understanding the various biophysical and social drivers, components, processes, and interrelated states of river systems is challenging. While there is a rich research history of river science, most are limited to location-specific studies conducted over small spatial and temporal scales. The application of the studies to entire riverine landscapes is questionable because larger river ecosystems are more complex (Thoms and Sheldon, 2019). Given the positive relationship between scale and complexity is an accepted paradigm in the study of natural ecosystems, larger river ecosystems are more complex than smaller river ecosystems (Thoms and Sheldon, 2019). Scale is important when considering the complexity of riverine ecosystems because patterns and processes operate at multiple scales in the riverine landscape to build a whole range of different physical templates.

Humans are a component of the riverine landscape because of the strong interactions between humans and the riverine environment. Thus, riverine landscapes are social-ecological systems, with humans embedded within the riverine landscape system rather than simply acting as external drivers of the biophysical processes of riverine landscapes (Huang et al., 2022; Thoms and Sheldon, 2019; Chen and Liu, 2014). A complex adaptive systems framework provides a means to view and manage riverine landscapes as a social-ecological system. A complex adaptive system has four important components; drivers, responders, templates, and controllers with which to formally identify and understand social and ecological components and their interactions (Thoms et al., 2022). These interactions are not only between ecosystem services but also between society and riverine landscapes. In other words, a complex adaptive system is a mechanism to understand riverine landscapes as social-ecological systems, and ecosystem services as an indicator to consider interactions between the environment and humans in the riverine landscape.

It is within this context of complex adaptive systems that this thesis will examine the interaction between the river landscape and the provision and use of ecosystem services. Using a complex adaptive system framework the thesis views riverine landscapes as a social-ecological system. Ecosystem services are used as an indicator of the outputs of interactions among the physical template of the riverine landscape and the use of those benefits by humans. The thesis also investigates how these interactions and ecosystem services may respond to climate change.

1.1.1. Chapter organization

This introductory chapter is organized into seven sections. Following this brief introduction, Section 1.2 focuses on the riverine landscape and illustrates the role of the riverine landscape in providing ecosystem services. In that section, the importance of the graded organizational structure of riverine landscapes and understanding hierarchy in river science is outlined. Section 1.3 introduces the concept of riverine landscapes as social-ecological systems and their ability to provide ecosystem services. Section 1.4 overviews the concept of ecosystem services; definitions are provided, along with a discussion of their importance. As the literature on ecosystem services is vast, the focus of that section is on distribution, abundance, use and social value. Section 1.4 also outlines how excessive use has led to the often-irreversible modification of vital ecosystems; links between biodiversity and stability of ecosystem services are described, as is the valuation of ecosystem services. A history of the ecosystem services concept and how it has changed over time is also provided along with a discussion on ecosystem services mapping. Section 1.5 brings together concepts of riverine landscapes and ecosystem services to review the potential effect of climate change on flow-dependent ecosystem services across riverine landscapes. The aim and objectives of the thesis are presented in Section 1.6 and finally, Section 1.7 describes the study area.

1.2. Riverine landscapes

1.2.1. What is a riverine landscape?

Riverine landscapes are those landscapes formed by fluvial processes. The action of flowing water and the subsequent erosion, movement and accumulation of sediment creates a network of channels and associated landforms. Riverine landscapes are a product of the interactive effect of hydrology and geomorphology. The geomorphic river landscape forms from the interaction of sediment, water and biota, forming fluvial features at multiple scales (Schumm, 1993). Hydrology through its temporal variability acts as a driver upon this template, representing an important natural disturbance and regulator within these landscapes. Thus, hydrogeomorphology, the interaction of hydrology and geomorphology, creates a dynamic mosaic of physical properties or niches, which influences the type, abundance, arrangement and persistence of ecosystems across riverine landscapes. The hydrogeomorphic character of riverine landscapes provides the template upon which evolution acts to forge various life-history strategies (Southwood, 1988). Riverine landscapes are complex, and this complexity is a function of spatial heterogeneity and temporal variance and is an emergent property that influences the organization of aquatic communities and the function of aquatic ecosystems (Thorp et al., 2008a).

Globally, a 7.56 million km network of river channels dissects the terrestrial landscape across a surface area of ~773,000 km^2 (cf. Allen and Pavelsky, 2018). This network contributes to the redistribution of resources across the global landscape. The flux of water and sediment through this network (temporal variability), combined with the influence of the underlying landscape geomorphology (spatial heterogeneity), and, the suite of anthropogenic changes create the dynamic diversity (biophysical complexity) of river ecosystems across the global river network. Knowledge of this complexity is critical for understanding riverine landscapes and the ecosystems contained within them. A goal of river science is to unpack the complexities of, and interactions within, riverine landscapes (Gilvear et al., 2016).

Riverine landscapes are nested hierarchical systems. They are commonly viewed from larger to smaller components such as catchments to river reaches to individual morphological units (Thoms et al., 2016). At the scale of reaches, the riverscape and floodscape are two important components of riverine landscapes (Figure 1.2). The riverscape is that area comprised of the active river channel and riparian zone (Thorp et al., 2008a). The riparian zone of the riverscape includes landforms such as anabranch channels and that area just beyond the active channel that frequently interacts with the river channel (Thoms et al., 2016). The floodscape is the floodplain; that landform formed by alluvial sediments and contains both active and inactive floodplain surfaces. These areas include isolated channels (oxbows), floodplain water bodies (wetlands, lakes) and terrestrial floodplains. Inundation is a crucial driver of the character of the floodscape because it connects to the riverscape during flooding. Thus, a riverine landscape includes an array of terrestrial to aquatic ecosystems and associated ecosystem services.

Figure 1. 2. Overview of riverine landscape units (River channel, Riparian zone and Floodplain). Source https://www.worldwildlife.org/magazine/issues/spring-2017/articles/modeling-resilience (WWF, 2017)

The seminal paper '*The stream and its valley*' (Hynes, 1975) highlighted the direct connection of rivers and streams with their terrestrial surroundings. This connection is mediated by the physical characteristics of the riverine landscape. Riverine landscapes contained within narrow valleys have a greater connection to their terrestrial catchment surfaces compared to those in broader valley systems. Within narrowed valleys, the riverscape experiences higher energies typically as long as the gradient is steeper, while in wider valley settings extensive floodplains exist and during overbank flows, the river swells across these valley floors depositing sediments due to reductions in flow energy (Thoms et al., 2022). Thus, variations in the riverine landscape character have implications for all forms of connectivity –longitudinal, lateral, vertical and temporal.

1.2.2. Conceptual river models

There have been many attempts to derive conceptual models of riverine landscapes in order to understand their structure, function and interactions. The River Continuum Concept (RCC) was an early attempt to build a single synthetic idea to describe the functioning of running water systems (Vannote et al., 1980). It provides a framework for predicting variability in biological organisms within a river from headwaters to mouth. The RCC assumes that predictable physical gradients along a river from headwaters to downstream areas regulate the biotic processes within the river and these physical forces produce a continuum of morphological and hydrological features and conditions within a riverine system that results in a consistent pattern of loading, transport, utilization and storage of organic carbon along the river (Vannote et al., 1980). The river continuum concept provides a useful prediction of longitudinal lotic ecosystem characteristics for river systems with geological constraints on the extent of forest-river interactions (Sedell et al., 1989). However, a major criticism of the RCC is that it did not account for the importance of interactions between river-riparian-floodplain areas (Junk et al., 1989) and variation between different river zones and river reaches (Sedell et al., 1989). The River Continuum Concept is not able to address the type and scale of river ecosystem behavior and is of limited value for predicting large river ecosystem function (Sedell et al., 1989).

The Serial Discontinuity Concept (SDC) proposed by Ward and Stanford (1983) is based on the river continuum concept but accounts for the disruption of the longitudinal continuum by dams and other impoundments. Interruption to the continuity of flow and sediment movement downstream of dams impacts basic ecosystem patterns along the longitudinal river. River impoundments significantly disrupt the process continuum of basic ecosystem patterns along the longitudinal river. The direction and intensity of discontinuity vary as a function of the specific parameter and the position of the dam along the river continuum

(Ward and Stanford, 1983). The impact of the placement of dams along the longitudinal stream profile might significantly modify the parameters below the dam, and a significant position of impoundment on a stream system will, directly and indirectly, affect all ecological aspects of the downstream running water ecosystem to some extent (Ward and Stanford, 1983). This means a significant decline in the biodiversity pattern below the dam and its relatively rapid increase as rivers continue to flow along the longitudinal pathways (Ward, 1998). The Serial Discontinuity Concept was extended to include floodplain rivers by incorporating the important lateral dimension of the flood pulse (Ward and Stanford, 1995). However, the concept does not account for interactions between rivers and their contiguous aquifers (Ward and Stanford, 1995).

The Flood Pulse Concept (Junk et al., 1989) explains the energy and nutrient dynamics of the floodplain and river channel. This river model stresses the importance of lateral exchanges and recycling of nutrients within the floodplain rather than longitudinal transport mentioned in the River Continuum Concept. The flood pulse is the primary factor for thriving biota in the river and river-floodplain systems. The process that fuels food webs in floodplains is the inundation of the floodplain by a flood pulse. The flood pulse is the facilitator for mobilizing material and energy; and the movement of that material and energy from the floodplain into the central channel. The range of geomorphological and hydrological conditions generates a variety of flood pulses. It also plays a crucial role in regulating geomorphic processes that shape river channels and floodplains, ecological processes which govern the life history of aquatic and terrestrial organisms (Thorp et al., 2008a). The flood pulse is termed a ‘batch process’ occurring in discrete time periods, rather than a continuous process (Junk et al., 1989).

The flood pulse concept was primarily based on observations from tropical rivers where rivers have a long and predictable pulse in discharge. Tockner et al. (2000) extended the

Flood Pulse concept theory to temperate systems with an emphasis on the role of temperature as a major factor in floodplain ecology. However, this concept may be less applicable to arid regions, due to flow variability (Thoms and Sheldon, 2000). According to Junk and Wantzen (2004), the impacts of short and long-term changes in the quality of the flood pulse on the life history of organisms, communities and biogeochemical processes require additional studies.

An alternative model to the concept of continuous, longitudinal gradients of physical conditions is proposed by the Riverine Ecosystem Synthesis (RES) (Thorp et al., 2006; 2008a). The RES views river systems as dynamic downstream arrays of hierarchically scaled ‘hydrogeomorphic patches’ formed by various factors, including catchment and valley geomorphology, hydrological patterns, riparian conditions and climate (Thoms et al., 2018). Central to the RES is the idea that local hydrologic and geomorphic conditions are more important to ecosystem structure and function than simple location along a longitudinal dimension of the riverine ecosystem (Thorp et al., 2008a). This concept is an integrated heuristic model of lotic biocomplexity that incorporates aspects of other conceptual models without the limitations of geographic or climatic regions, or specific river types. The RES is an integration of a general theory of hierarchical patch dynamics (Wu and Loucks, 1995; Wu, 1999) with hierarchy theory expressing relationships amongst pattern, process and scale in a landscape framework (Thorp et al., 2008a).

The Riverine Ecosystem Synthesis is a more robust concept to implement in perennial rivers of different climate and hydrological conditions because it is based on the physical model and has a hierarchically scaled investigative framework (Flotemersch et al., 2010). It also contains explicit ecological components linked to the physical model. Therefore, it relates to the whole riverine landscape (entire longitudinal and lateral dimension) including the floodscape and riverscape. The Riverine Ecosystem Synthesis recognizes that hydrogeomorphic-ecological linkages function at multiple scales (Delong and Thoms, 2016).

Godoy et al. (2016) highlighted two advantages of the Riverine Ecosystem Synthesis over other conceptual models: i) it helps understand the longitudinal and lateral discontinuity of ecological patterns in the riverine landscape, and ii) it suggests regional and local ecological processes vary both spatially and over time.

1.2.3. Foundational concepts of the structure and function of river landscapes

1.2.3.1. Hierarchy theory and scale

The hierarchy of riverine landscapes is based on hierarchy theory. Hierarchy theory derives from general systems theory and provides a conceptual framework for the analysis of scale in landscapes and ecological systems and can be applied to riverine systems. A hierarchical framework offers a way of organizing multiple scales of measurement (Parsons et al., 2004). A hierarchy is a graded organizational structure, a system of systems within systems (King 1997) and can be viewed as a series of organizational levels within the nested vertical structure. Functional process rates generally identify the boundary of a level. As riverine landscapes are nested hierarchically, three main properties govern the exchange of information between levels within a hierarchy. First specific levels of an organization are linked to particular spatial and temporal scales, where higher levels correspond to larger spatial scales, and longer temporal scales and Lower levels correspond to smaller spatial scales and shorter temporal scales (Parsons et al., 2004). Second, rate differences of at least one order of magnitude exist between different levels so that higher hierarchical levels have lower frequencies of behaviour than lower levels and the reactions are therefore slower than at lower levels (Parsons et al., 2004). Third, higher levels constrain lower levels due to larger time constraints (Thoms et al., 2016). For example, geology and climate are independent factors on a higher level that directly and indirectly control the formation of other factors (topography, vegetation, soil) in the hierarchy. As an outcome of hierarchy, rivers can be organized into nested hierarchical levels in which the features characteristic of higher levels constrain the expression of features at one level. For example: in a fluvial system, geomorphological factors and processes operating at one level of the hierarchy limit the formation of factors at lower levels (Thoms et al., 2016). Figure 1.3 shows the hierarchical organisation of hydrogeomorphic patches within the riverine landscape. Parsons and Thoms (2007) highlighted that a hierarchical understanding of river ecosystem organization will enhance river conservation and management because it facilitates a holistic, ecosystem perspective rather than a partial, single-scale, single component or single-discipline perspective.

[redacted]

Figure 1. 3. Conceptual diagram of hierarchical organisation system demonstrating a level of organisation nested within the level immediately above. Increased dash arrows show the decrease in the degree to which other standards within the hierarchy influence the level of organisation of interest. In the above figure, the focus level, L-3, is most directly influenced by L-2 and L-4 (Delong and Thoms, 2016).

In river science, the scale has been viewed as a common thread to integrate geomorphology, hydrology and ecology – assignment of scale to one level of organisation implies scales for all other levels, leading to a hierarchy of scales for a given sub-system (Delong and Thoms, 2016). According to the organizational hierarchy framework in river science, scales for each hierarchy need to be determined and linked to the appropriate levels of organizations according to the spatiotemporal dimension (Delong and Thoms, 2016). This guides the selection of appropriate scales of measurement in riverine ecosystem studies. It helps to solve the issue of scale mismatches between the various sub-disciplines, ecological processes and inappropriate data aggregation for research and minimize misleading interpretations. For instance, mismatched scales of observation between disciplines may fail to recognize the importance of pattern and process in hierarchical systems (Thorp et al., 2008a), because pattern and process do change with scale (Wiens, 2002). Thorp et al. (2013) argued that the selection of appropriate levels of the organization depends upon the purpose of the study and research question.

Hierarchy and scale are the common thread running through the hydrology, fluvial geomorphology and ecology hierarchies and are, therefore, a fundamental tenet of an integrated river ecosystem (Dollar et al., 2007). However, identification of the appropriate scales or levels of organization that link similar attributes across disciplines is rarely attempted because of entrenched views within individual disciplines. Rather, they must be defined relative to the level of the problem being addressed and defining and isolating the relevant level in a hierarchy is a critical step in framing an understanding of rivers (Dollar et al., 2007). The different hierarchies present in river ecosystems have concurrent levels of the organization and associated grain and extent (Figure 1.4). Linking levels of organization in different hierarchies can be achieved by matching scales. For example, I used the functional process zone of the geomorphological hierarchy matched with the flow regime level of the hydrological hierarchy and the ecosystem level of the ecological hierarchy (blue line in Figure 1.4), approach to study ecosystem services in the riverine landscape. Attention to the grain and extent of the different levels of the hierarchy is vital because the nested hierarchical processes only occur at certain ranges of space and time.

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*Figure 1. 4. Organizational hierarchies in river ecosystems (Thorp et al., 2008a)***.**
Note: The blue line represents the scale used for my study.

1.2.3.2. Interdisciplinary river science

River science is the interdisciplinary field of study focused on interactions between the physical, chemical, and biological components of riverine landscapes (Thoms et al., 2016) and how they influence and are influenced by human activities. These interactions are studied at multiple scales within both the riverscape (river channels, partially isolated backwaters, and riparian zone) and adjacent floodscape (isolated oxbows, floodplain lakes, wetlands, and periodically inundated flat landscapes). A fundamental basis of interdisciplinary river science is the importance of hierarchy and scale, and the use of hierarchy theory, as a means to link the different disciplines that make up river science (Thorp et al., 2008a). Dollar et al. (2007) proposed an integrated interdisciplinary framework of fluvial geomorphological, hydrological and ecological hierarchies for application in riverine landscapes. This framework matches levels of organisation of river morphology with commensurate levels of hydrological character and ecological response at appropriate spatial and temporal scales (Figure 1.4).

Riverine landscapes are complex systems with patterns and processes reflecting the interaction among three primary systems of geomorphology, hydrology and ecology (Thoms, 2005). Earlier studies viewed rivers from single disciplines. Viewing rivers from an individual disciplinary perspective is inappropriate for a full ecosystem understanding of river systems and the benefits they may provide to society (Thorp et al, 2008a). Pickett et al. (1994) argue the need for a new interdisciplinary philosophy of science that understands the interface between disciplines. This philosophy should be scale-sensitive and move away from the conventional reductionist falsification approach (Pickett et al., 1994), which limits the development of an appropriate understanding of complex systems such as river ecosystems. This demands a hierarchically based approach that integrates description, causal explanation, testing, and prediction (Pickett et al., 1999).

1.2.4. Conceptual framework of riverine landscapes

It has been established that rivers are diverse landscapes, envisaged as the product of multiple interacting abiotic and biotic factors (cf. Gilvear et al., 2016; Gupta, 2021). This interplay of physical, biological, and chemical processes promotes and supports the diversity of landforms and ecosystems contained within these landscapes (Fremier and Strickler, 2010, Gilvear et al., 2016). Identifying and understanding the various biophysical drivers, components, processes, and interactions of riverine landscapes is challenging. However, the various components and interactions within a riverine landscape can be examined and understood using flow-chain models (Dollar et al., 2007). Flow-chain models have four basic components representing the dynamic interplay of abiotic and biotic characteristics in riverine landscapes (Figure 1.5). Drivers are the main agents of change; functions are a series of controllers or processes that are governed by the agents of change; templates are those surfaces (both abiotic and biotic) upon which drivers and functions act; and finally, there are a series of responders. Responders can be sets of processes, organisms, or parts of the biophysical environment present across the riverine landscape. In this flow-chain model, flow is the primary regulator of change that acts upon the physical template of the riverine landscape. The product of this interaction is the hydrogeomorphic (physical) landscape that influences the abundance, composition and spatial organisation of aquatic habitats. Habitats within the riverine landscape are dynamic in time and space because of the regulating effect of hydrological variance. Aquatic communities are responders to this dynamic hydrogeomorphic product in this flow chain model. Controllers affect the action of the regulator of change on the transition from the hydrogeomorphic product to the response of aquatic communities. Predation and competition are two key controllers influencing community composition within riverine landscapes. These controllers interact via a series of feedbacks between the hydrogeomorphic product and life-history traits to modify the response of the aquatic community across the riverine niche landscape. This flow chain model is suitable for multiple scale settings, with both the agent of change and the template being scale-invariant. The flow-chain model also highlights the physical character of the riverine landscape as a strong driver of the condition of large river ecosystems (Thoms et al., 2018; Delong and Thoms, 2016). Thus, flow chain models provide a way of understanding how the interplay of hydrology and geomorphology influences the arrangement of patterns and processes across riverine landscapes. Flow-chain models have been used to demonstrate the effect of change in physical heterogeneity on food webs in river ecosystems (Thoms et al., 2017) and the ecological concept of disturbance in urban river systems (Grimm et al., 2017).

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Figure 1. 5. A riverine landscape flow chain model from Thoms et al., (2022).

1.2.4.1. River characterization

River characterization is a way to determine various biophysical characteristics within river networks. Characterising rivers can improve scientific understanding of how rivers function (Thorp et al., 2008b). Flotemersch et al. (2010) highlighted the primary purpose of river characterization is to be able to compare and contrast different river sections that make a river network and assist in the inference of ecosystem structure and function associated with different river sections. River characterisations can also aid in the prediction of responses to anthropogenic pressures in river networks (Sheldon and Thoms, 2006). Physical differences between and along rivers demonstrate how catchment geology, climate and topography interact to govern the amount and rate of water and sediment supplied to a river, and how the water and sediment supply control river pattern and process (Thoms et al., 2016). As geology, climate and topography change with time and in space, the physical characteristics of river systems also change in response. There are many approaches to river characterisation including river zones (production, transfer and accumulation), stream order, and geomorphological framework (Thomson et al., 2001; Thoms et al., 2018; Thorp et al., 2008b).

Rivers are process-response systems and display variations in biophysical character over multiple scales. River landscapes can be viewed at many different scales. Thoms et al. (2004, 2008, 2016) derived a seven-level organizational hierarchical framework for river systems (Figure 1.6). As described below, the framework considers the catchment as the primary unit and nested within this are the river network, functional process zone, river reaches, functional sets, functional units and microhabitats (Thoms et al., 2016). Functional process zones (FPZs) are the lengths of the river system that have similar geology, discharge and sediment regimes. Channel pattern is an indicator of differences between functional process zones; however, different functional process zones also have contrasting flow and sediment regimes. River reaches are repeated lengths of river channels within a process zone that have a similar channel style. They are typically based on river channel planform or bedform character, with a reach being delineated as many meanders bends or riffle–pool sequences. Each river reach may be divided into functional sets of typical units associated with specific landforms within the riverscape or the floodscape. Typical landforms may include side channels or anabranches, wetlands located within the floodscape, cut-offs, and the main active channel and associated landforms. The character of each functional set within the riverine landscape is determined by the magnitude, frequency, and duration of longitudinal, lateral, and vertical fluxes, which are related to the geomorphology of each landform. A functional unit is indicative of the physical conditions at a smaller scale. They commonly represent physical habitats associated with animal and plant communities present at a site. Functional units can be subdivided into mesohabitats (Harper and Everard, 1998). These are sensitive to variations in flow, sediment, and nutrient fluxes and as a result, may change yearly. Common mesohabitats include sand and gravel bars, in-channel benches, scour holes, gravel patches, undercut river banks, and other smaller features such as emergent and submerged vegetation, submerged wood, and other substrates (cf. Thorp et al., 2008b). Therefore, the division of a river system into component levels at different scales is important as it provides a practical way of identifying the interrelationships between physical and geomorphological factors across a range of spatial and temporal scales (Thoms et al., 2008)

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*Figure 1. 6. The hierarchical organizations of riverine landscapes (Thoms et al., 2008)***.**

There are two ways of analysing and characterising river networks: bottom-up and top-down methods. Bottom-up methods use field surveys to map river forms (Williams et al., 2013) and can be labor-intensive, time-consuming, and costly. Conversely, top-down methods, use available secondary data to delineate river form, particularly at the level of FPZs (c.f. Thoms et al., 2018). A GIS-based and remote sensing approach can be used to extract hydrogeomorphic variables from a geospatial dataset and these variables are then analysed to extract areas of similar river character or river types. This method is faster, and more cost-effective compared to the traditional field-based method and more efficient, especially in river basins where there is data scarcity and field-based work is hard to conduct due to rough or fragile terrain, steep slopes and remoteness (Williams et al., 2013).

1.2.5. Knowledge gap

Previous studies on the riverine ecosystems consider the physical template to be a uniform, unidirectional, continuous and homogenous ecological unit, whereas riverine landscapes are heterogeneous in terms of a physical template, biophysical character and providing ecosystem services capacity. The recognition of hydrogeomorphic attributes - appreciate riverine landscape as a composite of patches existing at multiple spatial and temporal scales. The types and arrangements of these physical templates influence ecological structure and function which ultimately impact ecosystem services. As elucidated by Thoms (2006) the structure and function of riverine ecosystems also vary across the riverine landscape (riverscape and floodscape). Thus, it is important to understand the spatial distribution of the ecosystem and its services and goods within and across the riverine landscape for better management and planning of the ecosystem services.

Most of the studies on the riverine ecosystem were done individually not considering the hierarchical organizations of riverine landscapes. The relationship between the character of the physical template and ecosystem is limited to a smaller scale for instance location specific, wetland and reach scale. In addition, not many follow the importance of scale as well as issues of mismatched scale between the various sub-disciplines. Thorp et al. (2006, 2010) highlighted the research on the link between the physical template and ecosystem services is largely in the infancy stage and only tentative predictions can be made on relationships between physical templates and ecosystem services. Therefore, the relationship between physical templates and flow-dependent ecosystem services as well as the abundance, distribution of flow-dependent ecosystem services within or across the physical templates have not been assessed. Furthermore, the studies on the riverine landscape ecosystems concentrated in Europe, China and the US (Hanna et al., 2017), and none of the studies have focused on the spatial variation of the ecosystem services within river networks on a large scale. As well as this type of study has not been done in the Himalayan River network. Therefore, there is a gap in understanding how physical and ecological processes operating at multiple scales interact to construct a range of different physical templates and deliver flow-dependent ecosystem services in the Himalayan River network.

Studies of riverine landscapes are dominated by those that view rivers as predictable downstream gradients of biophysical conditions, such as the RCC and SDC. This assumes the longitudinal linkage of ecosystem processes in rivers through the downstream flows of water, energy and material which gradually changes physical and ecological conditions. However, these models have not focused on the hierarchical variation of the ecosystem function and process within the whole river system. Therefore, there is a gap in understanding ecosystem function, services, and goods in the entire river network. Further, there is a knowledge gap in the implementation of the RES concept and FPZ approach in the Himalayan River system. This means RES is not tested in the Himalayan Rivers.

The review of the riverine ecosystem and its benefit to society has shown a lack of studies about the spatial organisation within a riverine landscape. This lack of spatial understanding of riverine ecosystem services is at odds with the way that rivers have been organised to understand riverine ecosystem structure and function. Multiple processes operate at multiple scales in the riverine landscape to construct a whole range of different physical templates (Thoms et al., 2008). Processes operating at different scales imply that there is a need to observe the influence or association between physical drivers and ecological response at an appropriate scale. The hierarchy framework helps to identify the right scale driver influencing an ecological response and determine the influences of physical drivers on ecological responses in a riverine landscape.

1.3. Riverine landscapes as social-ecological systems

1.3.1. What is a social-ecological system?

How humans interact with their environment and how the environment influences humans have been topics of study for centuries. These interactions occur and are important in the fundamental tenet of geography (Marsh, 1865; Turner, 2015). However, relationships between humans and their environment have changed over time. Hunter-gather societies epitomise the close connection between humans and their environment (Brierley, 2020). With developing knowledge and technology and increased populations has come an increasing ability to utilize resources and modify their environment over time, which has led to humans being conceptualized as external drivers of environmental systems. However, the idea that humans are external drivers of ecosystems is changing and in the last ten years or so, humans have increasingly been viewed as a component of environmental systems (Dunham et al., 2018). This is because of the increased positive and negative interactions and feedbacks between environmental and human systems. This interaction between society and nature, where humans influence natural systems and natural systems influence humans (Figure 1.7) is termed a social-ecological system (Stojanovic et al., 2016).

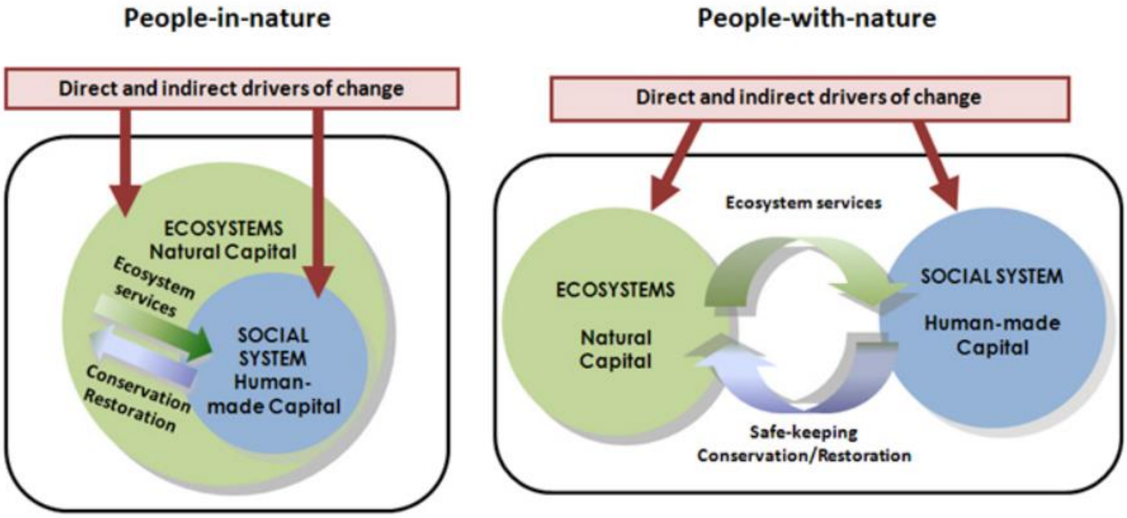


Figure 1. 7. Social-ecological systems as linked systems of people and nature (Perez-Soba and Dwyer, 2016). The left-figure people in nature represents the social-ecological system.

The concept social-ecological system emphasizes that humans must be seen as a part of natural systems not apart from nature (Berkes and Folke, 1998). Thus, social-ecological systems reflect the highly interconnected relationship between society and ecosystems (Figure 1.7) (Francis and Bekera, 2014). Social-ecological systems also represent a framework that conceptualizes the environment as an open system consisting of ecological and social processes and components, including biomes, humans, and wildlife. A social-ecological perspective is required to fully understand key processes and linkages between humans and the environment (Hand et al., 2018).

1.3.2. Riverine landscapes as social-ecological systems

An emerging trend in river science is to manage and monitor rivers as a social-ecological system. This means humans are seen as an integral part of the riverine landscape, not an external driver, emphasising the humans in nature perspective (Parsons, 2019). Riverine landscapes are social-ecological systems because of a high degree of coupling between natural and human components (Thoms and Sheldon, 2019). People depend on the resources provided by riverine landscapes while the riverine landscape is influenced, to varying degrees, by human activities (Parsons and Thoms, 2018). For instance, humans continue to rely on riverine ecosystems for food production, climate regulation, carbon sequestration, waste assimilation, flood control and recreation. Moreover, humans have further modified river landscapes for their needs and benefit. For example, the construction of dams to generate hydropower illustrates how humans may increase multiple ecosystem services with multiple benefits to people. Other examples include irrigation of floodplain surfaces, flood control, drinking water, recreation and transportation. On the other hand, such human activities underpin numerous threats to the riverine ecosystem such as habitat alteration, habitat fragmentation, changes to a flow regime, and water chemistry. These relationships highlight that the benefits for humans are a major driver of change and an integral part of the ecosystem concept - reflecting the high degree of coupling between humans and the environment (Thoms et al., 2022).

The social and ecological parts of river systems are linked through active feedback mechanisms whereby actions in one part of the system can cause other parts of the system to adjust or adapt to changing conditions (Bouchet et al., 2019). Therefore, when riverine landscapes are viewed as social-ecological systems, humans are defined as embedded within riverine systems rather than simply seen as external drivers of river systems (Parsons and Thoms, 2018; Thoms and Sheldon, 2019; Thoms et al.,2022). Furthermore, Dunham et al. (2018) argued that a full understanding of human influences is not possible without explicit consideration of riverine landscapes as social-ecological systems and incorporating the human dimension more explicitly in the research and management of riverine landscapes. According to Thoms and Sheldon, (2019), studying riverine landscapes as a social-ecological system will help to understand i) a shift in the perspective of what should be studied when framing questions about riverine landscapes; ii) acknowledging riverine landscapes are complex and adaptive will have consequences for what methods, scale, and practical approaches are required when studying highly coupled social-ecological relations; and iii) governing paradigms and practical approaches for the study of riverine ecosystems will be challenged.

1.3.3. The complex adaptive system as an approach to understanding riverine landscapes as a social-ecological system.

A complex adaptive system is composed of multiple interacting components that adapt or learn as they interact (Holland, 2006). The dynamic and adaptive nature of a complex adaptive system is of central importance for the study of complex adaptive systems as it focuses on how systems change their structure and function in response to external or internal pressure and interactions between system components (Chan, 2001). The dynamics of a complex adaptive system are governed by fundamental properties including self-organization; long and short-term interactions; non-linear dynamics and feedbacks; path dependency; openness; and, emergence (Levin, 1998).

Riverine ecosystems are complex adaptive systems and are influenced by the dynamic interplay of physical, biological, and chemical processes. Riverine ecosystems are also open systems that operate over a range of scales and are dominated by interactions between biological, physical and physical components and processes (Thoms and Sheldon, 2019). Identifying and understanding the various biophysical and social drivers, components, processes, and interrelated states of river systems is challenging. Scientists have increasingly come to realize that complicated issues cannot be addressed by a single disciplinary approach but instead require integrative, interdisciplinary consideration and collaboration (Warren

1979; Binder et al. 2013). In the broadest terms, a social-ecological perspective is required to fully understand key processes and linkages between people and nature (Hand et al., 2018).

1.3.4. Knowledge gap

The humans are part of the riverine landscape. However, all river models discussed in the previous section view society as an external driver of the environment rather than as a part of the environment and do not link or incorporate the social state of a riverine ecosystem (Vannote et al., 1980; Ward and Stanford, 1983; Junk et al., 1989). As a result, models of riverine landscapes are not able to describe natural processes and direct influences of humans at relevant scales in the environment. There is a knowledge gap about viewing the importance of the riverine landscape as a social-ecological system that considers society as an internal component of an ecosystem, not an external driver of ecosystem structure and function.

Riverine landscapes are complex ecosystems because they are composed of many components those components are both biophysical and social components. Riverine landscapes are influenced by the dynamic interplay of physical, biological, and chemical processes. They change in space and time due to response to a multitude of external and internal drivers (Thoms and Sheldon, 2019). Identifying and understanding the various biophysical and social drivers, components, processes, and interrelated states of riverine systems is challenging. Especially the links between riverine landscape and ecosystem services and this challenge applies to how riverine landscapes produce ecosystem services. Therefore, there is very little understanding of interactions and feedbacks between biophysical and social components in a riverine landscape.

1.4. Ecosystem services

1.4.1. What are ecosystem services?

Ecosystem services are the benefits society obtains from nature that contribute directly and indirectly to human well-being (MEA, 2005; TEEB, 2010). Intact ecosystems provide a range of services to society (van Oort et al., 2015). Ecosystem services have been classified into four broad categories: provisioning, regulating, cultural and supporting. Provisioning services are the products obtained from ecosystems (MEA, 2005), including for example drinking water, hydropower, timber, fuelwood, and food. Regulating services are those benefits obtained from the regulation of ecosystem processes (MEA, 2005), such as climate regulation, groundwater recharge, water purification, water retention in soil, and air quality regulation. Cultural services are non-material benefits people and society obtain from ecosystems (MEA, 2005), like recreation and religious ceremonies. Supporting services are those services that are necessary for the production of all other ecosystem services, for instance, the hydrological cycle, biodiversity maintenance, production of atmospheric oxygen and soil formation (MEA, 2005). Overall, ecosystem services are critical to the functioning of the Earth’s life support system that contributes to human welfare, both directly and indirectly, representing part of the total economic value of the planet (Costanza et al. 1997).

The concept of ecosystem services is an important bridge between natural and human systems. The concept has been used in many scientific and management contexts for a variety of purposes. These include raising awareness of the importance of conserving ecosystems and their biodiversity; increasing understanding of the significance of human activities on ecosystems and the importance of these activities to human well-being; providing a communication framework between policy-makers, scientists and the public on nature and society linkages; and, promoting awareness that maintaining natural capital through conservation and restoration is required to sustain the provision of ecosystem services that are valued by society (Bock et al., 2018). The ecosystem services concept has attracted widespread attention from both science and policymakers in influencing multiple disciplines and initiatives across countries at various scales to support and inform environmental management, natural resource management and biodiversity conservation strategies (Chaudhary et al., 2015). The concept of ecosystem services has also been used to support decision-making for sustainable development. Besides the protection of nature and the sustainable use of natural resources, managing ecosystem services can achieve other important socio-economic goals, such as poverty reduction or employment.

1.4.2. The use of ecosystem services

Natural capital is the stock of natural assets from which humans derive a range of services that make human life possible (Costanza et al., 2017). These assets include geology, soil, water, air as well as plants, animals and other biotas. Natural capital is synonymous with ecosystem services. The importance of natural capital for human well-being has been recognized; from as early as the Stone Age (Braat and de Groot, 2012). Natural capital and ecosystem services are especially important for subsistence livelihoods in rural areas in emerging countries (Chettri et al., 2021). In these countries, healthy functioning ecosystems provide services that are the foundation for human well-being including health, cultural values and food among other things. Ecosystem services that people in emerging countries utilize for their livelihood emphasize the equal role of provisioning, regulating, supporting and cultural ecosystem services (Chettri et al., 2021).

The demand and use of ecosystem services have grown exponentially in the last several decades (Thapa et al., 2018). This increase is associated with increases in population growth. As a result, anthropogenic activities and increased use of ecosystem services have led to the extensive and often irreversible modification of vital global ecosystems (Ellis, 2017). Li et al. (2015) reviewed the impact of a growing global human population, the subsequent increase in urbanization, agriculture, mining and other human activities on natural ecosystems and their ability to provide services to society. According to the MEA (2005), over 60 percent of global ecosystem services, are assessed as being degraded or used unsustainably in such a way that they will not be able to supply essential services by 2030. The MEA (2005) reported 15 out of 24 ecosystem services declined in their ability to function over the last 10 years. This included the provision of freshwater, marine fisheries production, the number and quality of places of spiritual and religious value, the ability of the atmosphere to cleanse itself of pollution, and the capacity of agro-ecosystems to provide pest control. Moreover, Costanza et al. (2014) estimated that changes in land use from 1997 to 2011 resulted in a decline in the value of global ecosystem services by $4.3 - $20.2 trillion per year. This loss in the value of ecosystem services has generated global concerns about the overuse of ecosystem services and thus threatens the ability of ecosystems to supply the continuous flow of services for present and future generations (DeGroot et al., 2012). Focusing on the maximum use exploitation and extraction of ecosystem services and the continual degradation of biodiversity, highlighted that there is a need to develop suitable biodiversity-safeguarding strategies, so effective measures can be established to control ecosystem service loss and its consequences (DeGroot et al., 2012).

1.4.2.1. Importance of biodiversity for understanding ecosystem services

Ecosystem services are closely linked to ecosystem biodiversity. Biodiversity refers to the variety of life on Earth at all its levels; from genes to ecosystems, and encompasses the evolutionary, ecological, and cultural processes that sustain life. Ecosystem services are ultimately dependent on biodiversity because biodiversity underpins ecosystem functioning (De Groot et al., 2010). Biodiversity plays multiple roles in the structure and functioning of an ecosystem because biodiversity is a regulator of ecosystem processes and various species often influence or contribute different functions. For instance, there are potential benefits of crop genetic diversity in enhancing the provision of services. Increasing crop diversity has shown to be directly or indirectly useful in pest and disease management and enhanced pollination services and soil processes (Jacobs et al., 2013). Most studies show that there is clear evidence that biodiversity has positive effects on the provision of ecosystem services (van der Velden., 2015).

Biodiversity plays a major role in nutrient cycling, provision of clean air and water, crop pollination, provision of food, water cycling, climate regulation, disease regulation, carbon sequestration and also has an economic value in their ecosystem services (Basak et al., 2021). For instance, aquatic invertebrates processing organic matter support higher trophic-level organisms like fish, whereas, hyporeheic fauna contribute to secondary production and water quality improvement (Kattel, 2022). Overall, fish contribute to recreational services; as angling is a major recreational activity and an important protein source in many countries. Higher biodiversity in riparian zones and floodplains is directly related to the enhanced ability of these components of the riverine landscape to provide ecosystem services (Gopal, 2014). Furthermore, studies have shown that the loss of functional diversity harms the functioning of ecosystems and the provision of services (Kremen, 2005). Although the maintenance of ecosystem services is often used to justify biodiversity conservation actions, it is still unclear how ecosystem services relate to different aspects of biodiversity and to what extent the conservation of biodiversity will ensure the provision of services (Egoh et al., 2009). The links between biodiversity and ecosystem functions and services need to be further identified and analysed to optimize both the sustainable delivery of ecosystem services and the conservation of species, habitats and landscapes (van der Velden, 2015).

1.4.3. The value of ecosystem services

The ‘value’ of an ecosystem service equates to importance or worth, within the context of the ecosystem service concept (Costanza et al., 2017). The value of ecosystem services illustrates the importance of ecosystem services to and by individuals and society. The value of ecosystem services is contextual, being relative to a certain place, and a group of people engaged in utilising the service of an ecosystem, (Dendoncker et al., 2013). A valuation can be defined as the act of assessing, appraising or measuring value, or as framing valuation (how and what to value, who values) (Dendoncker et al., 2013). Estimating the worth or value of something (Braat and de Groot, 2012) can be the monetary value, ecological value and or social value. Daily et al. (2000) highlighted well-being as a unit for valuation, therefore the ultimate goal of ecosystem services valuation is to improve the well-being of every individual, now and in the future (Dendoncker et al., 2013) as well as to contribute to more sustainable and equitable resource use. There are three value categories of ecosystem services. The first is the **ecological value**, which is based on biophysical accounting and highlights the value of nature’s functions to human society. This includes the ecological health of an ecosystem. This is commonly assessed via a series of ecological indicators such as diversity and ecological integrity. In the late 1970s, the ecological value of the environment was used to raise public interest in biodiversity conservation to protect natural systems against urbanization and the associated degradation of ecosystem services (Gómez-Baggethun et al., 2010). From an ecological viewpoint, the rationale behind the ecological value of the ecosystem services concept was mainly to demonstrate the disappearance of biodiversity that underpins critical services for human well-being (Braat and De Groot, 2012). It ensures the continued availability of ecosystem functions, and that the use of the associated goods and services should be limited to sustainable use levels (De Groot et al., 2002). The valuation of ecosystem services also helps to evaluate the actual product and supply of services.

Social value is the second value category for ecosystem services. Social value is based on people's perception of importance or equity. It incorporates community perceptions, priorities, values, attitudes and benefits and seeks to generate meaningful insights into the contribution of ecosystem services to human well-being rather than focusing purely on biophysical assessments. The social value that local people place on ecosystem services often helps to raise public support for conserving and protecting the ecosystems (Kandel et al., 2018). Moreover, a social value concept is a tool for eliciting people's preferences for particular ecosystem services and therefore assists in the analyses of trade-offs of ecosystem services (Martín-López et al., 2012). However, social preferences for ecosystem services depend on who is involved, where they live, and how they interact with their resources. Social values can be heavily influenced by location and demographic characteristics. For example, a wetland is likely to be valued differently by fishers, farmers and conservationists – fishers primarily for its capacity to maintain the abundance of specific game fish species, farmers for its ability to supply water for irrigation while conservationists for wetland capacity to provide habitat for endangered species. Thus, different users have different priorities for ecosystem services in wetlands and other landscape components.

The third category is **economic value**. Economic value describes the monetary terms placed on the stream of ecosystem services provided to individual's preferences and choices. This includes income generated from using ecosystem services and the monetary value people are willing to pay to preserve or enhance ecosystem services (Whiteoak and Binney, 2012). Economic value highlights the economic importance of the benefits nature provides and can be used to highlight and compare ecosystems as well as their services based on their relative contribution to individuals or society (Costanza et al., 2017). For example, Pant et al. (2012)

demonstrated how people in Nepal have benefited from forest ecosystem services. Pant et al. (2012) estimated the annual household benefits from several forest ecosystem services are equivalent to US$ 1,072 from provisioning services (forest goods), US$ 199 from regulating services (carbon sequestration) and US$ 228 from supporting services. Sharma et al. (2015) evaluated the economic benefit generated from wetlands in the Koshi Tappu Wildlife Reserve, Nepal to be worth US$ 16 million per year of which about 85 percent was from provisioning services. The monetary value of ecosystems can help to raise awareness of the importance of ecosystem services to society (Costanza et al., 2014). Economic value also serves as a communication tool to raise awareness and convey the relative importance of ecosystems and biodiversity to policymakers for better management (De Groot et al., 2012).

1.4.4. Evolution of the concept of ecosystem services

1.4.4.1. History and evolution of Ecosystem services.

The importance of ‘nature’, or the environment, to human well-being, has long been recognised. Publications documenting this link date back to early as 1817 (Figure 1.8), and over time this literature is based on the premise of the benefits those the environment provided to people and society. The modern-day concept of services provided by the environment only emerged in the 1970s (Lele et al., 2013), and the concept of ecosystem functions and services dates back to the mid-1960s (Gómez-Baggethun et al., 2010). However, the term 'function of nature' was first used by King (1966) in *Wildlife and Man* book. Since the 1980s the concept of ecosystem services has become increasingly influential in various scientific, management and policy fields of study that have resulted in a reshaping of the perception of human-environment interactions (Chaudhary et al., 2015).

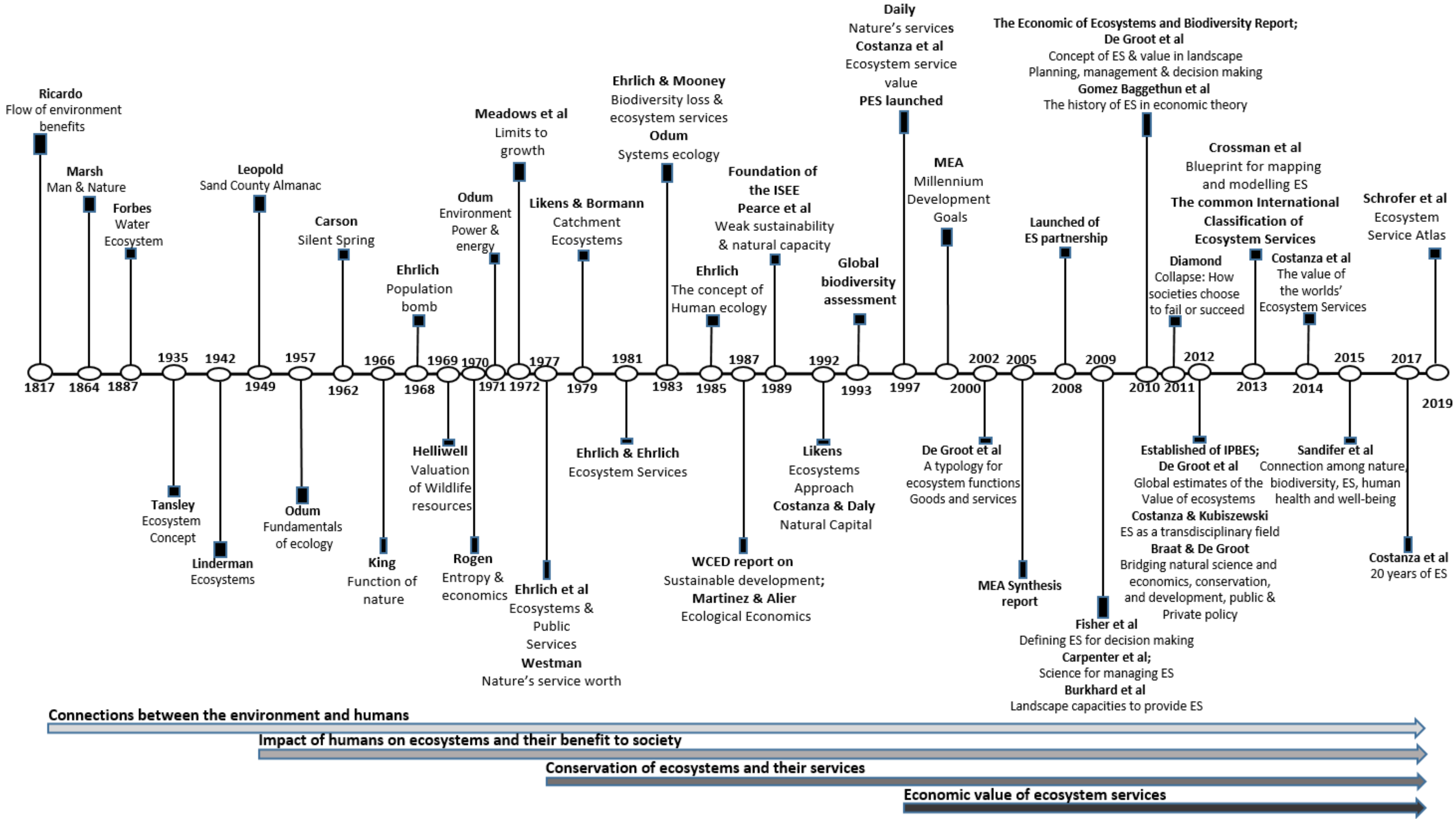


Figure 1. 8. History and evolution of the ecosystem services concept.

The development of the concept of ecosystem services has a history of more than 200 years (Figure 1.8). It started with a relatively basic recognition of interactions between people and their environment. Mooney and Ehrlich (1997) argue the scientific understanding of ecosystems and how they deliver essential services to society began with Marsh (1864) and the publication of *Man and Nature*. This publication, while noting the services provided by nature were important to humans, also challenged the notion that natural resources were not infinite. The implications of finite resources, and the role of humans, were highlighted by Leopold (1949), and have been a focus of much scientific research since. Since the late 1990s, there has been a trend toward monetisation and commodification of ecosystem services with an emphasis on the economic value of nature's benefits (Gómez-Baggethun et al., 2010). It is constructed of key manuscripts – those manuscripts cited over 1,000 times in peer-reviewed journals –accessed through web platforms "*Scopus*" and "*Google Scholar*" and the reviews of the concept by Braat and de Groot (2012); Chaudhary et al. (2015); Costanza et al. (2017); and Gómez-Baggethun et al. (2010).

The focus of studies on the concept of ecosystem services has changed over time (Figure 1.8). Four major periods or phases are identified, and these are associated with studies that focused on;

- Phase One (Connections between humans and the environment);
- Phase Two (The impact of humans on landscapes and associated ecosystems);
- Phase Three (Conservation of ecosystems and their services); and,
- Phase Four (The economic value of ecosystem services).

Phase one – the Connection Phase (1817 onwards) –primarily focused on the connection between people and various environments. This phase began with the study of Ricardo (1817) who described the flow of environmental benefits from the 'old world' to the 'new world' of the Americas. However, many (eg. Daily et al., 1997) attribute the publications of Marsh (1864) who articulated an account of *Man and Nature,* Forbes (1887) who wrote about *Water Ecosystems,* and Tansley (1935) who was first to write about the E*cosystem Concept* – to be the pioneers in highlighting services that nature provides to humans. Studies of environmental–human connections have continued into the 21st Century (Braat and de Groot, 2012; Chaudhary et al., 2015).

Phase two – the Degradation Phase (1942 onwards) – began with a series of publications outlining the ecological impact of humans on the environment (Figure 1.8). Here the influential work of Linderman (1942) - *Tropical Dynamic Aspects of Ecology,* Odum (1956) *Fundamentals of Ecology*, Carson's (1962) *Silent Spring*, King's (1966) *Wildlife and Man*, Ehrlich's (1968) *The Population Bomb*, Hardin's (1968) *Tragedy of the Commons* and Meadow et al.'s (1972) *The Limits to Growth,* all emphasized the harmful impacts of environmental change as a result of human activities on ecosystems (Chaudhary et al., 2015). Degradation occurred as a result of environmental pollution, land use changes, deforestation, the construction of dams and the subsequent regulation of downstream flow regimes. This phase also highlighted the usefulness or utility of nature to society and limits the public pleasure of nature (Braat and de Groot, 2012).

Phase Three – the Conservation Phase - began in the mid-1970s and marked a change in the emphasis on the importance of the environment to humans (Figure 1.8). Publications framed and highlighted the benefit of intact ecosystems and their functions as services to people and society. This change in the narrative increased the awareness of the importance of conversation and biodiversity. Notable publications at the beginning of the Conservation Phase are Westman (1977) '*Natures worth'*, Ehrlich and Ehrlich (1981) '*Ecosystem services*', and Pearce et al. (1989) '*Sustainability and natural capital*'. The publication of Costanza and Daly (1992) on *Natural capital and sustainable development* – represents an aim to demonstrate how the degradation of biodiversity and ecosystems directly influences those ecosystem functions that underpin critical services for human well-being. This was part of a change towards the importance of ecosystem conservation, intending to improve the sustainability of ecosystem services. This collective of manuscripts increased public interest in biodiversity conservation (Braat and de Groot, 2012).

Phase Four – The Economic Phase - commenced with the publication of Costanza et al. (1997) “ *The value of the world’s ecosystem services and natural capital”* (Figure 1.8). This publication represented an important juncture in the mainstreaming of the ecosystem and is one of the most highly cited ecosystem services publications (30,061 citations as of March 2023). The monetization of ecosystem services has had an impact on both the science and policy disciplines, and has been suggested to represent a paradigm shift in economic thinking for the treatment of nature in terms of exchange value (Gómez-Baggethun et al., 2010). The publication of *Nature's Services: Societal Dependence on Natural Ecosystems* (Daily, 1997), also provided a definitional base and stressed its importance for humanity and emphasised the need to link with policy. Both Costanza et al. (1997) and Daily (1997) contributed to a mainstreaming of ecosystem services academic research and provided a robust logical link to policymaking (Chaudhary et al., 2015).

Important transitions in the perception of ecosystem services continued to occur since the term was first introduced in the mid 1960s (Figure 1.8). Overall, the concept has changed from an academic focus to a policy focus, especially with the idea of Payment for Ecosystem Services (PES) as a potential market-based instrument for generating conservation finance (Chaudhary et al., 2015). The Millennium Ecosystem Assessment (MEA) synthesis report, published in 2005 was a landmark publication that strengthened the concept and provided a universal definition and means of classification of ecosystem services. It opened a wider understanding and use of the concept of ecosystem services and offered an excellent heuristic and classification system highlighting the importance of functioning ecosystems. The MEA (2005) classified ecosystem services into four groups - provisioning, regulating, cultural and supporting services (Fisher et al., 2009). The Economics of Ecosystems and Biodiversity (TEEB) study in 2010 and the establishment of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) in 2012 represent important activities where major global action can take place at a policy level. It also allows for both academic and non-academic actors to be involved in the science-policy interface of ecosystem services (Chaudhary et al., 2015). Overall, this preliminary analysis of the history and evolution of ecosystem services (cf. Figure 1.8) shows the focus on the importance of the environment to people has changed over time with a sequence of four phases: i) Connectivity, ii) Degradation, iii) Conservation and iv) Economic value.

1.4.4.2.Scientific research on ecosystem services

Research on ecosystem services has increased over time, reflecting their importance in influencing environmental sustainability (Wang et al., 2021). The number of publications that focus on ecosystem services, for the period 1984 to 2022, shows an exponential increase from 2005 (Figure 1.9). This growth in the number of publications is associated with the release of the MEA synthesis report in the same year. However, the number of publications on ecosystem services associated with river ecosystems is only 10.4 percent of the total number. Despite this, the pattern of publications over time for river ecosystem services is similar. The first publication that details ecosystem services associated with rivers was published in 1995 and before 2000 only eight papers were found while the number of publications increased in 2000 but decreased in 2001 (Figure 1.9). The number of publications underwent a substantial increase since 2002, while the number of ecosystem services papers on riverine ecosystems has rapidly increased from 12 papers in 2002 to 796 papers in 2022.

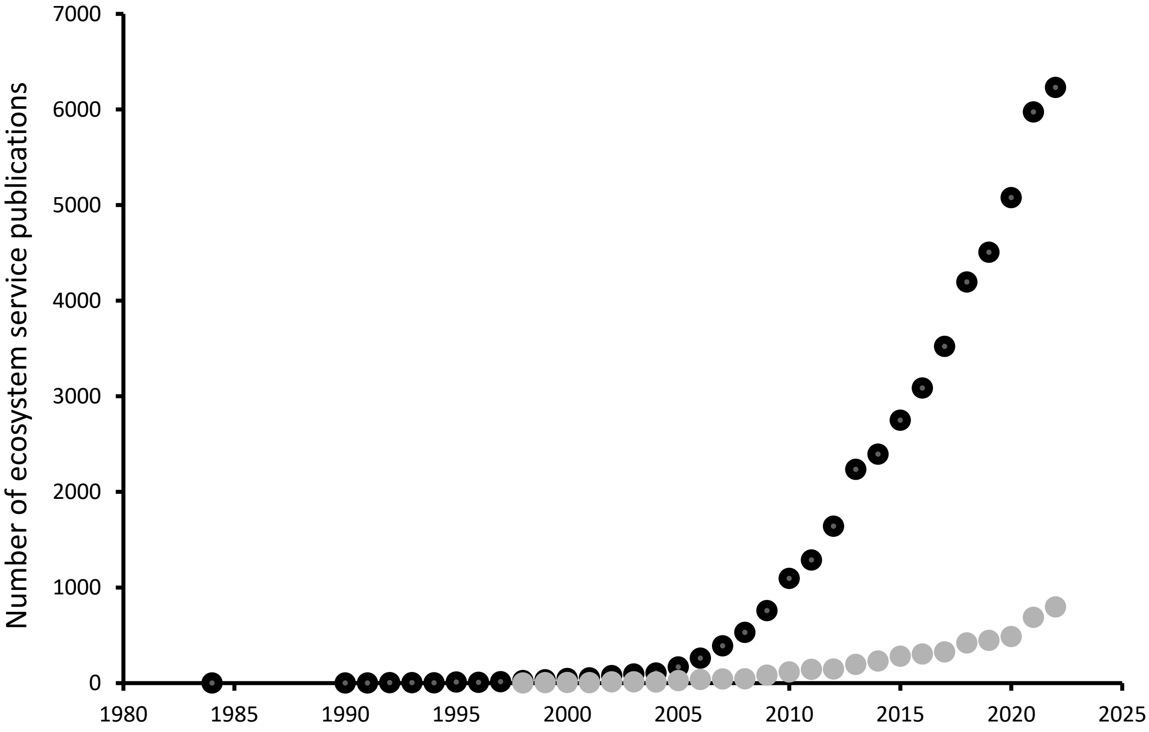


Figure 1. 9. Temporal distribution of the number of ecosystem services publications; black circle represents total ecosystem services publications and grey circle represents riverine ecosystem services publications (Source: Scopus).

1.4.5. Mapping of ecosystem services

Mapping of ecosystem services shows the spatial distribution of ecosystem services and thus helps us understand how ecosystems contribute to human well-being spatially, and support policies that have an impact on natural resources (Burkhard and Maes, 2017). Maps are important tools for creating a knowledge base on ecosystem services that are useful for decision-makers, planners, and institutions - enabling them to spatially identify which area should be maintained, protected, rehabilitated, and conserved to ensure the supply of ecosystem services (Burkhard et al., 2012). Spatial information about the distribution of ecosystem services is also important in the assessment of trade-offs among ecosystem services, synergies among multiple ecosystem services that allow for the prioritisation of multiple conservation goals. Given the importance of mapping ecosystem services as a key tool to guide decision making, the quality of such ecosystem services maps should be accurate to be able to provide the most valuable information (Burkhard et al., 2013).

There has been a rapid increase in the number of studies that map the spatial distribution of ecosystem services. Many different types of approaches for mapping ecosystem services have been developed and these approaches vary considerably in terms of scale and scope of the analysis as well as in the assessment method of ecosystem goods and services (Burkhard et al., 2009). There are three basic approaches to spatially mapping ecosystem services (Böck et al., 2018).

1) Valuation of ecosystem services through benefit transfer applies a monetary value based on landuse or landcover map.
2) Community value methods that incorporate survey-based social values and perceptions of place with biophysical data.
3) Social-ecological assessments that model the causal relationship between ecological variables (e.g., landcover, hydrological, remote sensing) and social variables (e.g., population, census data, different spatial layer data) to calculate and map the ecosystem services supply.

Paudyal et al. (2015) reviewed methods and tools used for the assessment and mapping of ecosystem services. These include freely available spatial tools such as Soil and Water Assessment Tool (SWAT), ARtificial Intelligence for Environment & Sustainability (ARIES), Integrated Valuation of Ecosystem Services and Trade-Offs (InVEST) etc.; expert opinion or professional judgment; user's perception or social and community values; participatory approaches; visual knowledge by repeat photography; participatory geographical information system (PGIS) tools; and remote sensing and GIS tools. Paudyal et al. (2015) also highlighted the importance of participatory methods in the gathering of spatial information on ecosystem services, especially in data-poor regions like the mountain regions of the Himalayas. The importance of tools such as SWAT and InVEST in gathering spatial data on ecosystem services in mountainous regions was also noted by Rimal et al. (2019). The most used method to map ecosystem services, according to Martnez-Harms and Balvanera (2012) is the application of existing knowledge about causal relationships between social-ecological variables and ecosystem services.

1.4.6. Ecosystem services in riverine landscapes

Riverine ecosystem services are the benefits provided by water-related ecosystem functions (Müller 2005). Here, and through the remainder of the thesis, these are termed flow-dependent ecosystem services because it is the interaction of water, geomorphology and ecology within the riverine landscape that generates and maintains provisioning, cultural, supporting and regulating services. The riverine landscape is the continually or periodically wetted components of a river consisting of the riverscape and floodscape (Thorp et al., 2008a). The riverscape comprises the active river channels and the riparian zone whereas the floodscape comprises aquatic and terrestrial components of the riverine landscape such as floodplains, wetlands, oxbows and floodplain lakes that are connected to the riverscape during floods. Together, these two parts of the riverine landscape provide an immense array of ecosystem services that benefit human well-being in the form of food, fibre, water, energy, building material, medicinal products, foliage for livestock and wildlife.

The floodscape is made up of floodplains, wetlands and oxbows. Riverine floodplains are some of the most productive ecosystems in the world (Opperman et al., 2010) and provide enhanced resource and habitat conditions for plants and animals because of soil moisture availability, structural complexity, microclimate characteristics and nutrient enrichments (Tockner et al., 2008). Indeed, far more species of plants and animals occur on floodplains than in any other landscape unit (Tockner et al., 2008). For instance, floodplain wetlands serve as critical habitats for colonially breeding waterbirds (Kingsford, 2000) as well as approximately 29 percent of wildlife species found in riparian forests (Tockner et al., 2008). The floodplain is also a very important habitat for threatened mammals, birds, reptiles, amphibians, species and an important breeding area for water birds (Doody et al., 2016). The wetting and drying of floodplains play a significant role in maintaining the spatial heterogeneity of floodplain vegetation communities and play a major role in riverine ecosystem processes (Sheldon and Thoms, 2006). Increased vegetation growth in response to flooding is one of the most important processes controlling the carbon and nutrient dynamics on floodplains and in the adjacent terrestrial and riverine ecosystems (Sims and Colloff, 2012). Floodplains are also of great cultural and economic importance; most early civilizations arose in fertile floodplains and throughout history, people have learned to cultivate and use their rich resources (Tockner et al., 2008). Despite their productivity and value, floodplains are also heavily influenced by human activities – extensively disconnected from the river and converted to land uses such as agriculture and urban areas (Opperman et al., 2010). These uses of floodplains potentially alter the provision of ecosystem services (Tockner et al., 2010).

The riverscape also generates important ecosystem services. Natural riparian zones are the interface between terrestrial and aquatic ecosystems (Gregory et al., 1991) and some of the most diverse, dynamic, and complex biophysical habitats on the terrestrial portion of the planet (Naiman and Décamps, 1997). The type, extent, density, and vertical structure of riparian vegetation influence many ecological processes that contribute to ecosystem services, including water infiltration, instream production, nutrient cycling, channel and habitat formation, sediment transport, and groundwater storage (Chicharo et al., 2015). Riparian zones possess an unusually diverse array of species and environmental processes. Riparian zones play essential roles in water and landscape planning, in the restoration of aquatic systems, and in catalysing institutional and societal cooperation for these efforts (c.f Naiman and Décamps, 1997). However, riparian zones are also certainly not untouched by human activities, some major threats to riparian ecosystems around the world include altered hydrologic regimes due to river regulation and water extraction, vegetation clearing for agriculture and other developments, grazing by livestock, development of human settlements and infrastructure, pollution and mining (Capon et al., 2013).

River channels are the other component of the riverscape. Surface freshwaters are a small fraction of global water and constitute 0.009 percent of water in the biosphere and the volume of water flowing from storage to sea in rivers is 0.00009 percent of the total water (Lovejoy and Hannah, 2005). River channels play a fundamental ecological role and provide economically important products and services (Nyingi et al., 2013). Healthy freshwater ecosystems provide vital ecosystem services to human societies, critical habitats for a large number of aquatic flora and fauna, including threatened species and habitat corridors for many migratory species. The biodiversity of channels also supports recreational activities and tourism and regulates a number of ecosystem functions including flood control, water purification, shoreline stabilization and sequestration of carbon dioxide (Nyingi et al., 2013). On the other hand, like other components of the riverine landscape, freshwater ecosystems have been greatly influenced by human actions. People modify the river channel for their benefit by constructing infrastructure like dams, levees, and weirs. These structures regulate the flow in the river and alter the natural flow regime, which has – a profound impact on ecosystems, affecting structure and, function, ecosystem services (Liu et al., 2019) decrease in connectivity, productivity, resources and diversity (Vörösmarty et al., 2010).

Ecosystem services represent a conceptual bridge between natural and human systems. Ecosystem services are an indicator to look at an interaction between the riverine landscape and humans, via the benefits derived from natural environments for humans. There are positive and negative links between anthropogenic activities and riverine ecosystems through dynamic and non-linear processes and it is important to recognize the linkage and feedback between flow-dependent ecosystems and society (Rüdisser et al., 2020). For instance, the riverine landscape provides an immense array of ecosystem services (freshwater, agricultural, fisheries, fuelwood) that benefit human well-being. In contrast, humans have further modified the river for their needs and try to maximise the supply of ecosystem services, often creating feedbacks that reduce the supply of ecosystem services and benefits. Thus, it shows that humans strongly influence and are influenced by the riverine landscape. Therefore, it is important to understand the riverine landscape as a social-ecological system from an ecosystem services point of view.

1.4.7. Spatial distribution of ecosystem services in the riverine landscape

The occurrence of ecosystem services links directly to ecosystem structure and function which is directly influenced by the hydrogeomorphic complexity of the riverine landscape (Thorp et al., 2010). The emerging evidence suggests heterogeneity of the underlying biophysical template should be a key consideration in understanding ecosystem services across riverine landscapes because different services will be supplied by different features of the biophysical template. Ecosystem services respond according to changes in the physical template as a result of the dynamic interaction of physical, biological and chemical components. Therefore, it may be expected that the spatial distribution of ecosystem services depends on the spatial arrangement of the physical template. Thorp et al. (2010) showed that the relationship between ecosystem structure and hydrogeomorphic features differs greatly in different stretches of the riverine landscape. For example, anastomosing and anabranching stretches provide high ecosystem services, meandering provides high to medium ecosystem services whereas constricted and straight channels provide low ecosystem services (Thorp et al., 2010). Similarly, Large and Gilvear (2015) demonstrated that ecosystem services are high in mid reaches and low in the gorge section, and ecosystem services vary considerably with longitudinal position and reach type. Tomscha et al. (2017) showed that the highest diversity of ecosystem services was concentrated in the floodplain. Knowledge of the spatial distribution of ecosystem services throughout the riverine landscape is important for effective management of natural resources, and also to aid in understanding the past, present, and future riverine conditions (Thoms et al., 2018). However, riverine landscapes also appear to display significant lateral complexity in biophysical character and ecosystem service capacity, from the river channel, through the riparian zone and across the floodplain. This complexity is compounded by variations in hydrological connections across the riverine landscape.

1.4.8. Knowledge gap

There has been an exponential increase in the research on ecosystem services since the publication of the Millennium Ecosystem Assessment (MEA) (Chaudhary et al., 2015). However, studies are biased towards certain ecosystem types. Zhang et al. (2019) found that forest, urban and terrestrial ecosystems are the most studied in terms of ecosystem services. In a study of ecosystem service assessment projects in Nepal, Lamsal et al. (2017) reviewed 140 projects and found the focus of studies to also be biased towards certain ecosystem types in the region. Approximately 33 percent of the total studies were from community forest management systems, 29 percent were in protected areas, and 18 percent had a watershed or catchment focus. Studies in national forests were only 8 percent and 2 percent were conducted in farm forests. Hardly few studies on the flow-dependent ecosystem services.

A review of 7985 ecosystem service studies from 15 countries by Chaudhary et al. (2015), highlighted a significant geographic disparity between studies. Most studies were from the USA (3118), then Europe (3077) and China (602). Furthermore, Zhang et al. (2019) found that the USA, UK, Netherlands, Spain, and Sweden were the top five countries in the world publishing studies on ecosystem services from 1981–2017. This review also highlighted that very few studies have been undertaken in riverine ecosystems. Of those ecosystem service studies undertaken in riverine landscapes, Hanna et al. (2017) found most were from Europe, China and the United States and highlighted the gaps in other regions (Figure 1.10). Thus, the geographical distribution of riverine ecosystem services studies is unbalanced. As a result, there is a significant knowledge gap and limited understanding of riverine ecosystem services in the Himalayan region (Figure 1.10) where more than 80 percent of people in the region are dependent on ecosystem services for their sustainable livelihood.

[redacted]

Figure 1. 10. Global distribution of riverine ecosystem services studies (Hanna et al., 2017).

The study of ecosystem services in the riverine landscape also shows a degree of bias in terms of the scale of investigations. For example, Thorp et al. (2008b) found that most riverine ecosystem studies were undertaken at a single scale, usually the reach scale. Furthermore, most studies focused on ecosystem services associated with the river channel (90 percent), and the remaining were undertaken in the floodplain or riparian zone. A study by Hanna et al. (2017) highlighted that studies on ecosystem services associated with riverine landscapes were undertaken at a watershed scale, only 2 out of 89 studies assessed ecosystem services in the riverine landscape (river channel, riparian zone and floodplain). Most assessed those in the terrestrial section of the watershed. Thus, our knowledge of riverine landscape ecosystem services at the scale of entire river networks is limited.

Mountain river ecosystems, including Himalayan riverine landscapes support high levels of biodiversity (Egan and Price, 2017). These landscapes and their associated ecosystems have an important role in supporting the livelihoods and traditions of the people and communities who inhabit them. Despite their importance in providing essential ecosystem services, there have been few studies and thus understanding of the riverine ecosystem services of Himalayan riverine landscapes is limited. Of those ecosystem services studies conducted in the Himalayan region, few investigate the full spectrum of ecosystem services. In other words, very few studies consider the four categories of ecosystem services: provisioning, regulating, cultural and supporting with provisioning and regulating services the focus of most studies in these mountainous regions (Hanna et al., 2018; Chaudhary et al., 2016; Zhang et al., 2019).

There have been several studies of the ecosystem services provided by riverine landscapes in the Himalayan region. Most ecosystem service research has focused on biophysical aspects and economic valuation. Very few studies have focused on the social perspective (community and local knowledge) of ecosystem services. Recently, community values and local knowledge have been shown to be essential components of natural resource management. Ecosystem services have also been promoted as a way of integrating social perspectives for better planning, management, and a strategy for sustainable development of the ecosystem (Paudyal et al., 2018). The provision and monetary value of ecosystem services are well researched, but the social use of ecosystem services originating in riverine landscapes is seen as a lower priority, despite the need for better planning, management and sustainable development of Himalayan regions. For instance, Chaudhary et al. (2015) revealed that 150 articles on economic valuation have been published, 137 articles on biophysical assessments and 11 on social values for the period 1965 to 2013. Given the increasing necessity for the integration of the social dimension of ecosystem services in the environmental policy agenda, understanding social preferences towards the protection of the ecosystems using the bridge of ecosystem services has become a research priority (Martín-López et al., 2012).

1.5. Climate change and hydrological change in the Himalayas

1.5.1. What is climate change?

The recent release of the IPCC’s sixth assessment report on climate change highlighted that the earth is warming faster than previously projected (IPCC, 2021). The world is now 1.1°C warmer than pre-industrial levels and is on a collision course with the critical threshold of 1.5 °C (Connors et al., 2022). A warmer planet means more extreme-heat events - warming will amplify permafrost thawing, the loss of seasonal snow cover, melting of glaciers and ice sheets (IPCC, 2021). Heavy precipitation will become more frequent and more intense in the future (Tse-Ring et al., 2010). Monsoon rains are expected to be devastating in the coming years, especially in South and Southeast Asia. The region will also become more variable: extremely wet years with more frequent floods may be scattered with very dry years featuring drought and extreme heat (Zhan et al., 2017). Droughts will become more intense and more frequent in parts of the world conducive to wildfire.

Climate scenarios can be used to predict and understand the effects of long-term climate changes. A climate scenario is a plausible representation of future climate that has been constructed for explicit use in investigating the potential impacts of anthropogenic activities, based on the estimation of greenhouse gas emissions (Mearns et al., 2001). Future climate scenarios provide a range of projected climate changes over a period of time and can be used by various sectors, such as agriculture or energy, for longer-term planning purposes (MoFE, 2019). Climate scenarios also assist in understanding the potential impacts of climate change on society. Climate responses to changes in greenhouse gases have been studied by many primarily via the development of climate scenarios. The Coupled Model Project Phase (CMIP5) of the IPCC 5th Assessment Report (AR5), for example, is a climate model based on the parallel approach that should provide better integration, consistency, and consideration of feedback, and more time to assess impacts and responses (Lutz and Immerzeel, 2013). This parallel process is initiated with a set of scenarios called Representative Concentration Pathways (RCPs). RCPs are based on the level of greenhouse gas concentrations and represent the range of radiative forcing values by the year 2100 (Kaini et al., 2019). IPCC AR5 has documented four RCPs to predict possible global future climate scenarios: i) RCP2.6 ii) RCP4.5, iii) RCP6.0 and RCP8.5 (IPCC, 2014). RCP2.6 represents a very low radiative forcing level achieved by ambitious mitigation action and emission reductions; RCP8.5 expects an intensive use of fossil fuels with little curbing of emissions; whereas RCP4.5 and RCP6.0 are two medium stabilization scenarios (IPCC, 2014).

1.5.2. Climate change in the Himalaya

Many studies have revealed evidence of historical climate change in the Himalayas. Studies based on meteorological observation and ice core records show that the temperature of the third pole increased by 0.16 – 0.36 °C/decade in recent decades (Su et al., 2016). Among the observed trends in climate variables, the increasing temperature trend is most consistent over the region (Wijngaard et al., 2017). For instance, the average temperature increased by 0.2°C/decade in the Koshi basin between 1975 to 2010 (Shrestha et al., 2016), 0.3°C/decade in the upper Brahmaputra basin between 1961 to 2005, whereas in the upper Indus, there have been both, increasing and decreasing temperature trends since 1960 (Wijngaard et al., 2017). In the Hindu-Kush Himalaya (HKH), the temperature is projected to continue increasing faster than the global mean temperature over the rest of the 21st century. Recent results project temperature increases across the HKH by 1-2°C during 2021-2050 (Immerzeel et al., 2013). Projected warming differs by up to 1°C between east and west, with greater increases in winter. In the Koshi basin, the daily maximum temperature increased by 0.1°C/decade and the minimum temperature by 0.3°C/decade from 1975 to 2010 (Shrestha et al., 2017).

Precipitation trends in the HKH region include both increasing and decreasing trends, with increasing trends in the western part of HKH and both decreasing and increasing trends in the central and eastern Himalayas from 1961 to 2005 (Wijngaard et al., 2017). Annual and summer monsoon precipitation will likely increase over the HKH region. Precipitation trends that have been reported in the HKH region show mixed signals with increasing precipitation trends in the western part of the HKH and no distinct trends in other parts of the HKH (Wijngaard et al., 2017). However, 1-day, 3-day and 5-day precipitation amounts show significant increasing trends. Furthermore, there is likely to be an increase in the future frequency and intensity of extreme precipitation events, for instance, the number of dry days, consecutive dry days, and very wet days (Zhan et al., 2017). The projected change in temperature and precipitation ranges from 1.3 to 4.6°C and -9.1 to +31.4%, under RCP4.5 and range from 3.3 to 7°C and -11 to +63 % under RCP8.5 by the end of the century in the Koshi River Basin (Kaini et al., 2019).

1.5.3. Impact of climate change on Himalayan hydrology

The HKH region plays a vital role in South Asian hydrology (Wijngaard et al., 2017). The region encompasses the headwaters of the 10 largest river systems in Southeast Asia (Amudarya, Tarim, Indus, Ganges, Brahmaputra, Irrawaddy, Salween, Mekong, Yangtze and Yellow). Climate change is expected to have a significant effect on runoff in the region and thus a substantial hydrological impact (Arnell et al., 2016). Detailed regional studies note that Himalayan areas are projected to experience marked climate change with an increase in temperature and erratic rainfall that will lead to significant hydrological changes (Wijngaard et al., 2017).

Significant overall, projections are that there will be greater volumes of water in the monsoon and less in the inter-monsoon period (Arnell et al., 2016). Studies on Himalayan catchments, from Afghanistan to Myanmar, indicate an increase in annual runoff as a result of increases in precipitation and net glacier melt associated with climate change (Immerzeel et al., 2013; Lutz et al., 2014). According to Nie et al. (2021), by the end of the century, streamflow under RCP8.5 is projected to increase by 28 percent for the Upper Tarim Basin, 51 percent for the Upper Indus Basin, 49 percent for the Upper Brahmaputra Basin and 41 percent for the Upper Ganges Basin compared to the reference period of 1981 to 2010. Therefore, water availability over the next century will not decline, but there will be a marked change in seasonal water availability with the inter-annual, seasonal and spatial distribution of water availability being highly variable (Immerzeel et al., 2013; Lutz et al., 2014; Bajracharya et al., 2018; Bharati et al., 2016; Bharati et al., 2014; Khanal et al., 2021). Furthermore, the projected magnitude and frequency of peak flows are expected to increase and shift a month in timing (Kaini et al., 2020; Khadka et al., 2020). Thus, potential changes to the flow regime of rivers in the Himalayas will vary in magnitude and this will differ across the region and over time and as a result of climate change.

1.5.4. Impact of climate change on the flow regime

The increase in temperature and variability in precipitation will affect the hydrological cycle, water storage capacity and water resources, which in turn will have an impact on water availability, discharge and flow regime. For instance, Bajracharya et al. (2018) mentioned that a >4°C rise in temperature and a 26% increase in precipitation would cause a >50% increase in streamflow and water yield. Koshi river systems are characterized by seasonal flow variability and will likely have a high degree of flow variability. Bharati et al. (2016) projected the frequency of 1-day minimum flows will decrease, and the frequency of 30 days maximum flows will likely increase, the frequency of the base flow index will likely decrease while the duration of low pulse events will likely increase in the Koshi basin. Similarly, it was projected the rising rate of floods will increase and the fall rate decrease. Both high and low flows will change, while the increase in the frequency of high flow and a decrease in the base flow portion for 2030 under A1 and B2 scenarios. Khadka et al. (2016) highlighted those high flows are expected to increase from 4 to 147 days in case I (ECHAM05) and 0 to 170 days in case II (HadCM3) and the magnitude of peak flows are more than four times and more than double in case I and II compared to baseline period in five sub-basins of Koshi basin by 2060. Stagl and Hattermann (2016) evaluated five GCM under three RCPs (2.6, 4.5 and 8.5) and highlighted that climate change might impact the long-term monthly, seasonal, and annual flow of rivers together with changes in the timing of peak flow and variability of high and low flows under future climate scenario. Thus, climate change must impact the hydrological regime in space, time and magnitude and might increase floods and flow pulse in the river in the river basin.

1.5.5. Flow is the critical component to regulating riverine ecosystem services.

The flow regime is the hydrological character that regulates and controls the structure and function of river systems (Poff et al., 1997). The flow regime is the critical driver of connectivity in the riverine landscape. The five components (magnitude, frequency, duration, predictability, and rate of change) of the flow regime influence the ecological dynamics of river systems directly and indirectly through their effects on other primary regulators (Karr, 1991; Poff et al., 1997). Alteration of any of these flow parameters can have dramatic effects on aquatic organisms, riparian species, energy flow in the system, sediment movement and floodplain interactions, and energy flow in the system (Poff et al., 1997).

River ecosystems depend on the dynamic interplay between flow and channel morphology which together set the physical template for fluvial communities and ultimately for ecosystem functioning (Mutz et al., 2013). The biota and ecological function of river systems depend on the magnitude and timing of flows and the longitudinal, lateral and vertical interactions of flow within the physical template (Lloyd et al., 2004). Together flow and physical habitat provide the source for the inputs, production or food resources that drive much of the biological response of riverine ecosystems (Kingsford et al., 2014). According to Bunn and Arthington (2002), four major principles link hydrology and aquatic biodiversity and these assist in understanding the impacts of altered flow regimes on freshwater ecosystems. First, flow is a major determinant of physical habitat in streams, which in turn is a major determinant of biotic composition; second, aquatic species have evolved life history strategies primarily in direct response to their natural flow regimes; third, maintenance of natural patterns of longitudinal and lateral connectivity is essential to the viability of populations of many riverine species; and, finally, invasion and success of exotic and introduced species in rivers are facilitated by the alteration of flow regimes. The flow regime is therefore a critical component of riverine landscapes that helps maintain the ecological integrity of the ecosystems these landscapes support (Bunn and Arthington, 2002). In describing the ecological functions associated with the components of a flow regime, high and low flow events are emphasised because they often serve as ecological bottlenecks that present critical stresses and opportunities for a wide array of riverine species (cf Poff et al., 1997). For instance, low flows might alter chemistry, concentrate prey species, dry out low lying areas in the floodscape and are often associated with higher water temperature and low dissolved oxygen conditions. Low flows also reduce connectivity thereby restricting the movement of some aquatic organisms (Mathews and Richter, 2007). High flows maintain the balance of species in aquatic and riparian communities, shape physical habitats of the floodplain, deposit gravel and cobbles in spawning areas, flush organic materials and woody debris into the channel, purge invasive species from aquatic and riparian communities, disperse seeds and fruits of riparian plants, drive lateral movement of river channels forming new habitats like oxbow lakes, and provide plant seedlings with prolonged access to soil moisture (Swanson, 2002). This suggests that flow is essential to maintain ecological processes and ecological integrity (Poff, 2002). In other words, the flow regime influences the ecology of the riverine landscape for biodiversity and the provision of ecosystem services.

1.5.6. The response of riverine ecosystem services to projected flow change

Projected flow regime changes could have various impacts on flow-dependent ecosystem services depending on the degree of change and other hydro-geomorphological characteristics (Cui et al., 2018). High flows increase hydrological connectivity and trigger booms in the productivity of riverine ecosystems (Leigh et al., 2015) It is predicted that positive impacts may include a higher capacity to increase and meet the development needs of hydropower generation, provide migration and spawning cues for aquatic animals, and provide new feeding opportunities for fish and birds (Chaudhary et al., 2016). Other benefits may include the recharge of the floodplain water table, maintenance of diversity in riverine and floodplain vegetation, control of the distribution and abundance of floodplain vegetation including encroachment, the deposition of nutrients in floodplains, maintain the balance of species in aquatic and riparian communities, deposit sand and gravel on a floodplain, irrigation, and access to water for drinking for domestic needs and livestock. High flows increase wetted perimeters and the lateral exchange of water and nutrients between riparian zones and stream (Capon et al., 2013). As a result, there could be increases in the abundance and diversity of plants, and a healthy riverine zone increases the habitat of grassland birds and climate regulation (Doody et al., 2016). The increase in the magnitude of high flow will increase the long duration of connectivity between the main river channel and floodplain. Consequently, fish and other mobile organisms can move upstream, downstream and into floodplains for breeding, new habitats, and take advantage of rich nutrition which will increase their Body Mass Index (Arthington et al., 2010).

On the other hand, increase the duration of extreme low flow during the dry season could have specific adverse impacts on river ecology and ecosystems, resulting in the deterioration of river health, alter water chemistry, lower dissolved oxygen, concentrate prey species, dry out low lying areas in the floodplain, degradation of aquatic and spawning habitats, reduce connectivity and extinction of various flora and fauna that depend on specific flow regimes as well as alteration of migratory routes.

1.5.7. Knowledge gap

There have been numerous studies that have considered the potential effect of climate change on water availability and water yield in the Himalayas. These have not, however, considered the effect on the flow regime and its components of magnitude, duration, timing, frequency and rate of flow change. In addition, studies on the potential effects of climate change have been limited in their temporal and special focus. In the relation to spatial scales most have done studies from regional to global scales and few studies have considered variations within river basins. In relation to temporal scales most of the studies have been limited to a time period of 30 – 50 years and very few studies have considered up to 100 years. The response of hydrological processes to climate change is highly scale dependent and varies spatially from catchment to global scales (Bharati et al., 2016). Many ecosystem processes and their response to flow regime changes are only apparent over longer temporal periods (Schmalz et al., 2016). Therefore, spatiotemporal impact assessment and comprehensive multi-scale assessments are needed to understand the nature and extent of the expected climate change as well as the response of the hydrological regime and the response of flow-dependent ecosystem services.

Despite an exponential increase in studies concerned with climate change effects on the ecosystem services in the riverine landscape in the last decade (Thoms et al. 2016) most studies focus on the impact on specific locations and reach scales. Therefore, there is a knowledge gap in understanding the response of flow-dependent ecosystem services to changes in flow regimes caused by climate change, and how these will occur in the different components of the riverine landscape (riverscape and floodscape) as well as for an entire stream network.

1.6. Research aim, objective, and questions

The literature review above has identified knowledge gaps in understanding how the spatial variation in the riverine landscape supports the production of flow-dependent ecosystem services and the ways that humans use those services to support their well-being: rivers as social-ecological systems. Climate change acts to alter the flow regime and potentially the spatial supply of flow-dependent ecosystem services in the riverine landscape, but the implications of these changes for human systems are unknown. In the Himalayas, climate change is expected to have marked impacts on temperature and precipitation, with concomitant effects of flow regimes and the interactions of people with rivers through the use of flow-dependent ecosystem services. Addressing these knowledge gaps, this thesis aims to determine the relationship between the physical template and flow-dependent ecosystem services of a large Himalayan river basin and assess the influence of climate change on this relationship.

Two objectives are put forward to address this aim

Objective 1. To examine the congruency between the physical template of a large Himalayan river basin and the supply of flow-dependent ecosystem services.

Objective 2. To examine the effects of climate change on the response of flow-dependent ecosystem services within a large Himalayan River Basin.

A series of research questions corresponding to each objective is formulated and the overall aim will be addressed by answering the four research questions.

Research question 1. Does the abundance, distribution, use and value of flow-dependent ecosystem services vary according to the spatial character of the physical template of the riverine landscape?

Research question 2. Does the flow regime vary in space and time within the riverine landscape as a result of potential climate change?

Research question 3. Does the capacity of the physical template to supply flow-dependent ecosystem services differ laterally across the riverscape and the floodscape areas of the riverine landscape? Does the response of ecosystem services to climate change differ laterally across the riverine landscape?

Research question 4. Does the response of flow-dependent ecosystem services to climate change vary according to the geomorphological organization of the river system?

The objectives and research questions are addressed in four research manuscripts. These manuscripts have either been accepted or submitted or are ready to submit for publication. Overall, the thesis is organised into six chapters.

Chapter One: This introductory chapter gives a background to the thesis through a comprehensive literature review evaluating the role of riverine landscape in the provision of ecosystem services - the importance of graded organizational structure; hierarchy of influence where larger-scale factors establish the conditions within; elaborates on riverine landscapes as social-ecological systems and how physical templates; ecosystem services are defined, their importance and use, as well as excessive use, led to the extensive and often irreversible modification of vital global ecosystems; the function and structure of ecosystem in different existing river concept, linkage among climate change, riverine landscapes and ecosystems, ending with a summary of research gaps and aim of this study.

Chapter Two: examines the occurrence, use and relative value of ecosystem services across the river network of the Koshi River. It is presented in the manuscript “The heterogeneity of ecosystem services across the riverine landscape of the Koshi River Basin, Nepal" and published in the *Annals of the American Association of Geographers.*

Chapter Three: examines the effect of climate change on the flow regime within sub-basins of the Koshi River Basin. It is presented in the manuscript "Future climate and its potential impact on the spatial and temporal hydrological regime in the Koshi Basin, Nepal." and is published in the *Journal of hydrology: Regional studies.*

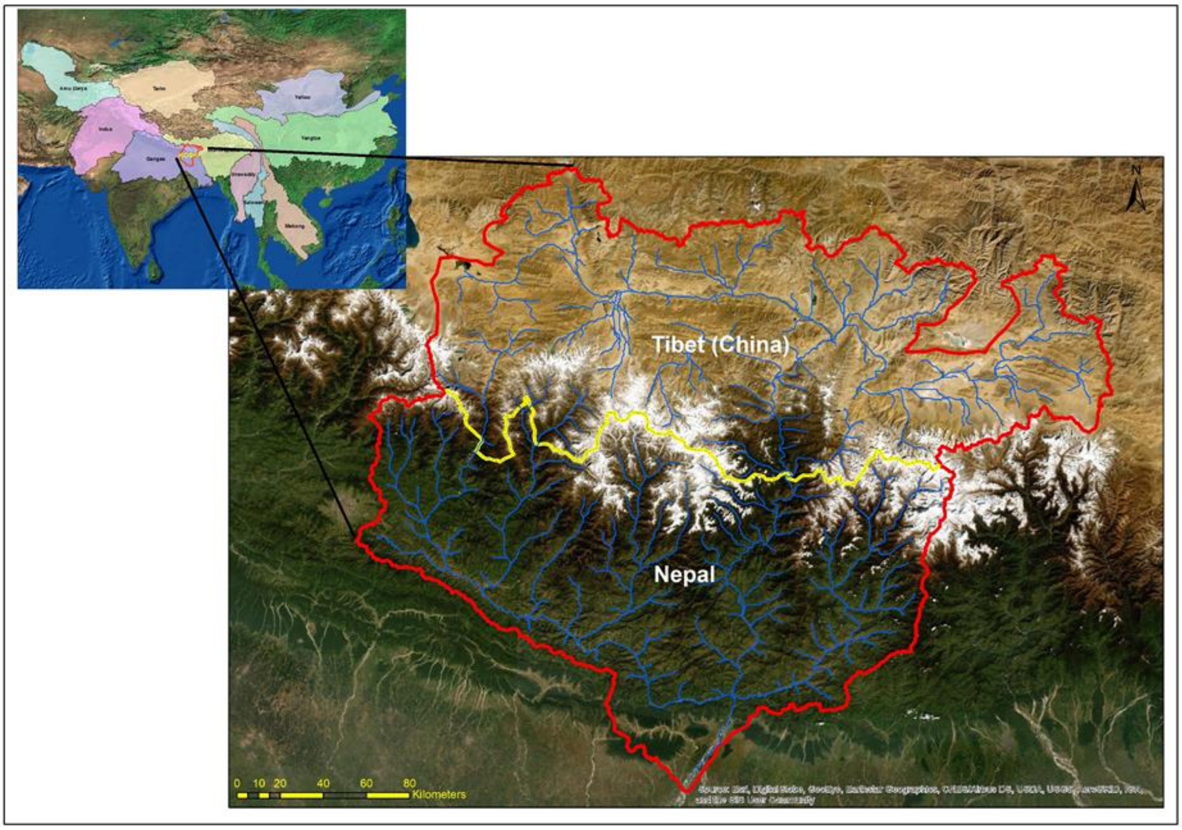
Chapter Four: examines the spatial distribution of flow-dependent ecosystem services within the riverine landscape and the response of the ecosystem services to climate change within the riverine landscape. It is presented in the manuscript "The response of flow-dependent ecosystem services to climate change within the riverine landscape of the Sunkoshi Basin, Nepal". It is ready to submit to *Ecohydrology*.

Chapter Five: examines the response of flow-dependent ecosystem services to climate change within the river network of the larger river basin. It is presented in the manuscript "The role of the geomorphological organisation in the response of flow-dependant ecosystem services to climate change in a river network". It is ready to submit to *River Research and Applications*.

Chapter Six: The final chapter of this thesis is a synthesis of the research undertaken in the four preceding manuscripts. It summarises the major research findings and their original contribution to the importance of riverine landscapes as a social-ecological system; suggestions for future research and finally concluding remarks.

1.7. Study area

The Koshi River Basin is the main river system of the greater Himalayan region and one of the most complex of Himalayan river basins (Figure 1.11). The basin is located in the latitudes between 26°51′ and 29°79′ N and longitudes between 85°24′ and 88°57′E. It is a transboundary basin shared by China, Nepal and India but in this study, we only included the parts within Nepal and China. The river originates on the high-altitude Tibetan Plateau and passes through eastern Nepal and ultimately joins the Ganges. Within the basin, the elevation varies from 30 m to 8848 m (Mount Everest peak) and more than 85% of the basin lies above 2000m from the mean sea level (Khadka et al., 2020). This variation in elevation has brought different climatic zones, ranging from humid tropical in the Terai to Arctic on the high Himalayas (Dixit, 2009). The basin covers five physiographical zones and encompasses a great diversity in topography, climate, vegetation, demography and culture and has a high ecological significance, serving as a vertical linkage. The climate in the southern part of the basin is strongly influenced by the South Asian monsoon, whereas to the north, the Tibetan Plateau lies in a rain shadow area. In the Nepal portion, there are four distinct climatic seasons: pre-monsoon (March-May), monsoon (June–September), post-monsoon (October–November) and winter (December–February). About 80 % of the precipitation occurs between June and September (the monsoon season). A large part of the Koshi Basin in Nepal (south of the Himalayan range) receives an average annual precipitation of about 1,800 mm. Rainfall is intense during the monsoon (June to September) with large local variation because of orographic effects. The upper part of the basin contains a huge amount of snow and glaciers as a freshwater reserve. The total glaciated area in the basin was 2984 km^2 with an estimated ice reserve of 295 km^3 (Bajracharya et al., 2011). The glaciers in the Koshi basin are categorized as temperate summer accumulation-type glaciers they are mainly fed by the summer monsoon (Khadka et al., 2020). The average annual discharge is 1,545 m^3/s in Chatara (Sinha et al., 2019). A Koshi River is a high-energy stream that transports large volumes of sediments to the lower reaches. This sediment transport has resulted in the creation of a megafan of around 15,000 km^2 on the plains. In the meandering sections of the river, the Koshi River has destroyed agricultural areas of about 1,295 km^2 of land in Nepal and about 7,770 km^2 of land in Bihar, India as a result of sand deposition. These areas were renowned for their rice fields and orchards (Mahato, 2013). According to the 2011 census, the total population of the Koshi River Basin is just over 11.5 million with 49.6% men and 50.4% women (Doody et al., 2016).



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Figure 1. 11. Location of the Koshi River Basin.

The Koshi River Basin has been selected as a key river basin for this study to understand the response of flow-dependent ecosystem services to climate change within the riverine landscape. The Koshi River Basin is one of the most important river systems in Nepal. It is a lifeline for people residing in the basin because it provides fresh water for household use, water for irrigation, farming, and livestock (Shrestha et al., 2016). The basin plays a key role in the irrigation of downstream areas and has a large potential for hydropower development.

It contains rich biodiversity and is a source of valuable ecosystem services that directly sustain the lives and livelihoods of the 40 million (Including population from India) basin inhabitants (Uddin et al., 2015). The basin is also home to sensitive and crucial ecosystems, with protected areas that support a high level of biodiversity – it is a hot spot of ecosystem services and functions as a vital corridor for various fauna (Sharma et al., 2019). The ecosystem services (e.g., supporting, provisioning, regulating, and cultural) provided by the Koshi River system contribute to the well-being of the populations that reside in the basin as well as the downstream areas, and the global community.

The Koshi River Basin is very sensitive to climate change and the impact of climate change has been observed in the Koshi River Basin (Baidya et al., 2008; Department of Hydrology and Meteorology, 2017; Shrestha et al., 2017; MoFE, 2019; Srivastava et al., 2021). Many studies suggest that in the future the climate in the Koshi River Basin will change, impacting several sectors (MoFE, 2019, Kaini et al., 2020; Bajracharya et al., 2023). Thus, the impact of climate change on rainfall and temperature patterns is expected to influence the hydrological flow regime and therefore flow-dependent ecosystem services. Furthermore, the diverse topography, young geological formations, a high degree of glaciation and strong monsoon influence, climate change make it highly prone to erosion, sedimentation and natural hazards, including glacial lake outburst floods (GLOF), landslides and debris flow, droughts and flood. The Koshi Basin suffers from frequent floods and 10 major floods have occurred within the last 60 years, with substantial physical impacts. The flood on 18th August 2008, for example, deposited 1-2 m of sediment on the southern plain of the basin (Chen et al., 2013).

1.8. References

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Chapter 2: The heterogeneity of ecosystem services across the riverine landscape of the Koshi River Basin, Nepal

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Sketch on the availability of mountain ecosystem services.

Picture Source: https://www.grida.no/resources/12619

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We, the Research PhD candidate and the candidate's Principal Supervisor, certify the following text, tables and figures are the candidate's original work.

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2.1. Abstract

A foundational tenet of the ecosystem services concept is that they arise from biophysical processes. Riverine landscapes are process-response systems where river flow and geomorphology generate a heterogeneous physical template that influences ecological processes, suggesting that the supply of ecosystem services in riverine landscapes should be congruent with the character and heterogeneity of the physical template. In this study, we examine the congruency between the physical template (river functional process zones; FPZs) and the supply of river flow-dependent ecosystem services from riverine landscapes of the Koshi River Basin, Nepal. The supply of ecosystem services was congruent with FPZs. Social factors were shown to mediate the use and value of ecosystem services between FPZs. Heterogeneity of the physical template interacts with place, social activity and demography to influence the use and potential value of ecosystem services across the riverine landscape. These spatial patterns of greater use of some types of riverine ecosystem services in certain areas of the riverine landscape are indicative of a highly coupled agricultural or ‘green loop’ social-ecological system (SES) and show that maintaining riverine template heterogeneity is an important element of this green loop SES that supports 40 million people in the Koshi River Basin.

2.2. Introduction

Ecosystem services are a well-established framework for identifying the benefits people obtain from nature and assessing the contributions of those benefits to human well-being (Kumar and Martinez-Alier 2011). Ecosystem services have been associated with biomes such as oceans, deserts and mountains (MEA, 2005). The ecosystem services supplied by riverine landscapes (including rivers, floodplains and wetlands) are highly valuable: the economic value of ecosystem services supplied by rivers and their floodplains has been estimated to exceed US$25,681 ha^{-1} (Costanza et al. 2014). Moreover, approximately 25% of global terrestrial ecosystem services are supplied by floodplains (Tockner and Stanford 2002). Monetary or other values assigned to the ecosystem services of riverine landscapes illustrate their importance to society and aid decision-making about trade-offs between the use of riverine ecosystems and their ongoing capacity to continue to supply ecosystem services (Costanza 2020; De Groot et al. 2012).

A foundational tenet of ecosystem services is that they arise from biophysical processes in ecosystems (MEA 2005). While early research in ecosystem services recognized that the nature of ecosystem services differs among biomes (e.g. Daily 1997) the focus of much ecosystem service research to date has been about quantifying the supply and economic value of ecosystem services (eg. Costanza et al. 2014). The link between biophysical processes and ecosystem services has recently been revived to include a spatial element that examines the supply of ecosystem services in relation to the physical character of landscapes at multiple spatial scales (cf. Grêt-Regamey et al. 2014; Rieb and Bennett 2020). Commensurate with the foundational tenet of ecosystem services, these studies show a non-uniform distribution of ecosystem services that varies within the underlying template of biophysical processes at spatial scales ranging from individual landscape units (Mitsch and Gosselink 2015) to continents (SchrÖter et al. 2019). Thus, heterogeneity or the spatial variation in biophysical processes (White and Brown 2005) suggests the supply of ecosystem services may be related to spatial variations in biophysical processes. Understanding the spatial distribution of ecosystem services avoids assumptions of spatial homogeneity may provide better information for decision making about use and conservation trade-offs.

In riverine landscapes, humans derive provisioning (fuelwood, hydropower, water for drinking and irrigation etc.), regulating (climate regulation, groundwater recharge, water yield, carbon sequestration etc.), supporting (habitat protection, habitat for birds and animals, soil formation etc.) and cultural (tourism, cremation, religious bathing etc.) benefits from intact riverine and flow dependent ecosystems (Yeakley et al. 2016). However, rivers are heterogeneous landscapes as a result of biophysical processes at multiple spatial scales (Gilvear et al. 2016). The supply of flow dependent ecosystem services across a riverine landscape is a function of hydrogeomorphic complexity, that is, the complexity of the physical template of the riverine landscape (Thoms et al. 2017). Strong positive relationships between the diversity of physical river channel features and the supply of ecosystem services were demonstrated at the reach scale (i.e. less than one kilometre in length) in the River Allan, River Tyne and Yana River by Large and Gilvear (2015). Similarly, Tomscha et al. (2017) showed different geomorphic reach types to be associated with specific ecosystem services. The emerging evidence suggests that heterogeneity of the underlying physical template should be a key consideration in understanding ecosystem services across riverine landscapes because different services will be supplied by different features of the physical template. However, studies of the relationship between the character of the physical template and ecosystem services are restricted to reach or site scales of less than one kilometre (cf. Gilvear et al. 2016). Increasingly, the study and management of river systems have shifted from a reach/site-based scale to a larger landscape- or catchment/river basin-scale that considers the entire river network (Gilvear et al. 2016). This shift is associated with a recognition that smaller-scale approaches fail to address problems that contribute to longer-term declines in the sustainability of rivers at the basin-scale (Likens et al. 2009).

Many models explain the organisation of the physical river template within a river network. The structure of the river template has been portrayed as a simple continuous downstream gradient (cf. the River Continuum Concept of Vannote et al. 1980) or a mosaic of hydrogeomorphic river zones that differ in length, physical composition and spatial arrangement (Thorp et al. 2006). The spatial pattern of physical character of the river template reflects variations in hydrological regimes, sediment regimes, and valley conditions throughout a river network as well as a myriad of physical-ecological feedbacks. The Riverine Ecosystem Synthesis of Thorp et al. (2006) portrays river networks as a series of river zones that do not occur in a regular manner along river networks. These river zones or Functional Process Zones (FPZs) have been shown to have unique physical properties and river features (Collins et al. 2014), biological communities (Elgueta et al. 2019) and food web character (Thoms et al. 2018). Given the foundational tenet that biophysical processes generate ecosystem services, the type, abundance and arrangement of ecosystem services across a river network are expected to be congruent with the type and distribution of FPZs in the river network (cf. Thorp et al. 2010).

This study investigates the spatial distribution of flow dependent ecosystem services in relation to the spatial arrangement of the physical template (FPZs) in an entire river network. Given potential differences in the hydrogeomorphic character among FPZs we expect that the supply, use and value of ecosystem services will be congruent with the type and distribution of FPZs across the river network.

2.3. Study Area

The Koshi River Basin is a transboundary system draining the eastern Himalayas (Figure 2.1). Its headwaters are located in the Tibetan Plateau of China and, for most of its length, the Koshi River flows through Nepal before joining the Ganga River in India. The Koshi River Basin has a catchment area of 55,930 km^2 at the Nepal – India border, of which approximately 51% is in China and 49% is in Nepal. Six major physiographic zones are found within the Koshi River Basin – the Tibetan Plateau, High Himalaya, High Mountains, Middle Mountain, Siwalik, and Terai, each with unique geology and topography. Alluvial deposits dominate in the Terai zone, sedimentary rocks in the Siwalik zone, while the Middle Mountain and High Mountains physiographic zones are dominated by sedimentary and metamorphic rocks. Crystalline rocks dominate in the High Himalaya physiographic zone, and fossiliferous sedimentary rocks in the Tibetan Plateau. Elevation varies from 19 m ASL in the southern regions of the basin to 8,848 m ASL in the northern regions. Slopes range from 0° to 84° (Mishra et al. 2019). Precipitation is strongly influenced by the South Asian monsoon across most of the basin, but the Tibetan plateau lies in the rain shadow. As a result, precipitation ranges from 207 mm per year in the trans-Himalaya region to 3,000mm per year in the eastern mountains (Shrestha et al. 2017). The Koshi River Basin is characterized by a range of climatic conditions – from humid tropical conditions in the Terai physiographic zone to arctic conditions in the High Himalayan physiographic zone (Dixit et al. 2009). For example, temperatures in the northern regions of the Koshi River Basin can reach as low as -19°C in winter, while maximum temperatures of 45°C have been recorded in summer in the southern regions. The long-term average annual discharge of the Koshi River at the Chatara hydrological station is 1,545 m^{3}s^{-1} (Mishra et al. 2019).

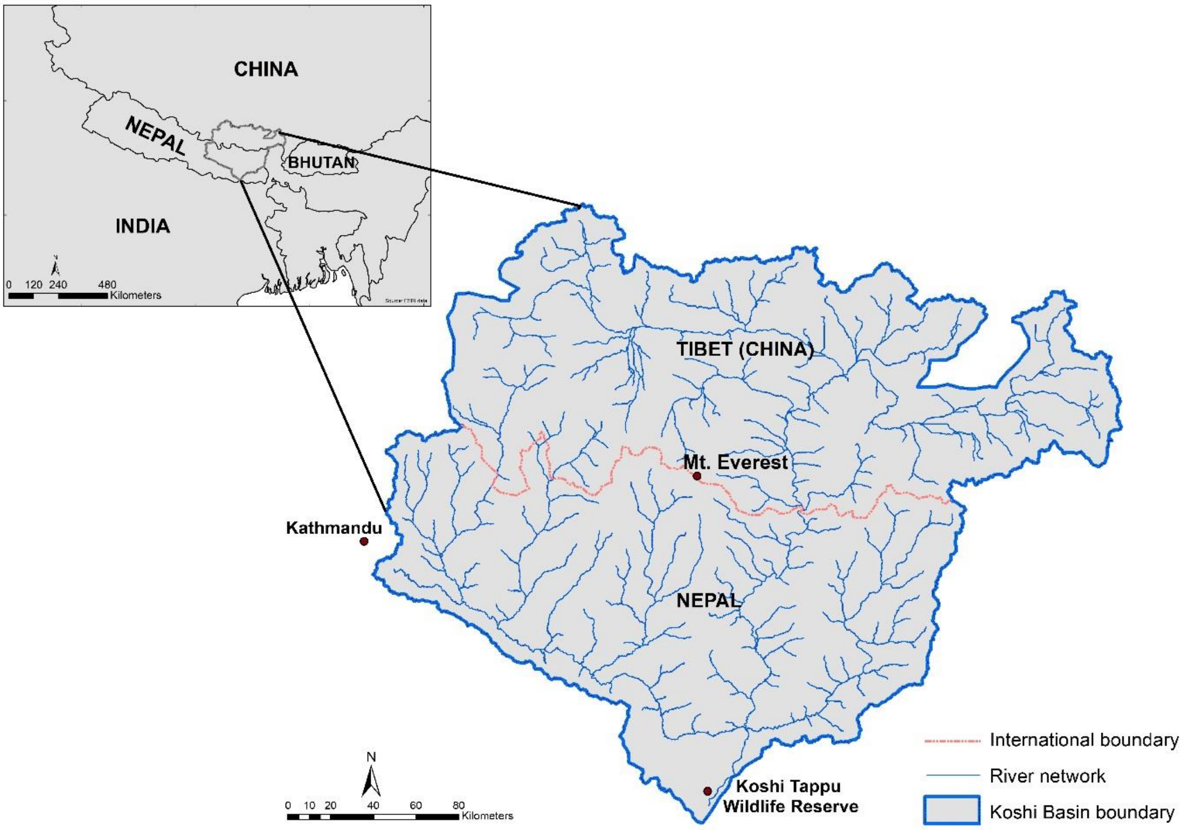


Figure 2. 1. The Koshi River Basin and its location within Southeast Asia (inset).

A diversity of regional fluvial morphologies has been described in the Koshi River Basin (cf. Kafle et al. 2015; Mahato and Shulka 2013; Mishra et al. 2019). For example, in the upper basin, extensive fluvial flat lands (floodplains) and highly sinuous river channels are associated with wide valley surfaces and low channel slopes (Mishra et al. 2019). This contrasts with the highly constrained narrow valley, high energy river systems associated with the High Himalaya physiographic zone. Relatively constrained fluvial systems, with narrow floodplain surfaces and bedload dominated river channels, are also characteristic of most of the High Mountains and Middle Mountain physiographic zones of the Koshi River Basin. Local variations in valley width are associated with increases in floodplain surface area, however, the relatively narrow valleys and steep adjacent slopes facilitate a high degree of coupling between underlying basin character and the presence of fluvial landforms (Mishra et al. 2019). In the lower elevation part of the basin, where the Koshi River emerges from the

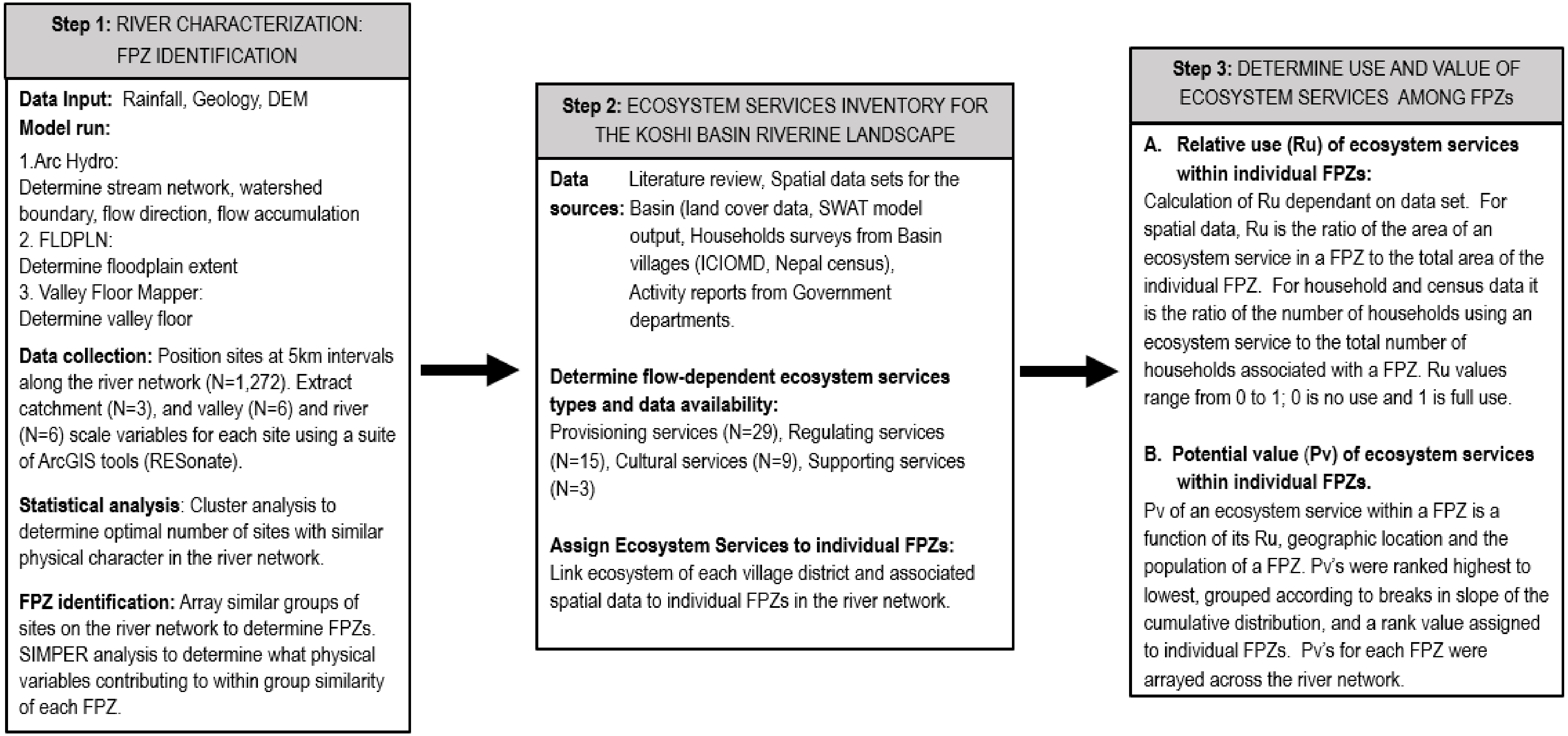
Himalayas, the suite of fluvial landforms changes. River systems become more dynamic with increasing valley widths and the multi thread braided river channel transports large quantities of bedload material. The dynamic nature of the Koshi River in the southern regions of the basin is reflected with lateral channel movements of up to 115 km over the past 200 years (Kafle et al. 2015). In the Siwalik physiographic zone of the Koshi River Basin the supply of bed load material has resulted in the construction of a mega fan with a surface area of >15,000 km^2. Further downstream in the Terai physiographic zone, the Koshi River has a meandering channel and is associated with large floodplain surfaces (> 1,300 km^2) which are heavily cultivated (Danish et al. 2013).

The Koshi River Basin has been listed as a global biodiversity hotspot (Mitteremeier et al. 2004). Important ecosystems and protected areas include snow and glacial landforms, barren land, rangelands, forests, wetlands, alpine meadows with grassland, water bodies and floodplains (Bhatta et al. 2015). There is also a diversity of land cover across the basin including grasslands (which occupy 40.34% of the land surface area), native forests (24.45%) and agriculture (12.45%). Other landcovers in the Koshi River Basin include barren land (11.26%), snow/glaciers (9.45%), shrubland (1.52%), natural water bodies (0.5%), and urban areas (0.03%) (Uddin et al. 2015). The natural resources of the Koshi River Basin also provide services including hydropower, water for domestic use, irrigation, floodplains for agriculture, recreation and cultural sites (Shrestha et al. 2017). The Koshi River Basin has a total hydro potential of 22,350 MW (Khadka 2021). There are approximately 40 million people residing within the basin and population densities vary from < 5 persons per km^2 on the Tibetan Plateau to between 200 and 500 persons per km^2 in the Middle Mountain and Terai physiographic zones (Wahid et al. 2017). The livelihood of most of the population is dependent on the provision of ecosystem services with a direct link to water, including water dependent agricultural activities within the basin (Hussain et al. 2018).

The Koshi River Basin can be described as a ‘green-loop’ system characterized by high direct dependence on local ecosystems, with little or no external economy through which to secure natural resources from elsewhere (cf. Cumming et al. 2014). Of the 40 million people within the Koshi River Basin, the majority (83%) are agriculturally dependent (Shrestha et al. 2017). Analysis by the Koshi Basin Programme showed basin demography is closely related to regions of agricultural production and access to other natural resources. Thus, population densities are higher in the lowland regions of the Basin – the Terai physiographic zone - compared to the mountainous Himalaya and the Tibetan Plateau physiographic zones. Within the Nepal section of the Koshi River Basin the average population, according to the 2011 census, was 176 persons per km^2. This varies across the basin, presumably with topography (Dixit et al. 2009). River valleys and their associated fertile floodplains are areas of higher population densities.

2.4. Methods

The distribution, use and value of ecosystem services among FPZs of the Koshi River Basin were determined using three steps (Figure 2.2). First, FPZs were identified. Second, an inventory of ecosystem services within the FPZs of the Koshi River Basin was constructed. Third, the relative use of each ecosystem service and their potential value among the FPZs of the Koshi River network was calculated. In this study, I used two Digital Elevation Models (DEMs). First, the 30 m Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) DEM was used for river characterisation and second, the 90 m Shuttle Radar Topography Mission (SRTM) DEM was used to simulate the SWAT hydrological model.



Step 1: RIVER CHARACTERIZATION: FPZ IDENTIFICATION

Data Input: Rainfall, Geology, DEM

Model run:

1.Arc Hydro:
Determine stream network, watershed boundary, flow direction, flow accumulation
2. FLDPLN:
Determine floodplain extent
3. Valley Floor Mapper:
Determine valley floor

Data collection: Position sites at 5km intervals along the river network (N=1,272). Extract catchment (N=3), and valley (N=6) and river (N=6) scale variables for each site using a suite of ArcGIS tools (RESonate).

Statistical analysis: Cluster analysis to determine optimal number of sites with similar physical character in the river network.

FPZ identification: Array similar groups of sites on the river network to determine FPZs. SIMPER analysis to determine what physical variables contributing to within group similarity of each FPZ.

Step 2: ECOSYSTEM SERVICES INVENTORY FOR THE KOSHI BASIN RIVERINE LANDSCAPE

Data sources: Literature review, Spatial data sets for the Basin (land cover data, SWAT model output, Households surveys from Basin villages (ICIOMD, Nepal census), Activity reports from Government departments.

Determine flow-dependent ecosystem services types and data availability:
Provisioning services (N=29), Regulating services (N=15), Cultural services (N=9), Supporting services (N=3)

Assign Ecosystem Services to individual FPZs:
Link ecosystem of each village district and associated spatial data to individual FPZs in the river network.

Step 3: DETERMINE USE AND VALUE OF ECOSYSTEM SERVICES AMONG FPZs

A. Relative use (Ru) of ecosystem services within individual FPZs:
Calculation of Ru dependant on data set. For spatial data, Ru is the ratio of the area of an ecosystem service in a FPZ to the total area of the individual FPZ. For household and census data it is the ratio of the number of households using an ecosystem service to the total number of households associated with a FPZ. Ru values range from 0 to 1; 0 is no use and 1 is full use.

B. Potential value (Pv) of ecosystem services within individual FPZs.
Pv of an ecosystem service within a FPZ is a function of its Ru, geographic location and the population of a FPZ. Pv's were ranked highest to lowest, grouped according to breaks in slope of the cumulative distribution, and a rank value assigned to individual FPZs. Pv's for each FPZ were arrayed across the river network.

Figure 2. 2. An approach to determine the congruency between the physical template and ecosystem services within the Koshi River Basin.

NOTE: Arc Hydro= Arc Hydro ArcGIS tool, FLDPLN= An advanced 2D flood model, RESonate= Automated hydrogeomorphic data extraction toolbox in ArcGIS, DEM= Digital Elevation Model, SWAT = Soil and Water Assessment Tool

2.4.1. Step One: River characterisation and Identification of FPZs

The drainage network (streamlines), watershed boundary, flow direction and flow accumulation of the Koshi River Basin were prepared from 30 m ASTER Digital Elevation Model (ASTER - DEM) from Arc Hydro tool in ArcGIS. These outputs were inputs for running the Floodplain Model (FLDPLN, Kastens 2008). FLDPLN was used to determine floodplain extent as a function of floodwater depth. The valley floor area was delineated using Valley Floor Mapper. The output valley floor was overlain on Google Earth and ESRI satellite images to see the model simulated extent of the valley floor. Once the outline of the valley floor almost matches reality. Then the valley floor was converted to a polygon shapefile for further analysis in ArcGIS as well as used as a surrogate for potential floodplain areas.

Data collection sites were created at 5 km intervals along the drainage network (n=1,272) based on user-defined stream lengths in RESonate (automated hydrogeomorphic data extraction program in ArcGIS) toolbox in ArcGIS and became the focus for the extraction of 15 hydrogeomorphic variables used to delineate FPZs (Table 2.1). At each data collection site, watershed, valley, and channel scale variables were extracted using RESonate tools (Maasri et al. 2021; Thoms et al. 2018; Williams et al. 2013). The watershed-scale variables were elevation, annual rainfall and dominant geology (Table 2.1). Elevation was determined from the 30 m ASTER - DEM digital National Elevation Dataset. Mean long-term annual rainfall data (n=30 years) were obtained from rainfall stations in the Koshi River Basin from the Department of Hydrology and Meteorology, Nepal and the Asian Precipitation – Highly

Resolved Observed Data Integration Toward Evaluation (APHRODITE) dataset allowed for spatial infilling in the Tibetan plateau region of the Basin. Geology data were from Chen et al. (2013) and assigned according to their rock type, erodibility, and potential sediment yield (cf. Thoms et al. 2018). The valley-scale variables were valley width, valley floor width, the ratio of valley width to valley floor width, the left and right valley slopes, and down valley slope, determined from the DEM of the watershed (Table 2.1). The six channel-scale variables were channel belt width, channel belt sinuosity, channel belt wavelength, channel sinuosity, planform class and the number of river channels, determined from the streamlines of the basin (Table 2.1). For in-depth river characterization processes and tools, readers are suggested to refer to the RESonate User Manual (Kotlinski et al. 2016; Williams et al. 2013). Data sources used to derive the 15 hydrogeomorphic variables used for the river characterization of the Koshi River are given in Table 2.1.

The dataset of hydrogeomorphic variables (1,272 sites by 15 variables) was analysed using multivariate statistical techniques to identify groups of sites with similar physical characteristics. Sites were classified using the flexible unweighted pair-group method with arithmetic averages (UPGMA) fusion strategy, as recommended by Belbin and McDonald (1993), based on the 15 variables. Groups of sites with similar physical character were selected from the dendrogram representation of the cluster analysis, whereby the least number of groups with maximum similarity was chosen. This step required the identification of an inflexion point in the relationship between the number of groups in the classification and their corresponding similarity value (Thoms et al. 2018).

Table 2. 1. Variables used to characterize Functional Process Zones in the Koshi River network.

Variable	Scale	Data source
Elevation (m)	Watershed	The ASTER regional Digital Elevation Model (DEM) is the primary elevation database, and it is available from www.rds.icimod.org
Geology	Watershed	The regional geology was extracted from Chen et al. (2013)
Mean annual precipitation(mm)	Watershed	The DHM and APHRODITE provide historical annual precipitation data, and these are available at www.rds.icimod.org
Valley width (m)	Valley	The valley width was derived from the digital elevation model for the Koshi Basin (DEMKB); data available at www.une.edu.au database
Valley floor width (m)	Valley	The valley floor width was derived from DEMKB; data available at www.une.edu.au database
Ratio of valley to valley floor width	Valley	The Ratio of valley-to-valley floor width was derived from DEMKB; data available at www.une.edu.au database
Left valley side slope	Valley	The left valley side slope was derived from DEMKB; data available at www.une.edu.au database
Right valley side slope	Valley	The right valley side slope was derived from DEMKB; data available at www.une.edu.au database
Down valley slope	Valley	The down valley slope was derived from DEMKB; data available at www.une.edu.au database
Width of the river channel belt (m)	Channel	The spatial geometry of streamlines within the Koshi basin was extracted from the DEMKB. Data are available at www.une.edu.au database
Wavelength of the channel belt width (m)	Channel	The spatial geometry of streamlines within the Koshi basin was extracted from the DEMKB. Data are available at www.une.edu.au database
Sinuosity of channel belt	Channel	The spatial geometry of streamlines within the Koshi basin was extracted from the DEMKB. Data are available at www.une.edu.au database
Sinuosity of main river channel	Channel	The spatial geometry of streamlines within the Koshi basin was extracted from the DEMKB. Data are available at www.une.edu.au database
River channel planform class	Channel	Manually derived from Google Earth satellite image
Number of river channels	Channel	Manually derived from Google Earth satellite image

DHM = Department of Hydrology and Meteorology
ASTER = Advanced Spaceborne Thermal Emission and Reflection Radiometer
APHRODITE = Asian Precipitation – Highly Resolved Observed Data Integration Toward Evaluation of Water Resource
DEM = Digital Elevation Model, DEMKB = The Digital Elevation Model for the Koshi Basin

This analysis was also used to construct a FPZ nomenclature for the Koshi River Basin. Once identified, the sites were overlaid on the drainage network with their corresponding group nomenclature from the cluster analysis. Groups equate to FPZs. Sequences of the same group delineate FPZ segments in the river network - lengths of the river with similar valley-floodplain settings and river morphologies, inferred to be influenced by similar geomorphic processes (Thoms et al. 2018). Finally, Analysis of Similarity (ANOSIM) and SIMilarity PERcentage analysis (SIMPER) was used to determine differences in hydrogeomorphic variables and which hydrogeomorphic variables contribute to group similarity of each FPZ, respectively.

The floodplain area for all continuous FPZ segments was also determined. The valley floor area delineated for each FPZ segment was used as a surrogate for the floodplain area. Where two different FPZs met, valley floor polygons were split laterally across the valley at each site. The total floodplain area of each FPZ type and the distribution of floodplain areas among individual segments of each FPZ was calculated in ArcGIS.

Verification of the location of some FPZs that emerged in the Koshi River network was undertaken in several ways. First, a field-based study of nine random sites assessed the physical riverine landscape character according to the valley-scale hydrogeomorphic variables used in the classification. Second, the studies of Mahatao and Shukla (2013) and Sinha et al. (2019) on the regional variability of fluvial landforms provided information on geology, topography, valley slopes, valley dimensions as well as general descriptions of the physical character of river networks within the Koshi Basin. Collectively, these data form an independent, albeit limited, field-based verification of the FPZs delineated in the river network.

2.4.2. Step Two: Ecosystem services associated with FPZs of the Koshi River Basin

Four sources of information provided data on flow-dependent ecosystem services supplied by the riverine landscapes of the Koshi River Basin. First, a review of the ecosystem service literature for the region enabled the construction of a database of potential ecosystem services in the riverine landscape. Second, spatial data sets obtained from the International Centre for Integrated Mountain Development (ICIMOD) provided land cover information for 2010 at a resolution of 30m for the entire Koshi River Basin. This land cover data is categorized into 9 classes: i) agricultural (Kharif), ii) agricultural (Rabi), iii) barren area, iv) built-up area, v) forest, vi) grassland, vii) shrubland, viii) water body and ix) snow/glacier (http://rds.icimod.org). These were used as a proxy ecosystem and used to help deliver the riverine ecosystem services. The services provided by these ecosystems were classified as follows. For instance, the forest ecosystem provides carbon sequestration services. Similarly, floodplain/ barren land provides sand, gravel and boulder etc. These data sets were used as a proxy for ecosystem services. In addition, the Soil and Water Assessment Tool (SWAT) model, developed for the Koshi River Basin, also provided data on ecosystem services across the entire basin. SWAT is a basin modelling tool that can simulate water-dependent provisioning and regulating ecosystem services, and proxy variables, to estimate associated supporting and cultural services through river networks (cf. Crossman et al. 2013; Francesconi et al. 2016). Third, household surveys were undertaken as part of the Poverty and Vulnerability Assessment (PVA, source: http://rds.icimod.org/Home/DataDetail?metadataId=22324&searchlist=True) in 2011-2012 (Gerlitz et al. 2014) and the Nepal Census in 2011 (CBS 2012), provided household-level data on the use of ecosystem services for each Village Development Committee district (VDC) in the Nepal section of the basin. Fourth, data obtained from various Nepalese government departments (eg. Nepalese Tourism Board, Nepal Electricity) provided information on a variety of ecosystem services, including the location of dams, and cultural/tourism/recreational sites and activities.

The source of information dictated how the supply or occurrence of individual ecosystem services within an FPZ was determined. The area or number of individual ecosystem services present within an FPZ segment was calculated from spatial data (i.e., the landcover and SWAT model data) and locational data from the Nepalese government. The use of household-level survey data first required VDCs to be linked to a specific FPZ. An FPZ shapefile was overlain on the VDC shapefile of the Koshi River network to determine the VDCs directly associated with a specific FPZ. Most VDCs were associated with only one FPZ. In situations where a VDC overlapped two FPZs, the areal proportion of a VDC within a FPZ was used to allocate the number of households associated with specific individual ecosystem services per FPZ. As a result, data from 726 VDCs (CBS 2012; Gerlitz et al. 2014) were used in this study of ecosystem services associated with the FPZs of the Koshi River. The ecosystem services identified and their accompanying information source is given in Table 2.2.

2.4.3. Step Three: Use and value of ecosystem services among FPZs

There are many approaches to determine the use and value of ecosystem services (De Groot et al. 2012); most focus on economic valuation (eg., Costanza et al. 1998). Evaluating the benefits of river ecosystem services differs according to discipline (i.e. environmental science, social science and economics), and is influenced by data availability (cf. Costanza and Farber 2002; Hanna et al. 2018). Most evaluations of the benefits from ecosystem services are economic but this study took a different approach, developing two indicators of benefit - relative use and potential value - for individual FPZs in the Koshi River.

Table 2. 2. The ecosystem services associated with the riverine landscape of the Koshi River Basin. Ecosystem services in bold are those where data were available. The different symbols represent data sources; ● = 2011 Nepal census data, △ = 2011 ICIMOD household survey data, ■ = Nepal government reports, □ = Spatial data (Land cover and SWAT).

Ecosystem Service type	Ecosystem services	
Provisioning	Domestic water use ●△	Driftwood △
	Timber/Pole ●	Branches/twigs △
	Wood ●	Grazing livestock △
	Bamboo ●	Hydropower ■
	Thatch for roofing ●	Irrigated agriculture □
	Fuelwood/firewood ●	Rain-fed agriculture □
	Fishes △	Water bodies □
	Crab/Snail/Tortoise △	Aggregate (sand-gravel-boulders) □
	Game (Wild animals) △	Forest □
	Medicinal and ornamental plants △	Alpine grassland/grassland □
	Wild edible fruits △	Shrubland □
	Wild edible vegetables △	Transport
	Staple crops (paddy and wheat) △	Industry
	Cash crops (vegetable, potato, pulse) △	Paha (Agricultural field frog)
	Leaf litter △	Horticultural crops
	Foliage △	Fibre
	Forage/grass △	Bushmeat
	Fodder △	Natural plants
Regulating	Climate regulation □	Biodiversity conservation □
	Water Yield □	Habitat provision □
	Nutrient regulation □	Hydrological cycle
	Groundwater recharge □	Water retention
	Sediment transport □	Water purification
	Sediment yield □	Seed dispersal
	Nutrient deposit □	Pollination
	Sediment retention □	Air quality regulation
	Carbon sequestration □	Pollution transport and dilution
	Flow regulation □	Flood protection
	Habitat-terrestrial □	Erosion control
	Habitat-aquatic □	Soil stability
	Habitat corridors □	Waste treatment
Cultural	Cremation ●	Wildlife watching □
	Research ■	Picnic
	Rafting/Boating ■	Swimming
	Fishing ■	Social gathering (women)
	Pilgrimage ■	Traditional market
	Religious bathing ■	Sense of place
	Tourism ■	Traditional cultural practices
	Temple/Religious site ■	Education
Supporting	Aquatic habitat □	Ecosystem resilience
	Terrestrial habitat □	Genetic diversity
	Habitat protection □	Pollination
	Nutrient cycling	Soil formation

Relative use describes whether an ecosystem service is used by people in the Koshi River Basin and value describes the importance and demand for the use of an ecosystem service by people in the Koshi River Basin.

The relative use of each ecosystem service is expressed as the ratio of either the area or number of individual ecosystem services to the total area or the total number of that ecosystem service across all FPZ segments. The relative use of ecosystem services determined from spatial data used the areal calculation while those ecosystem services determined from household-level census and PVA activity data used the numerical calculation. For example, the relative use of provisioning services was the ratio of the number of households using an ecosystem service within an FPZ segment to the total number of households associated with that FPZ. Similarly, the ratio of the number of cultural sites within an FPZ to the total number of cultural sites within the river network provided a relative use for cultural ecosystem services. By comparison, the relative use of supporting ecosystem services was the ratio of the area of an ecosystem service to the total area of an FPZ, whereas the relative use of regulating services was the ratio of the number of regulating ecosystem services in an FPZ to the total number of that regulating service within the Koshi River Basin. Relative use of individual ecosystem services ranges from 0 to 1; where 0 represents an ecosystem service that is not used within a FPZ and 1 represents a situation where all households use a particular ecosystem service present within a FPZ. The total relative use of each ecosystem service group (provisioning, regulating, supporting, cultural) was the sum of all relative use values for each FPZ type. Similar methods have been used by Large and Gilvear (2015) and Tomscha et al. (2017) for determining the relative use of ecosystem services within smaller river reaches.

The potential value of ecosystem services in FPZs was calculated as a function of the relative use of an ecosystem service within an FPZ, the geographic location of the FPZ, and the associated population density of the FPZ. Thus, the approach taken does not derive an economic value but integrates the biophysical context (the FPZ and its location within the river network) with the overall demand (relative use and population density of a FPZ) for an ecosystem service. The population density was determined for each FPZ within the river network. For the Tibetan section, population data from the 2011 Chinese census was clipped according to their direct association with a FPZ. For the Nepal section, population data for each VDC (Gerlitz et al. 2014; CBS, 2012) associated with a FPZ was used. Each FPZ was assigned a geographic location score, which ranged from 0 to 1, based on its elevation and climate, using the method outlined by Haines-Young et al. (2012). Potential values were grouped and groups of potential values were determined from the number and position of inflexions present on the cumulative distribution curve of all potential values for the Koshi River Basin network and then ranked low to high. A rank value was assigned to each FPZ and arrayed spatially on the river network. The spatial organisation of ecosystem service rank values was undertaken to examine the association between FPZs and their ecosystem service value across the river network.

2.4.4. Statistical analyses

The nonparametric Kolmogorov-Smirnov test was used to determine pairwise differences in the supply, relative use and potential value of ecosystem services among FPZs within the Koshi River network. SIMPER analyses determined the contribution that each ecosystem service made to the mean similarity of the relative use and value within each FPZ.

2.4.5. Limitations of the study

The major limitations of the present study lie in the limited household and ecosystem services data availability and accurate information in the high Himalayan areas of Tibet and Nepal (The northern part of our study area). These areas are very remote and have less accessibility.

Due to the unavailability of ES data, we used landcover and SWAT outputs as proxy ecosystem services to fulfil those gaps.

2.5. Results

2.5.1. Functional Process Zones of the Koshi River Basin

Five FPZs emerged from the classification of the 1,272 sites in the Koshi River network (Figure 2.3A). These five FPZs explain 79.9% of the similarity between sites within this river network. FPZs had significantly different physical characteristics (ANOSIM: Global R = 0.702). From the cluster analysis, the first separation grouped sites via valley widths, explaining river channels contained in wide and narrow valleys. This corresponded to the low elevation floodplains in the Terai and the high elevation floodplains of the Tibetan Plateau, plus river channels associated with narrower river valleys (Figure 2.3A). Further, into the dendrogram, sites were differentiated based on down valley slopes and channel patterns (Figure 2.3A). Thus, high Himalayan River channels were associated with narrow gorges, high down-valley slopes, and in-channel velocities. Braided river channels with multiple channels were associated with moderate down valley slope. Meandering rivers were associated with relatively open valleys and well-developed floodplain surfaces (Figure 2.3A) and occur in the lower slopes of the southern Himalayan region.

The composition of the FPZs in the Koshi River Basin differed in terms of their total length and the number of individual segments (Table 2.3). The most abundant was the High Elevation Floodplain River FPZ covering 35% of the river network (Table 2.3). The next most abundant was the Meandering River FPZ, followed by the Braided River, High Himalayan River and Low Elevation Floodplain River FPZs (Table 2.3). In terms of the number of individual segments comprising each FPZ, the Braided River FPZ had the highest number of single segments followed by the High Himalayan River FPZ, the High Elevation

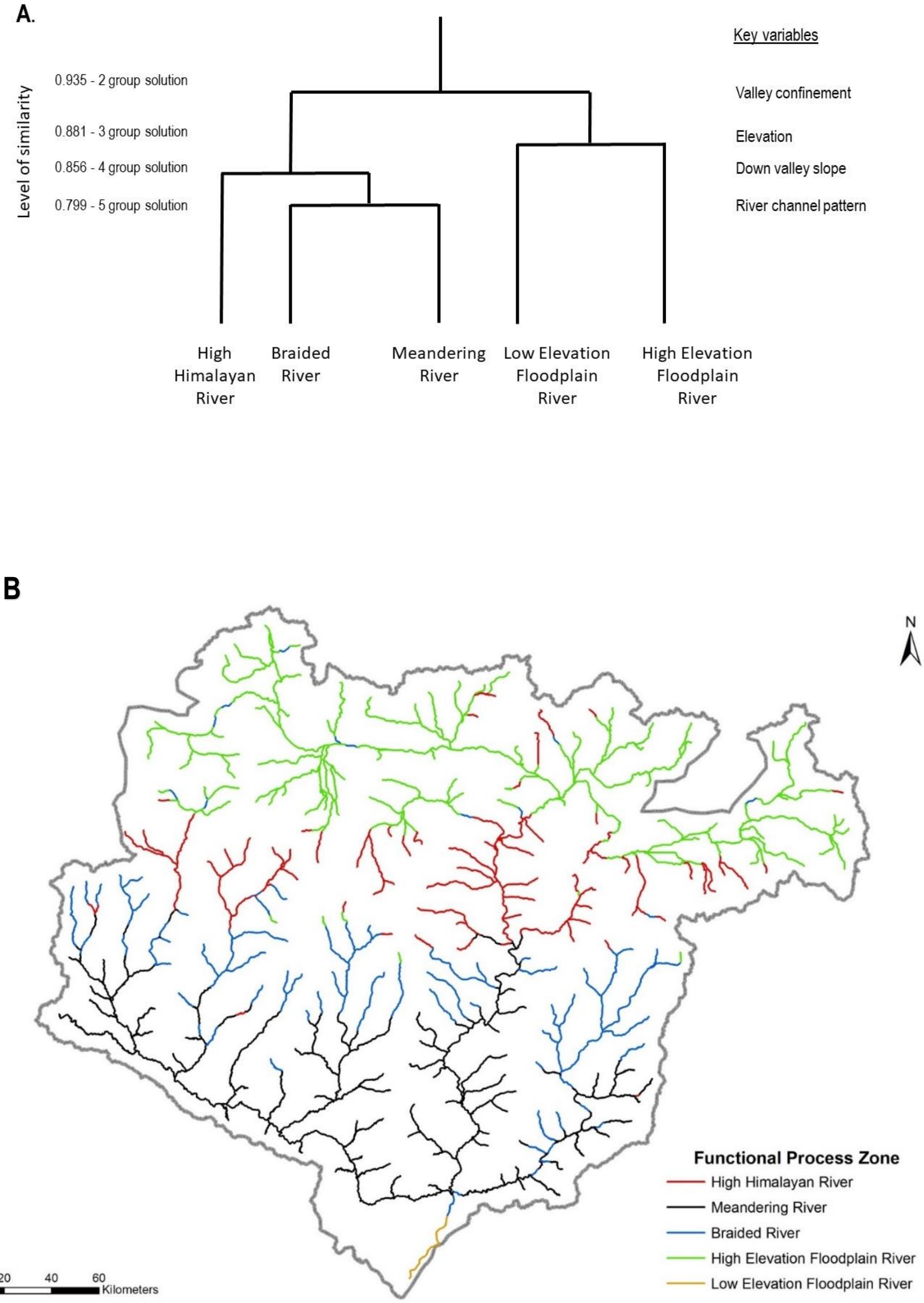
Floodplain, the Meandering River FPZ, and lastly the Low Elevation Floodplain River FPZ with two individual segments (Table 2.3).

The spatial organisation of the five FPZs displayed a broad pattern within the Koshi River Basin (Figure 2.3B). Within the network, FPZs are arranged as a mosaic from the Tibetan Plateau through the Himalayas to the lowland regions of the Terai. Therefore, FPZs occupy discrete areas of the river network, and some FPZs repeat in different places within the river network. Braided River FPZs are most frequently adjacent to either Meandering River or High Elevation Floodplain River FPZs.

There is 3,278 km^2 of floodplain in the Koshi River Basin, which represents 5.86% of the total basin area and 80% of the total surface area of the riverine landscape in the basin. Floodplains are located in two distinct regions of the basin, the high and low elevation areas of the river network, i.e., the Tibetan and Terai regions respectively (Figure 2.3C). Overall, 72.33% of the floodplains in the Koshi River Basin are in the Tibetan Plateau (High Elevation Floodplain River FPZ).

Table 2. 3. The character of the Functional Process Zone in the Koshi River network.

Functional Process Zone (FPZ)	Total channel length (km)	Proportion of total (%)	Number of segments	Floodplain area (km^2)	Influencing variables identified via the SIMPER analysis	Physical character
High Himalayan River	739.4	13.40	42	471	• Valley confinement • Down valley slope	Highly constrained sections of the river network associated with the High Himalaya physiographic zone, where river channels flow through narrow, deep valley sections that are dominated by steep bed slopes – like river channels in Canyon Zones (cf. Schumm, 1997).
Meandering River	1756.6	31.83	24	335	• Valley confinement • Down valley slope • River channel pattern	Single-channelled sections of the river network with a sinuosity of less than 1.3 and are associated with moderate-to-low down valley slopes. Increases in river valley widths and lower down valley slopes enable floodplain development.
Braided River	1069.2	19.37	56	175	• Valley confinement • Down valley slope • River channel pattern	Sections of the river network are dominated by relatively high energy multi-channelled river systems. These braided river settings have higher down valley slopes and abundant sediment supply.
High Elevation Floodplain River	1913.1	34.66	22	1900	• Valley confinement • Elevation	Floodplain dominated zones occur in those areas of the river network with extended river valley widths. High elevation floodplains are in the Tibetan Plateau region of the Koshi River basin.
Low Elevation Floodplain River	40.6	0.74	1	397	• Valley confinement • Elevation	Floodplain dominated zones occur in those areas of the river network with extended river valley widths. Low elevation floodplains are in the Terai region of the Koshi River basin


A.
Level of similarity
0.935 - 2 group solution
0.881 - 3 group solution
0.856 - 4 group solution
0.799 - 5 group solution
Key variables
Valley confinement
Elevation
Down valley slope
River channel pattern
High Himalayan River
Braided River
Meandering River
Low Elevation Floodplain River
High Elevation Floodplain River
B
N
Functional Process Zone
High Himalayan River
Meandering River
Braided River
High Elevation Floodplain River
Low Elevation Floodplain River
0 10 20 40 60
Kilometers

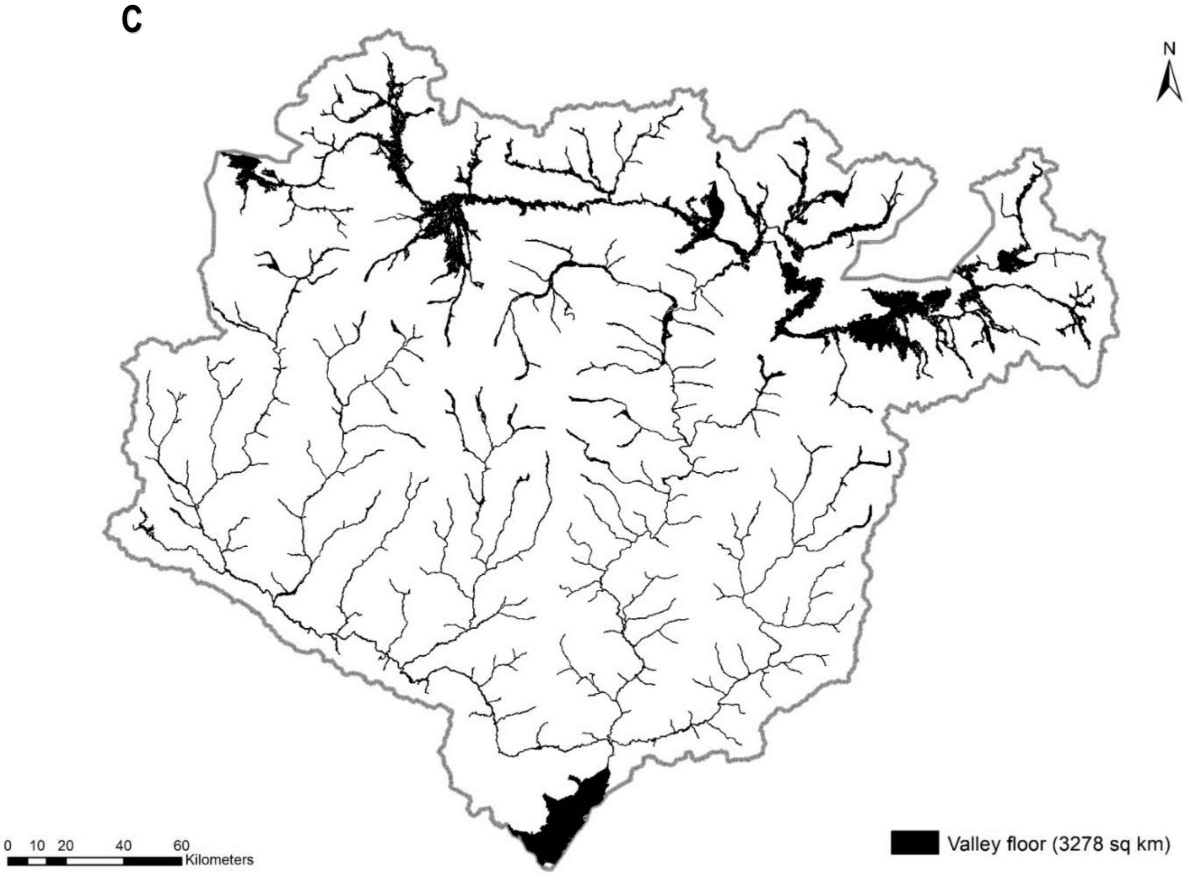
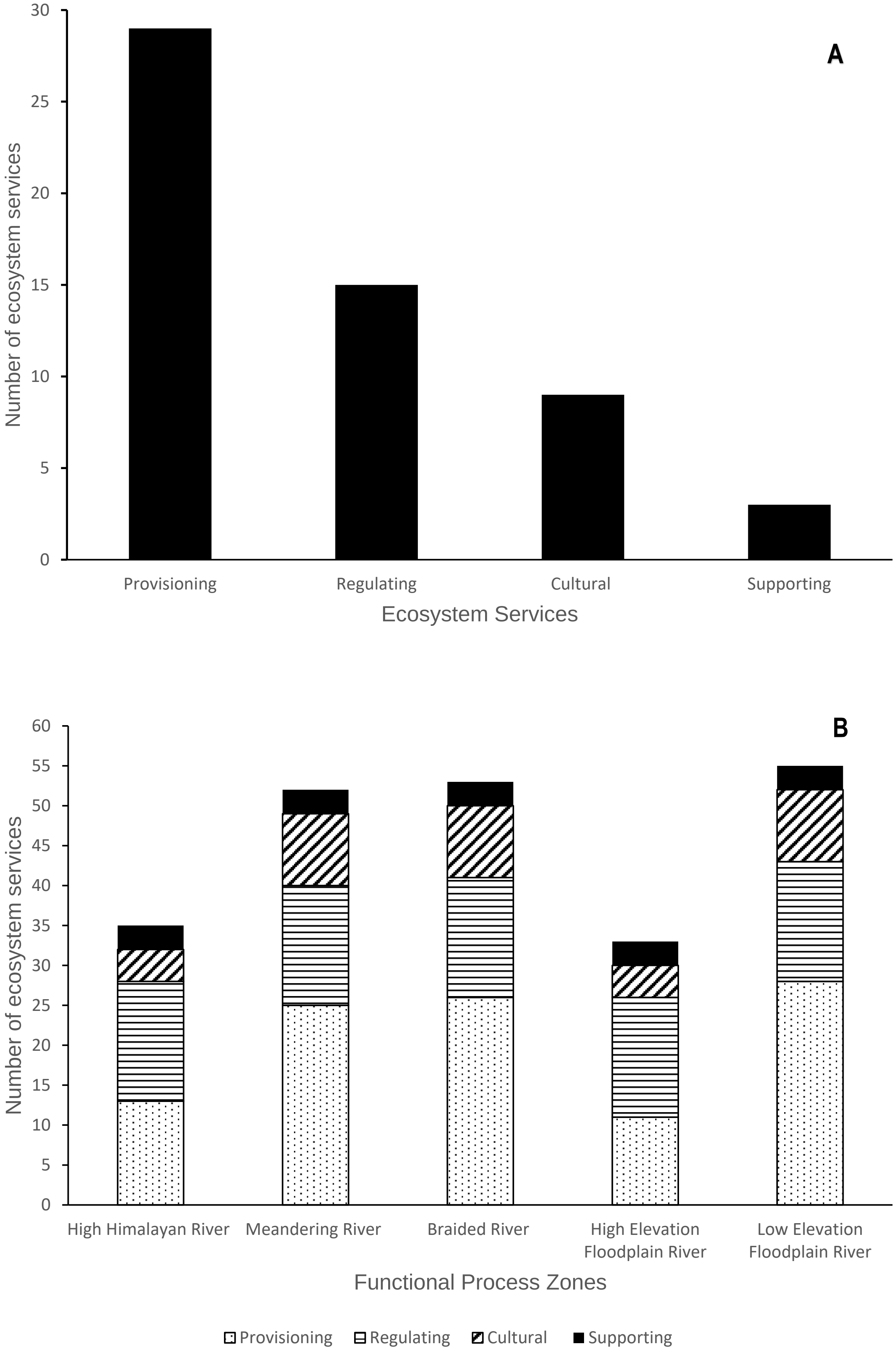


Figure 2. 3. Elements of the riverine landscape of the Koshi River Basin. A. The classification dendrogram of the Koshi river network used to derive Functional Process Zones (FPZs). B. Spatial organisation of FPZs within the Koshi River network. C. Distribution of major areas of valley floor/floodplains.

2.5.2. The occurrence of ecosystem services within FPZs

The literature review revealed 86 ecosystem services that had been previously identified to occur across the riverine landscape of the Koshi River Basin. Among 86 ecosystem services, only data were available for 56 of these ecosystem services (Table 2.2) and for all FPZ types in the Koshi River Basin. Of these, provisioning services are more abundant (29) than regulating (15), cultural (9) and supporting (3) services (Figure 2.4A). The total abundance of ecosystem services was highest in the Low Elevation Floodplain River FPZ and lowest in the High Himalayan River and High Elevation Floodplain River FPZs (Figure 2.4B). There was a significant difference in the occurrence of supporting, regulating, provisioning and cultural services among the FPZs (Kolmogorov Smirnov test: $p<0.01$ for all pairwise tests). Provisioning services dominated in the Low Elevation Floodplain River, Braided River and Meandering River FPZs, while regulating services were relatively more abundant in the High Elevation Floodplain River and High Himalayan River FPZs (Figure 2.4B). Cultural and supporting services were relatively evenly distributed among the five FPZs of the Koshi River Basin (Figure 2.4B).

Some ecosystem services occurred in all FPZs. Overall, 11 provisioning services, 15 regulating services, 4 cultural services and 3 supporting services were common to all FPZs (Figure 2.4C). Of the remaining 15 provisioning services two were shared between two FPZs: hydropower in the Meandering River FPZ and Braided River FPZ; and wild edible fruits in the Braided River FPZ and Low Elevation Floodplain River FPZ. However, two provisioning services (forest and shrubland) were shared among four FPZs (High Himalayan River, Meandering River, Braided River and Low Elevation Floodplain River FPZs), and the remaining 11 services were shared among three FPZs (Meandering River, Braided River and Low Elevation Floodplain River FPZs). By comparison, five cultural services (rafting/boating, fishing, pilgrimage, religious bathing and the presence of temples) were shared among three FPZs (Meandering River, Braided River and Low Elevation Floodplain River FPZs). The provisioning services of game, wild edible vegetables and driftwood were unique to the Low Elevation Floodplain River FPZ (Figure 2.4C).


A
Number of ecosystem services
30
25
20
15
10
5
0
Provisioning
Regulating
Cultural
Supporting
Ecosystem Services
B
Number of ecosystem services
60
55
50
45
40
35
30
25
20
15
10
5
0
High Himalayan River
Meandering River
Braided River
High Elevation Floodplain River
Low Elevation Floodplain River
Functional Process Zones
Provisioning
Regulating
Cultural
Supporting

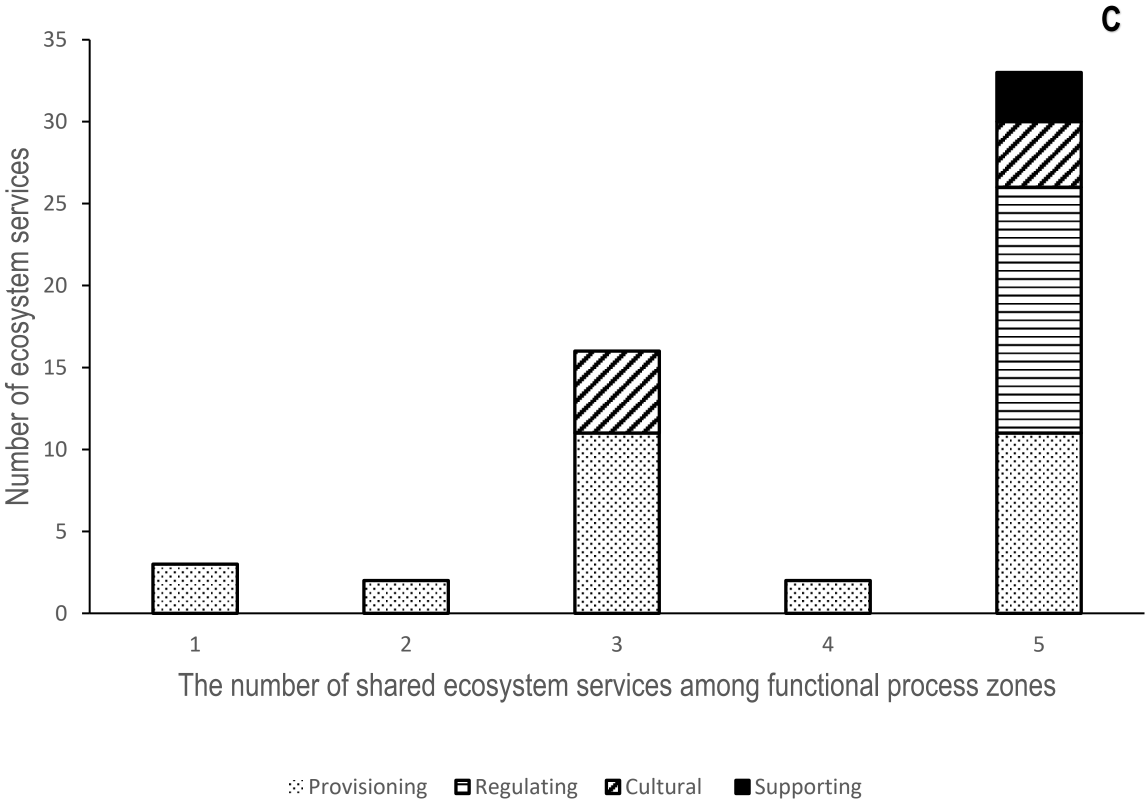


Figure 2. 4. Ecosystem services of the Koshi Basin riverine landscape. A. The abundance of ecosystem services. B. The abundance of ecosystem services in the functional process zones. C. The number of ecosystem services shared among the functional process zones of the Koshi River Basin, where 5 means that an ecosystem service occurs in all functional process zone types.

2.5.3. Use and value of ecosystem services among FPZs

The relative use of the 57 ecosystem services differed significantly among FPZs (Kolmogorov Smirnov test: $p<0.01$ for all pairwise tests). Overall, the relative use of ecosystem services was higher in the Meandering River FPZ compared to the Braided River FPZ, Low Elevation Floodplain River FPZ, High Himalayan River FPZ and High Elevation Floodplain River FPZ (Figure 2.5). Relative use of the four ecosystem service groups also differed among the five FPZs. The relative use of provisioning services was highest in the Meandering River FPZ while the relative use of regulating services was highest in the High

Himalayan River FPZ (Figure 2.5). By comparison, the relative use of cultural services was highest in the Meandering River FPZ, whereas the relative use of supporting services was highest in the High Himalayan River FPZ (Figure 2.5).

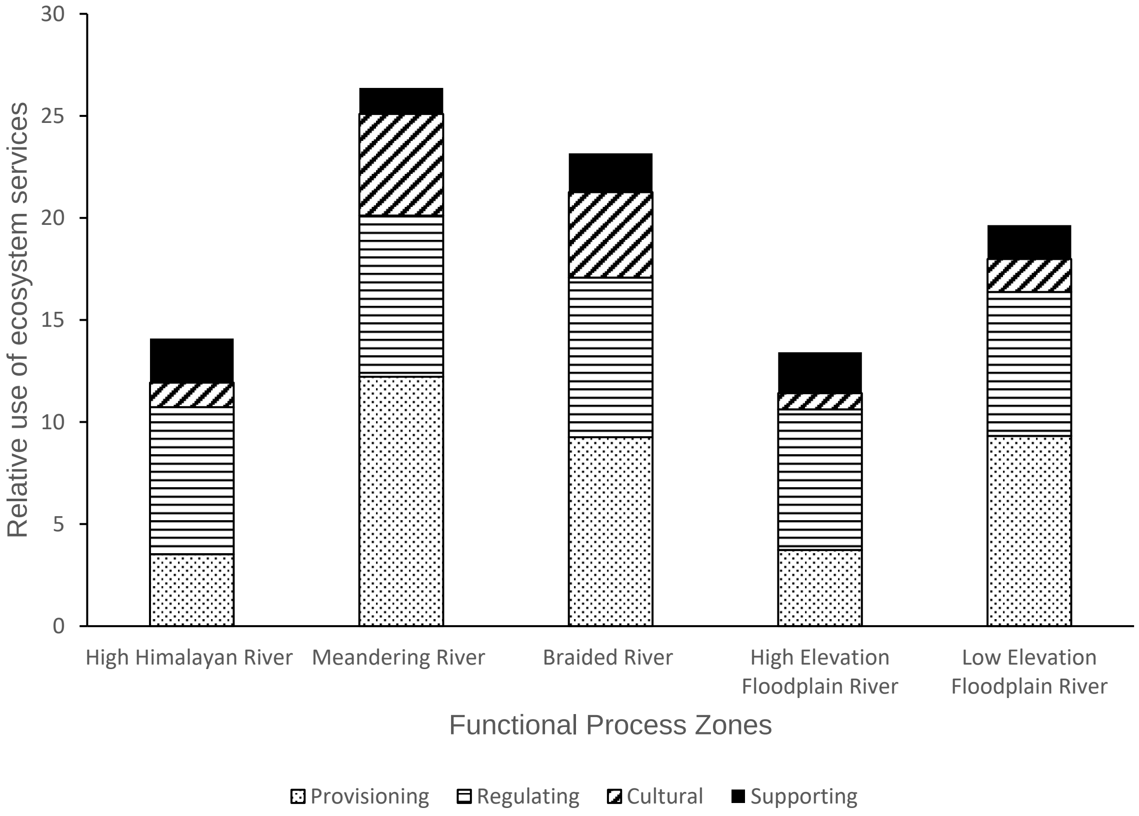


Figure 2. 5. The relative use of ecosystem services within the functional process zones of the Koshi River basin.

The potential value of ecosystem services varied significantly among most of the FPZs (Kolmogorov Smirnov test: $p<0.01$ for all pairwise tests). Of the 10 pairwise FPZ comparisons, only two were not significantly different to one another; i.e. the potential value of ecosystem services in the High Elevation Floodplain River FPZ and High Himalayan River FPZ. In decreasing order of potential value (where higher numbers are greater potential value), median potential value of ecosystem services was 3.3 for the High Elevation Floodplain River FPZ, 17.5 for the High Himalayan River FPZ, 505.1 for the Braided River

FPZ, 4,245 for the Meandering River FPZ and 9,899 for the Low Elevation Floodplain River FPZ.

Five groups of potential values for ecosystem services emerged from an analysis of the cumulative distribution of potential values; Group 1: 15-18, Group 2: 19-30, Group 3: 30-53, Group 4: 54-132 and Group 5: >132, where higher numbers represent greater potential value. The spatial distribution of these groups varied across the Koshi River Basin drainage network (Figure 2.6). In terms of length, Group 5 occupied 2,015 km or 35% of the river network and was the dominant potential value. This was followed by Group 2 (1,987 km or 34%), Group 1(1,110 km or 19%), Group 3 (355 km or 6%) and Group 4 (303 km or 5%). However, in terms of riverine landscape area, 51% of the riverine landscape was occupied by Group 2, followed by Group 5 (23%), Group 1 (22%), Group 3 (2%) and Group 4 (2%).

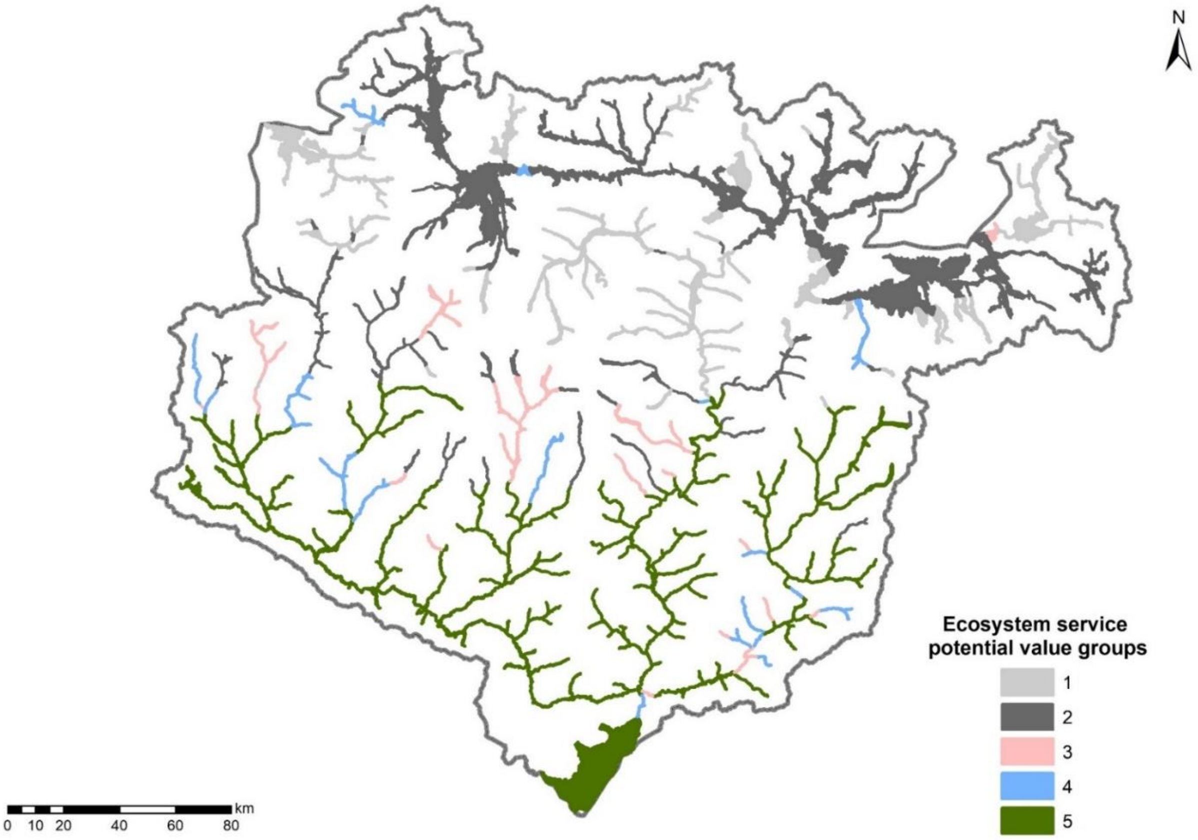


Figure 2. 6. The distribution of the potential value of ecosystem services across the Koshi River basin. Groups are explained in the text but in general represent a continuum of lower (Group 1) to higher (Group 5) potential value.

The spatial distribution of the five potential value groups (Figure 2.6) shows Group 5 to be located predominantly in the lower elevation regions of the river network, and associated with the Low Elevation Floodplain River and Meandering River FPZs. In contrast, the lowest potential value of ecosystem services (Group 1) was located mainly in higher elevation regions of the basin in the High Himalayan River FPZ (Figure 2.6). Overall, the High Elevation Floodplain River FPZ was associated predominantly with Group 2. The Braided River and High Himalayan River FPZs were mostly associated with Groups 3 and 4. A broad pattern of increasing potential value in ecosystem services from the Tibetan Plateau through to the lowland regions of the basin is evident (Figure 2.6). However, there are areas of the river network that interrupt this general pattern suggesting a non-uniform distribution of the potential value of ecosystem services across the river network. Some potential value groups are repeated with distance along the river network in association with the distribution of FPZs in the river network. Thus, the similarity between the spatial distribution of FPZs and the ecosystem service potential value group was low, with a 15.85% similarity between the two for the Koshi River Basin drainage network.

2.6. Discussion

A foundational premise of river science is that the physical river template and associated biophysical processes are heterogeneous (Gilvear et al. 2016). Given the relationship between biophysical processes and ecosystem services, the supply of ecosystem services is not expected to be uniform throughout the river network. However, studies of flow dependent ecosystem services have not examined heterogeneity in the river template and have been reach or site based. This study of the Koshi River Basin has found a direct relationship between the heterogeneity of the river template and the supply, use and value of ecosystem services at the spatial scale of an entire river network. The approach of uncovering congruence between FPZs and ecosystem services in this river network is directly transferable to other river basins, regardless of their size. Knowledge of the heterogeneity in the supply, use and value of ecosystem services in a river network will support evidence-based decision-making about river conservation activities and the use of river resources. The findings of this study advance our knowledge of ecosystem services in riverine landscapes in three areas, each of which is discussed below.

2.6.1. Congruency between the physical template and ecosystem services

A unique assemblage of ecosystem services exists among the five FPZs of the Koshi River Basin. Significant statistical differences among all FPZs confirm the congruency between the physical template and the supply of ecosystem services. Similar congruencies have been shown to occur in terrestrial landscapes, namely for agricultural (Qiu et al. 2020; Rieb and Bennett 2020), forested (Grêt-Regamey et al. 2014) and urban systems (Haase et al. 2014; Qiu et al. 2017). In general, these terrestrial-based studies support the foundational tenet that ecosystem services are generated by biophysical processes (Potschin et al. 2016). Our study of the Koshi River Basin demonstrates that this congruence also occurs in riverine landscapes.

Landscape structure is a mediator of the supply of ecosystem services (cf. Tamy et al. 2016; Rieb and Bennett 2020). The review and meta-analysis of Mitchell et al. (2015a; 2015b) suggests landscape structure affects how ecosystem services are supplied across landscapes. Within riverine landscapes Thorp et al. (2010) hypothesized that large scale-hydro-geomorphological differences would influence the supply of ecosystem services. For example, floodplains are known hotspots that generate a wide range of ecosystem services such as fertile soils and carbon storage (Tockner and Stanford 2002). The importance of riparian and floodplain areas in supplying bundles of ecosystem services, at local spatial scales, has been shown by Tomscha et al. (2017), Van Looy et al. (2017) and Hornung et al. (2019). By comparison, river channel environments that experience extreme disturbances, from extended periods of drying or flooding, intermittently supply a limited array of ecosystem services (cf. Ruiz et al. 2021). Large-scale regional differences in hydro-geomorphology and the supply of ecosystem services are evident in the Koshi River Basin. The extensive floodplain ecosystems that characterize the Low Elevation Floodplain River FPZ, located in the Terai region, supply a greater number of ecosystem services compared to the other FPZs. This dominance is primarily from the enhanced supply of provisioning services (Figure 2.4). In contrast, the supply of provisioning services in the High Himalayan River FPZ is reduced (Figure 2.4), presumably because this FPZ is dominated by a high energy river channel system constrained within narrow bedrock-controlled valleys, with no floodplains and limited riparian areas. In contrast, the Meandering River and Braided River FPZs are less controlled by valley widths, and have some floodplain areas and a greater ability to supply provisioning services. Thus, regional scale differences in the physical template of the Koshi River Basin, as expressed by the presence of FPZs, are associated with variations in the supply of unique bundles of ecosystem services.

The influence of structure on biophysical processes is a function of landscape composition and location or place (Phillips 2018). In terms of riverine landscapes, composition can be represented as the number of FPZs, each with a different physical character or hydro-geomorphology; and, place is the position of FPZs within the stream network. Place factors, including climate and biological production, represent the local or regional environmental context. FPZs have been shown to have a non-uniform distribution along river networks (cf.

Thoms et al. 2018) and some FPZs repeat downstream. However, according to the Riverine Ecosystem Synthesis of Thorp et al. (2006; 2010), similar FPZs are considered to have equivalent biophysical features and processes, thus they may have equivalent ecosystem services regardless of place. In the Koshi River Basin, the two floodplain-dominated FPZs differ in terms of their ecosystem service assemblages. Overall, the Low Elevation Floodplain River FPZ supplies a greater number of provisioning (n=28) and cultural (n=9) ecosystem services compared to the High Elevation Floodplain Rivers FPZ (n=11 for provisioning services and n=4 for cultural services). In terms of provisioning services, only 40 percent were found in both floodplain FPZs. The main differences between the two floodplain FPZs relate to those provisioning services supplied by various vegetation communities and reflect the influence of broader environmental factors like elevation, temperature and photosynthetic activity (Mitsch and Gosselink 2015). The Tibetan region of the Koshi River Basin, with an average elevation of 4,380 m asl, has lower mean annual temperatures and a significant snow pack coverage compared to other regions of the basin (Dixit et al. 2009). All of these factors have the potential to limit the occurrence of certain floodplain vegetation communities and the ability to supply provisioning ecosystem services. Thus, not all floodplains are the same and the place is a factor influencing the ability to supply ecosystem services regardless of the type of FPZ or physical template.

Landscape heterogeneity – the spatial variation in the organization of components in a landscape – affects the supply of many ecosystem services (Rieb and Bennett 2020). Landscape heterogeneity influences ecosystem interactions and regulates ecosystem responses to extrinsic and intrinsic stressors (Turner and Gardner 2015), subsequently influencing the supply of ecosystem services. For example, Qiu and Turner (2015) show landscape heterogeneity affects the supply of hydrologic ecosystem services and explained surface-water quality conditions in the Yahara River, Wisconsin, USA. In the Yahara River catchment, surface-water quality was negatively correlated with percent cropland and positively correlated with the percent forest, grassland and wetland in the basin. In general, empirical and theoretical evidence indicates landscape configuration (e.g. distribution of land uses, the proximity of source and buffer ecosystems) mediates the transport of water and nutrients across agricultural landscapes (Kreiling et al. 2020), thereby affecting hydrologic ecosystem services (Qui and Turner 2015).

Heterogeneity is a feature of the physical template of riverine landscapes, as evident by the character and organisation of FPZs. The distribution of FPZs in the Koshi River Basin does not support the traditional clinal or gradient models of river system organisation. Rather there is a mosaic structure, as hypothesized by the River Ecosystem Synthesis (cf. Thorp et al. 2006; 2010). For example, the High Elevation Floodplains River was the dominant FPZ in the upper reaches of the Koshi River network. This FPZ transitioned into the ‘gorge like’ High Himalayan River FPZ, and eventually further downstream into the Low Elevation Floodplain River FPZ. Because of the relationship between the physical template and ecosystem services, there is also ‘mosaiced’ heterogeneity in the supply of ecosystem services. This occurs as the non–uniform distribution of ecosystem services across the riverine landscape of the Koshi River Basin. While the supply of ecosystem services was most abundant in the Low Elevation Floodplain River FPZ, the Braided River and Meandering River FPZs located in the mid sections of the basin were both abundant in terms of the supply of ecosystem services. Distinct zones of unique assemblages of ecosystem services exist across the riverine landscape of the Koshi River Basin. This knowledge is fundamental to improving management of the basin, especially for assessing the environmental impacts of future water developments and for the process of decision making around trade-offs.

2.6.2. The social – ecological riverine landscape

Heterogeneity of ecosystem service use is also a feature of the Koshi riverine landscape. Significant statistical differences in total relative use values among all FPZs infers congruency between the physical template and ecosystem service use. However, the character of heterogeneity in total relative use did not match that of ecosystem service supply. Ranking FPZs in terms of total relative use showed the Meandering River FPZ to have the strongest use followed by the Braided River FPZ, Low Elevation Floodplain River FPZ, High Himalayan River FPZ and the High Elevation Floodplain River FPZ. By comparison, the rank order for ecosystem service supply had the Low Elevation Floodplain River as the FPZ with the greatest supply followed by the Braided River FPZ, Meandering River FPZ, High Himalayan River FPZ and the High Elevation Floodplain River FPZ. There are two components of heterogeneity; compositional and configurational (Lovett et al. 2005). Compositional heterogeneity is the number, type, and abundance of spatial units in the landscape, whereas configurational heterogeneity is the spatial arrangement of those units (Lovett et al. 2005). Thus, a mismatch in configurational heterogeneity occurs between ecosystem service use and supply in the riverine landscape of the Koshi River Basin.

Studies assessing relationships between the supply and social demand (use) of ecosystem services have increased over the past decade (Bennett et al. 2021). Most are focused on agricultural landscapes. Regardless of the landscape, mismatches between ecosystem service supply and demand have been proposed to reflect the ability to access, receive and modify the benefits from ecosystems (cf. Hanna et al. 2020); community demographics and types of ecosystem service bundles available (Flotemersch et al. 2019); and, social preferences for particular bundles or individual ecosystem services (Martin-Lopez et al. 2012). Patterns of differential use of ecosystem services that emerge from diverging social preferences toward ecosystem services will influence configurational heterogeneity of ecosystem service use.

Differences in the relative use of bundles of provisioning, regulating, supporting and cultural ecosystem services occur among FPZs, regardless of whether the ecosystem services may be present in multiple FPZs. Overall, the relative use of provisioning and cultural services was dominant in the Meandering River FPZ while regulating and supporting services were dominant in the High Himalayan River FPZ, compared to other FPZs (cf. Figure 2.5). In addition, differential use of individual ecosystem services occurred within FPZs, and this differed among FPZs. In terms of provisioning ecosystem services, despite being more abundant in the Low Elevation Floodplain River FPZ (n=28) compared to other FPZs (n= 11, 12, 25, and 26 for the High Elevation Floodplain River, High Himalayan River, Meandering River and Braided River FPZs, respectively) actual use was dominated by those individual services associated with agricultural activities. In the remaining FPZs, all provisioning ecosystem services were used in similar proportions, with an enhanced total relative use. Thus, social factors influence on the heterogeneity of relative use of ecosystem services.

The concept of value is central to the science and practice of managing riverine landscapes (Gilvear et al. 2016). Despite a well-developed body of theory and evidence that explores concepts of value in different ways across different disciplines and landscapes, our knowledge of the value of ecosystem services within riverine landscapes is limited (Basak et al. 2021). A degree of congruency was also observed between the physical template and ecosystem service value. Differences in potential value were only recorded between the two FPZs. As result, there was a marked simplification of the configurational and compositional heterogeneity of the potential value of ecosystem services compared to the heterogeneity of the relative use and supply of ecosystem services.

Valuation of ecosystem services has primarily been conducted within the context of the economic value of these services to society (Costanza et al. 1998). Economic analyses can be hindered by limited data, especially in remote regions like the Himalayas. The approach taken in this study is similar to the contingency analysis of Castro et al. (2011) and relies on the availability and relative use of ecosystem services as well as demographic information – the transfer of benefits to society. Given the spatial demography of the Koshi River Basin, we would expect heterogeneity in the value of ecosystem services to reflect basic demographic patterns, with enhanced ecosystem values in the Low Elevation Floodplain River FPZ and those river valleys with easy access such as the Meandering River and Braided River FPZs. Overall, our findings show marked differences between the upper and lower regions of the Koshi River Basin. Higher ecosystem service values in the lower regions of the basin reflect the greater supply, use and population using these services compared to the upper regions.

Riverine landscapes are coupled and complex social–ecological systems (Pingram et al. 2019; Weigelhofer et al. 2021). Congruency between the physical template and the supply, use and value of ecosystem services provides evidence for this coupling. The Koshi River Basin is a ‘green-loop’ system (cf. Cumming et al. 2014) characterized by the direct dependence of mostly agricultural communities on local flow-dependent ecosystem services providing benefits to people within the Koshi River Basin. The majority of communities are centred on the riverine landscapes of the basin. However, the differential patterns of ecosystem service heterogeneity highlight the character of the coupling between the natural and human sub-systems. The supply of ecosystem services reflects the primacy of the physical template. However, the place or location of FPZs and their associated ecosystem services, social values of associated bundles of ecosystem services and demography have a marked and differential influence on the use and value of the ecosystem services. These spatial differences between supply, use and value are also indicative of a developing coupled agricultural or ‘green loop’ social – ecological system (cf. Hamann et al. 2015).

2.6.3. Riverine landscapes as Complex Adaptive Systems – a model for the Koshi River Basin

The social – ecological landscape of rivers is increasingly conceptualised as a complex adaptive system by virtue of its hierarchical organisation and ability to adjust multiple forms to an array of physical, ecological and social processes (Thoms and Sheldon 2019). Identifying and understanding the various interactions between biophysical and social drivers, processes, and interrelated states that comprise social – ecological riverine landscapes is challenging. Conceptual models aid in understanding this complexity. Flow chain models demonstrate interactions between various components of complex adaptive systems at multiple spatial scales. Flow-chain models have been used to demonstrate the efficiencies of environmental flow regimes on the biophysical processes (Yarnell and Thoms, 2022) and the ecological concept of disturbance in urban river systems (Grimm et al. 2017). Flow-chain models have four basic components representing the interplay of biophysical and social characteristics in riverine landscapes. *Drivers* are the main agents of change; *functions* are a series of controllers or processes that are governed by the agents of change; *templates* are those surfaces (both abiotic and biotic) upon which drivers and functions act; and, finally there are a series of *responders*. Responders can be sets of processes or actors that are parts of the social-ecological environment present across the riverine landscape.

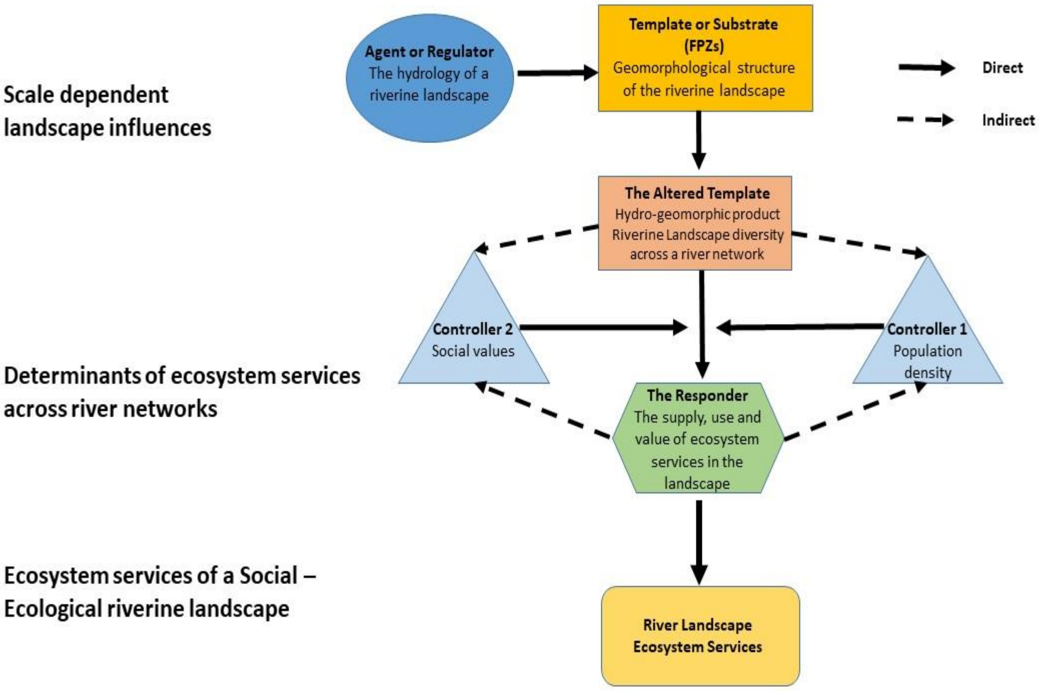


Figure 2. 7. A flow-chain model for describing process interactions and the character of ecosystem services across riverine landscapes. The flow-chain model has four basic components: the abiotic or biotic agent or regulator of change, or driver; the template or substrate upon which the driver acts; controllers of the driver or agent of change; and an entity or process that responds to the driver or agent of change. Responders can be sets of processes, ecosystem services, organisms, or parts of the physical environment.

A flow chain model of the Koshi River Basin (Figure 2.7) shows the supply, use and value of ecosystem services of the riverine landscape to be the product of multiple biophysical and social interactions. The flow regime is the main driver that acts upon the geomorphological structure of the riverine landscape, and this can be expressed as Functional Process Zones with similar hydrogeomorphic characteristics. The output of this interaction directly influences the assemblage of ecosystem services that can be supplied by the riverine landscape - the type, abundance and position in the network (cf. Thoms et al. 2018).

Controllers, such as population density, social values, and geographic location or place, influence the supply, use and value of ecosystem services in the riverine landscape. Controllers interact via a series of feedbacks between the supply of ecosystem services and their use and value. Overall, this framework helps to understand the complex relationships between flow, the physical template (ecological) and ecosystem services (social) within coupled social-ecological riverine landscapes.

The flow chain representation of the interactions between the physical template and ecosystem services is a heuristic model of the Koshi River Basin riverine landscape. Like any landscape model, there are limitations, and it could be improved with additional data. While our study was fortunate to have ecosystem service data for all FPZs identified in the basin, data were not available for all individual FPZs. This is especially important in mountainous regions where access can be restricted. Understanding variations among similar FPZs located in different regions of the basin is important for considering finer level interactions between the physical template and ecosystem services. Variations in data availability were also noted across the four ecosystem service groups. Provisioning and regulating services (Table 2.2, Figure 2.4) dominated the ecosystem services for the Koshi River Basin. This may reflect bias in the sampling design. However, the distribution among the four ecosystem service types in the Koshi River Basin is similar to that reported from other studies in different geographic regions (cf. Bennett et al. 2009; Burkard et al. 2009; Ezenwaka and Graves, 2014; Kamlun and Arndt, 2019). In the Koshi River Basin, the contribution between the four ecosystem service types was 51.8, 26.8, 5.4 and 16.1% for provisioning, regulating, supporting and cultural services respectively compared to the mean across nine other studies of 40, 29, 20 and 11% respectively. This may suggest that our sampling of ecosystem services across the four types was sufficient.

2.7. Summary

The Himalayas are a biodiversity hotspot (Chettri et al. 2008) identified as a global conservation priority region (Brooks et al. 2006). The Koshi River Basin is a large river system draining the Himalayas and home to >40 million people, many of whom depend on the ecosystem services of its riverine landscape. The supply of ecosystem services (e.g., supporting, provisioning, regulating, and cultural) provided by the riverine ecosystems contributes to the wellbeing of the populations that reside in the basin and the basin communities further downstream in India. Despite the multi-dimensional (ecological, socio-cultural and economic) importance of ecosystems to human society, there have been limited efforts to assess the provision of ecosystem services in the riverine landscape of the Himalayas. Efforts to manage flow dependent ecosystem services must be cognizant of the physical template and social interactions in controlling the spatial distribution across riverine landscapes.

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Chapter 3: Future climate and its potential impact on the spatial and temporal hydrological regime in the Koshi Basin, Nepal.

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The Himalayan River is composed of baseflow, snow and glacier melt during winter season.

Source: Lisa Owen (2017)

MANUSCRIPT INFORMATION PAGE

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3.1.Abstract:

Study region:

Koshi River basin, Eastern Nepal.

Study focus:

Climate change is increasingly evident as the global surface temperature is warming with erratic rainfall patterns across the globe. In this regard, the Koshi Basin in the Himalayan region is also impacted, and it is important to understand the spatio-temporal details of the impact in the basin under future climate change. This study assessed the potential climate change and its impact on the hydrological regime using the Soil and Water Assessment Tool (SWAT) and Indicators of Hydrological Alteration (IHA) based on RCP4.5 and RCP8.5 of ensemble downscaled CMIP5 GCM runs.

New hydrological insights for this region:

Results show the upper part of the basin warming faster than the lower part, the pre-monsoon season warming more than other seasons. There is no clear uniform trend in precipitation. However, the south-eastern part of the basin will get more precipitation. Sub-basins will get more precipitation during the post-monsoon under RCP4.5, and during the monsoon under RCP8.5. The annual water availability will not decline but water availability within seasons and regions is shown to be highly variable. There is also a change in the spatial pattern of river discharge and the western part of the basin is likely to experience more impact. Therefore, these findings will be valuable in identifying how particular sub-basins within the Koshi Basin will be impacted by climate change and in stipulating effective planning and management of water resources for the future.

Keywords: Climate change, hydrological regime, Koshi Basin, RCP 4.5 and 8.5

3.2.Introduction

The Himalayas are one of the world's regions that are highly sensitive to changing climates (Yao et al., 2019). There is a noticeable increase in temperatures in the Himalayas, higher than the global average with an increase in erratic rainfall patterns (Sharma et al., 2019). The area has warmed by around 1.8 °C over the past half-century, considerably higher than the warming rates for the Northern Hemisphere and the global mean (Yang et al., 2014; Kang et al., 2010; Liu and Chen, 2000). Seasonal and annual temperatures have also risen in higher-elevation areas across the Himalayas (Yao et al., 2019; Liu and Chen, 2000). This fast warming has had a great effect on the Himalayan environment and most noticeably in the rapid retreat of Himalayan glaciers and shrinking snow areas (Kulkarni et al., 2013). Similarly, earlier studies have reported that Hindu-Kush Himalayan (HKH) region and Tibetan Plateau have experienced a significant change in precipitation events over the past decades (Zhan et al., 2017). However, some studies have revealed a significant change in recent extreme precipitation events in some regions of the HKH (Zhan et al., 2017). These changes in the temperature and precipitation ultimately affect the volume and timing of river flows. More broadly, climate change has notably altered the hydrological cycle, the shift in snowline, water availability, water balance, and flow regime and soil moisture in the Himalayan region.

Temperature is one of the vital factors and also the most sensitive parameter in climate science. An ongoing temperature analysis conducted by scientists at NASA reported the average global temperature on earth has increased by about 1.1 °C since 1880 (Source: https://earthobservatory.nasa.gov/world-of-change/global-temperatures). In addition, the global annual average temperature rises by 1 °C in 2016 and 0.98 °C in 2020 resulting in the first and second warmest year since 1880 (NOAA, 2021). Looking at the rate of change, it can be projected that there is likely to be an ongoing significant increase in temperature in the

Himalayan region in the future. Earlier studies indicate projected temperature change, but those changes might vary according to space and time in terms of magnitude and rate of change (Kulkarni et al., 2013; Knutti and Sedláček, 2013; Lutz et al., 2016a). For instance, Kulkarni et al. (2013) highlighted that warming was projected to rise by 4.6°C in Western Himalayas, 4.3°C in Central Himalayas and 4.1°C in Eastern Himalayas by 2100. As far as the Koshi Basin, the mean temperature is likely to increase by 4.6°C under RCP4.5, while 7°C under RCP8.5 by 2100 (Kaini et al., 2019).

Precipitation in the Himalayan region is most affected by the Indian summer monsoon as well as the winter westerlies precipitation and varies according to space and time. The monsoon decreases from southeast to northwest whereas the influence of the westerlies decreases from west to east (Nie et al., 2021). Precipitation is the major freshwater contribution to the hydrological system in the Himalayan region (Perry et al., 2020). Kulkarni et al. (2013) showed that Indian summer monsoon precipitation is likely to increase by 20–40% at the end of this century. In the Koshi Basin, most studies project that rainfall is likely to increase during the monsoon and decrease during winter, while the increase is likely to be more in the southern part compared to the northern part (Kaini et al., 2019; Rajbhandari et al., 2016). Furthermore, there is likely to be an increase in the future frequency and intensity of extreme precipitation events, for instance, the number of dry days, consecutive dry days, and very wet days. Overall, several studies suggest that the irregularities in precipitation are expected to increase in the coming periods (Kulkarni et al., 2013; Immerzeel et al., 2012; Krishna et al., 2011; Jeelani et al., 2012).

Projected changes in the temperature along with precipitation patterns and intensity are likely to change river flow regimes resulting in flow variability and uncertainty in water availability (Dixit et al., 2009). The visible impact of climate change is even more palpable in the upstream part of the Himalayan region (Immerzeel et al., 2010; Viviroli et al., 2007).

However, the response of changing climate to river flow is likely to differ within the basins of the Himalayas due to the source of runoff and hydrological processes varying by location and season (Immerzeel et al., 2012). For instance, the runoff is governed by snow and glacier melt in most of the upper part of the Himalayan basin whereas the runoff in the lower part of the basin is governed by rainfall and groundwater with minimal contribution of snow and glacier melt. Climate change is likely to impact the long-term monthly, seasonal, and annual flow of rivers together with changes in the timing of peak flow and variability of high and low river flows under future climate scenarios (Stagl and Hattermann, 2016). Thus, changes in river flows have an important impact on water such as water availability, irrigation, flood management, and overall water resources planning. Furthermore, changes in water availability can affect the water-dependent ecosystem and its associated services (hydropower, fisheries, irrigated agriculture etc.) which will influence many people's livelihoods depending on riverine ecosystem services. The Koshi Basin is one of the most populated basins in Nepal where the livelihood of these communities is mainly dependent upon the hydrological regime and its associated river ecosystem services. Studies suggest that there are likely to be considerable impacts on water resources with severe consequences for the livelihoods of communities in the Koshi Basin due to climate change projection (Macchi and ICIMOD, 2010; Bhatta et al., 2015). Thus, there is an urgent need to understand the potential climate change and its impact on the hydrological regime in the Koshi River basin.

The Koshi Basin is characterized by extreme topographic and climate heterogeneity. The orography (mountain land altitude) and lapse rate (the rate at which air temperature falls with increasing altitude) in the Koshi Basin differ vastly across the sub-basins, from the southern plains to the northern Himalayas as well as from the eastern to the western region of the basin. This means the regional differences in climate in the Koshi Basin. Thus, changes in climate and their impacts will vary across the sub-basins of the Koshi Basin as well as regional differences in the response of flow in the basin. Detail regional studies highlighted that Himalayan regions are likely to experience noticeable climate change with an increase in temperature and erratic rainfall that will lead to significant hydrological changes but what is unknown is how much of a spatio-temporal impact Koshi Basin will have in future in terms of climate change as well as what will be the response of the hydrological regime to this changing climate. In this regard, the major consequences of climate change will depend on the temporal and spatial scales. Therefore, we hypothesize that the impacts of climate change are scale-dependent, and impacts are likely to be highly variable depending on temporal (intra-seasonal) and local spatial scale rather than being uniform across the entire basin and on an annual scale. Furthermore, most climate change studies to date have considered the Koshi Basin as an entirety (MoFE, 2019) as well as only occasional consideration of future climate change scenarios up to 2100 including comparisons among different sub-basins. Therefore, spatiotemporal impact assessment and comprehensive multi-scale assessments are needed to understand the nature and extent of the expected climate change as well as the response of the hydrological regime and that’s what this paper is all about.

3.3.Data and methods

3.3.1. Study area

The Koshi Basin is a lifeline for local inhabitants because it provides fresh water for household use, irrigation, farming, and livestock (Shrestha et al., 2016). The basin has a large potential for hydropower development and plays a key role in the irrigation of downstream areas. It contains rich biodiversity and is a source of valuable ecosystem services that directly sustain the lives and livelihoods of the 40 million basin residents, including the population in the Indian part of the basin (Wahid et al., 2017). It is a transboundary basin shared by China, Nepal and India. In this study, we included only the Chinese and Nepalese parts until the

Koshi River flows into the plains (Figure 3.1). It has a catchment area of 55,930 km^2 at Nepal – India border, of which approximately 51% is in China and 49% in Nepal. The river originates in the Tibetan Plateau, passing across eastern Nepal and ultimately joining the Ganges. Within the basin, the elevation varies from about 65 m in the southern region to 8848 m (Mount Everest peak) in the northern regions above the mean sea level. The slopes in the basin range from 0° in the south to 84° in the north (Mishra et al., 2019). This variation in elevation results in vastly different climatic zones, from humid tropical in the lower plain area to arctic in the high Himalayas (Dixit et al., 2009). In the Nepalese section, there are four distinct climatic seasons: winter (December–February), pre-monsoon (March-May), monsoon (June–September) and post-monsoon (October–November). The Koshi River basin is comprised of six major physiographic zones – the Tibetan Plateau, High Himalaya, High Mountains, Middle Mountain, Siwalik, and Terai; each with unique geology, topography and climate.

The Koshi Basin is characterized by extreme topography, climate heterogeneity and seasonal flow variability. The orography and lapse rates of the Koshi Basin differ vastly within the basin (Pandey et al., 2020a). Furthermore, the basin is influenced by two synoptic circulation systems i.e, easterlies (South Asian monsoon precipitation) during summer and westerlies (winter precipitation) during winter. The climate in the southern part of the basin is strongly influenced by the South Asian monsoon, whereas the northern part of the basin (Tibetan Plateau) lies in a rain shadow area. As a result, precipitation varies from 207 mm per year in the trans-Himalaya region to 3000 mm per year in the eastern mountains (Shrestha et al., 2017). Winter precipitation plays a vital role in the accumulation and melt of snow and ice. About 80% of the precipitation occurs in the monsoon season, intense with large local variation because of orographic effects (Kaini et al., 2019). A large southern part of the basin in Nepal receives an average annual precipitation of about 1,800 mm (Bhatt et al., 2014). The upper part of the basin contains a huge amount of snow and glacier as a freshwater reserve (Shrestha et al., 2017). The total glaciated area in the basin was 2984 km^2 with an estimated ice reserve of 295 km^3 and the total snow cover area was 5458 km^2 (Khadka et al., 2016; Bajracharya et al., 2011). The annual average discharge in the Khurkot hydrological station at Sun Koshi is 469 m^3/s and in the Chatara hydrological station at Sapta Koshi is 1545 m^3/s (Sinha et al., 2019).

The elevation variation within the basin is very sharp within a short areal distance, from 65 - 300 m a.s.l. in the southern plains, to 100 – 300 m a.s.l. in the foothills of the Siwalik region, while the middle mountain region has steep slopes and deep-cut valleys with an elevation of 1,000 - 3,000 m a.s.l. The northern Himalayas with elevations above 3,000 m a.s.l. up to 8848 m a.s.l., is generally above the snow line (Dhital, 2015). Temperature varies considerably in the basin according to elevation. The northern part of the basin is very cold with temperatures reaching -19°C (Dingri meteorological station) in winter and the southern lower part of the basin is very warm with the temperature reaching 45°C (Rajbiraj meteorological station) in summer. The mountains record the maximum temperature in May, while the southern plains (Terai) reach the maximum in April. The annual evapotranspiration (ET) rates are generally less than 1,000 mm. However, some parts of the basin such as Sun Koshi have extremely high potential evapotranspiration and suffer from frequent droughts and soil erosion (Wahid et al., 2017).

There is also a diversity of land-use across the basin. There is a clear dominance of grasslands (40.34%), followed by native forests (24.45%), and then agriculture (12.45%). Other land-use types include barren land (11.26 %), snow/ glaciers (9.45%), shrubland (1.52%), natural water bodies (0.5%), and urban areas (0.03%) (Uddin et al., 2015).

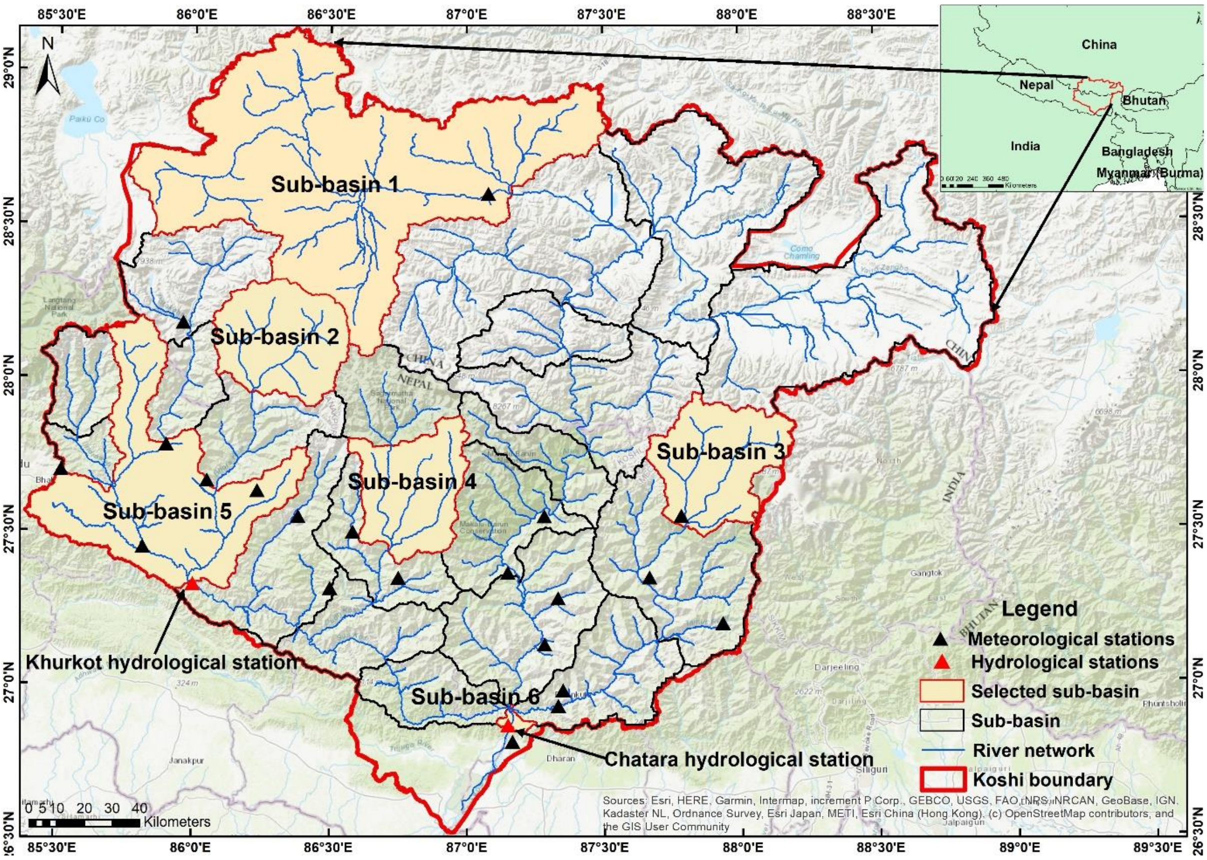


Figure 3. 1. Location map and location of used hydrological and meteorological stations in the Koshi Basin, with the six sub-basins covered in this study.

3.3.2. Observed and historical data

Climate data (temperature and precipitation) in Nepal was collected from the Department of Hydrology and Meteorology (DHM), Nepal. Additional climate data from Nielamu and Dingri stations within the Chinese part of the Koshi Basin was acquired from the Tibet Meteorological Bureau. The network of temperature, precipitation and hydrological stations used in the SWAT model is given in Figure 3.1. Overall, daily data for the period of 1981 to 2010 from 11 temperature stations, 21 precipitation stations, and 2 hydrological stations (Khurkot and Chatara) was used in this analysis. The land use data for 2010 at a 30m resolution was obtained from International Centre for Integrated Mountain Development

(Uddin et al., 2015). The soil data was obtained from the Soil and Terrain Database Programme (SOTER) (Dijkshoorn and Huting, 2009). SRTM DEM of 90m×90m resolution was used to delineate the watershed in the model.

3.3.3. Future climate scenario for the basin

For this study, we used a 10 km resolution future climate scenario dataset developed by Lutz et al. (2016a) for the Indus, Ganges, and Brahmaputra (IGB) domains as a part of the Himalayan Adaptation, Water and Resilience (HI-AWARE) project. In this dataset, the GCMs were tested using AR5 data downloaded from the CMIP5 model archive. In total 94 GCMs were tested for Representative Concentration Pathway (RCP) 4.5 and 69 for RCP8.5 (Lutz et al., 2016b). This ensures that the entire range of possible future climates in terms of temperature and precipitation change is included. For each model run, the normal annual difference in temperature and precipitation for future 2071-2100 climate conditions over a reference period 1971-2000 was determined in terms of temperature anomaly (ΔT) and percentage change of precipitation (ΔP), respectively (Lutz et al., 2016b). Based on the 10th and 90th percentile values of these projected changes, four combinations of climatic conditions – dry and cold, dry and warm, wet and cold, and wet and warm – were derived for each RCP. Finally, the model runs that were closest to the percentile values were selected to be included in the model ensemble used for the climate change impact study as well as the percentile values were used to avoid outlier GCMs, which are likely to be unreliable (Rajbhandari et al., 2016). Finally, eight GCMs were selected (Table 3.1), four for RCP4.5 and four for RCP8.5 based on the average annual response, changes in extreme behaviour in precipitation and temperature as well as validation of model performance to climatic reference data. These climate models cover a wide range of possible futures and are also able to replicate the most important processes in the region (Lutz et al., 2016b).

Overall, the following methods were used for the selection of climate models which perform better for the IGA domain (Lutz et al., 2016 a, b)

1) The initial selection of the climate model from the entire pool of climate models is based on changes in mean air temperature and annual precipitation mean sum.
2) Refined selection based on the projected change in four indices for climatic extremes.
3) Final selection based on model skills in simulating the annual cycle of temperature and precipitation.

The selected climate scenario data was statistically downscaled and bias-corrected using the quantile mapping (QM) method. The bias-corrected data was downscaled to 10 x10 km spatial resolution by applying bilinear interpolation. The downscaled climate scenario data from Lutz et al. (2016a) can be downloaded from http://rds.icimod.org/clim. For a detailed description of model selection, statistical downscaling and bias correction method of climate data, readers are suggested to refer to Kaini et al. (2019), MoFE, (2019), Trzaska, S. and Schnarr, (2014) and Lutz et al. (2016a,b). The Koshi River basin is a part of the Ganges Basin and Lutz et al. (2016a) dataset was clipped by our study area for climate change analysis.

The selected eight GCM data were used to prepare an ensemble average of the four GCMs for each RCP4.5 and RCP8.5. This provided two ensemble average data, each one for RCP4.5 and RCP8.5. These average ensemble data were prepared for daily time steps for analysis. An ensemble average can reduce the overall uncertainty in model predictions (Pandey et al., 2019). Among four RCPs, we used only two RCPs: i) extreme RCP8.5 which assumes the increased radiative forcing will stabilize at 8.5 W/m^2 in 2100 and ii) medium stabilization scenario, RCP4.5 considers stabilization at 4.5 W/m^2 in 2100. We chose not to include RCP2.6 in the climate model ensemble because robust, realistic climate change scenarios are required to support adaptation planning, as RCP2.6 requires that carbon dioxide (CO_2) emissions start declining by 2020 and go to zero by 2100 which is highly unlikely. Furthermore, we excluded RCP6 scenarios too because the range of changes from RCP4.5 and RCP8.5 scenarios covers the entire range of radiative forcing resulting from RCP4.5, RCP6 and RCP8.5 (Lutz et al., 2016b). Table (3.1) shows the chosen climate model used for the study.

Table 3. 1. Selected climate models and scenarios as part of a study done by Lutz et al. (2016a).

RCP	Projected Climate Conditions	Selected GCM
RCP4.5	Warm, dry	CMCC_CMS r1i1p1
	Warm, wet	CSIRO-MK3-6.0_r4i1p1
	Cold, wet	BNU_ESM r1i1p1
	Cold, dry	inmcm4_r1i1p1
RCP8.5	Warm, dry	CMCC_CMS r1i1p1
	Warm, wet	CanESM2 r3i1p1
	Cold, wet	bcc-csm1-1 r1i1p1
	Cold, dry	inmcm4_r1i1p1

The climate change impact over the sub-basins was investigated by using future climate scenario data up to 2100**.** We used the GCM climate dataset 1995s (1981 -2010) as the reference data period and 2025s (2011-2040), 2055s (2041-2070), and 2085s (2071 -2100) as the projected future data period covering 30 years to determine the change in climate as well as its response on hydrology between the reference and future projection in the Koshi Basin.

3.3.4. Uncertainty Analysis for future climate projections

There will always be some degree of uncertainty in future climate projections because of the different representation of atmospheric processes in the GCMs and the development of future socio-economic pathways. As well as a lack of understanding of atmospheric processes and observation, limitations in the structure of GCM models and highly variable simulation uncertainty also contribute to the overall uncertainty in projection scenarios. Considering these uncertainties in climate change projections is important for decision-making and developing adaptation strategies (MoFE, 2019). The uncertainties in the future projections can be understood using responses among the selected models and the RCPs (Change, 2014)

In this study, uncertainty analysis for precipitation and temperature projections was carried out based on the following approaches.

1) The uncertainties are represented by the responses among the models for RCP4.5 and RCP8.5.
2) The uncertainties are represented by the inter-quantile range among the models for RCP4.5 and RCP8.5 for the different time periods.
3) Agreement on decrease or increase in the change of climate variables among multiple models compared to the reference period.

3.3.5. Hydrological modelling

The hydrological model SWAT (Winchell et al., 2013; Arnold et al., 1998) was used to simulate the hydrological processes under present and future climate conditions. It is the combination of the basin-scale model with GIS (Srinivasan and Arnold, 1994) and uses spatial data (soil type, land cover/land use and elevation) and temporal data (climate data) to represent the hydrological performance of the heterogeneous catchments. It is a complete model incorporating surface land and channel environmental processes as well as combining studies of water quality, water quantity and climate change. It is capable of simulating hourly, daily, monthly and yearly data over long periods (Picchio et al., 2020).

The final outlet was defined at the Chatara hydrology station to delineate the sub-basins of the Koshi River Basin (Figure 3.1). This resulted in the creation of 27 sub-basins and 35 hydrological response units (HRU). HRU is the smallest unit of the basin and is a combination of unique soil types, land features, and slope classification (Shrestha et al., 2016). From 27 sub-basins, we selected only six sub-basins 1, 2, 3, 4, 5 and 6. These sub-basins were spatially distributed in the Koshi Basin from east to west and north to south, where sub-basin 1 is the northern sub-basin; 2 is the western sub-basin; 3 is the eastern sub-basin; 4 is the central sub-basin; 5 is the southwestern sub-basin, and 6 is the southeastern sub-basin in the lower outlet in Koshi (Figure 3.1). The reason for selecting these sub-basins compared to other sub-basins was based on the criteria of influence of monsoon (east to west and south to north precipitation gradients) and the criteria of influence temperature variability (north to south). As well as these sub-basins represent the trans-Himalayan, high Himalayas, middle mountain and southern plain - the physiographic region of the basin. Most sub-basins where no observation and monitoring stations are excluded from analysis and reporting. For instance, the northern part of the sub-basins (Figure 3.1).

Elevation bands were created to model the process of snowmelt and orographic distribution from temperature and precipitation in SWAT. The model generates the elevation band automatically based on the area coverage percentage. An elevation band helps in discretizing the topographic influence of temperature and precipitation on snowmelt and discharge (Bajracharya et al., 2018). Each sub-basin in the model was divided into ten elevation bands, and each band was assigned a mean elevation and area coverage percentage. The SWAT model applies the following mass balance equation (Arnold et al., 1998) to simulate the hydrology within a sub-basin:

$$SW_t = SW_0 + \sum_{i=1}^{n} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \tag{1}$$

Where SW_t: soil water content at time step t, SW_0: initial soil water content, R_{day}: daily precipitation, Q_{surf}: runoff, E_a: evapotranspiration, w_{seep}: percolation, and Q_{gw}: groundwater flow.

To accommodate the snowmelt (i.e., melted water from snowfall and snow cover) dynamics in the hydrological analysis, SWAT classifies precipitation as rain or snow by comparing the mean daily temperature with the user-defined air temperature threshold. The snowmelt in SWAT is calculated as a linear function of the difference between average snowpack-maximum air temperature and snowmelt threshold temperature by using the following formula (Neitsch et al., 2011):

$$SNO_{mlt} = b_{mlt} SNO_{\mathrm{cov}} \left[\frac{T_{snow} + T_{\max}}{2} - T_{mlt} \right] \tag{2}$$

Where SNO_{mlt}: daily snowmelt amount (mm), b_{mlt}: daily melt factor (mm/day C), SNO_{cov}: the fraction of HRU area covered by snow, T_{snow}: daily snowpack temperature (°C), T_{max}: daily maximum air temperature, and T_{mlt}: the optimum temperature for snowmelt (℃).

3.3.6. Evaluation of the Performance of the SWAT Model

Model evaluation is essential to measure the consistency of its output. It is considered reliable if the evaluation statistics fall within an acceptable limit (Moriasi et al., 1983). Accordingly, a model is considered suitable for monthly river flow simulation, if Percent Bias (PBIAS) is within ±15% and Sutcliffe Simulation Efficiency (NSE) is above 0.75 (Bajracharya et al., 2018). We calculated the PBIAS, NSE, and Coefficient of Determination (R^2) to verify our SWAT results. The SWAT model was calibrated and validated at two points: the Khurkot hydrological station on Sun Koshi River which is the tributary of the Koshi River and the Chatara hydrological station on the Sapta Koshi which is the main outlet of the Koshi Basin (Figure 3.1). SWAT was calibrated for 1986 to 1994 and validated for 2000 to 2008 at Khurkot hydrological station, Furthermore, SWAT was also calibrated for 1986 to 2001 and validated for 2002 to 2010 at Chatara hydrological station on a daily scale. The following suggestion was made by Fontaine et al. (2002), we used a warm-up period of 5 years for calibration to develop suitable initial conditions for groundwater and soil water storage.

The model was calibrated by using SWAT-CUP (Abbaspour, 2013). SWAT-CUP enables sensitivity analysis, calibration, validation and uncertainty analysis of SWAT models. Calibration parameters were based on literature review, volume, baseflow and adjustment of peak flows. During calibration, lapse rate, water capacity of the soil layer, SCS runoff curve number, Manning N, and snowmelt were found to be the most sensitive parameters. The temperature lapse rate was adjusted to 5.6°C/km based on Khadka et al. (2014). The SCS curve number varied from 40 to 90 based on land use type. The Manning N for the main channel was calibrated from 0.03 to 0.06. Snowmelt parameters, such as snowfall temperature and minimum snowmelt rate, were adjusted to the values of 0ºC and 7mm/ºC-day, respectively (Bajracharya et al., 2018).

The calibrated and validated SWAT model was forced with historical ensemble climate variables from the period of 1981-2010. The discharge obtained from the simulated SWAT model for this period was treated as baseline data to evaluate changes in future flow.

3.3.7. Capabilities and Limitations of the SWAT Model

For a heterogeneous river basin like the Koshi, it requires calibrating and validating the model if not for every sub-basin but for a cluster of sub-basins or large watersheds to simulate a reliable result. The key difficulty of calibrating and validating a hydrological model developed in a river basin like Koshi with limited data availability is the absence of observed streamflow data. Due to the unavailability of observed data and accurate information on snowmelt and glacier melt in the high Himalayan areas of Tibet and Nepal, results may have limitations. Even though the model performs all its estimates at a very small areal unit, the model has not been built and calibrated to simulate small catchments. Furthermore, SWAT's snow/glacier component is relatively weaker than the rainfall-runoff component (Pandey et al.,2020b; Bharati et al., 2019) Thus, the use of other snow/glacier models is recommended, if these components are important and need to be analyzed in detail (Adnan et al., 2019; Bharati et al., 2019).

However, the model was capable to reproduce or capture reasonably the hydrograph patterns, average flow conditions, high flow conditions, and flow duration curves in the Koshi Basin. The calibration and validation statistics based on available data, mostly downstream, show the satisfactory performance of the SWAT model in Khurkot and Chatara (the hills and Terai of Nepal) hydrological stations, and the results obtained from these stations can be confidently used for further activities. Our results are in line with earlier studies done in the Koshi Basin (Bharati et al., 2014, 2016, 2019; Devkota and Gyawali, 2015; Kaini et al., 2021).

3.3.8. Indicators of hydrological alteration

The Indicators of Hydrological Alteration (IHA) version 7.1 tool (The Nature Conservancy, 2009) was used to calculate parametric statistics of flow components from daily time series river flow data as mentioned by Richter et al. (1996). In Parametric statistics, the assumption is that data are normally distributed, and the data are characterized by a mean and standard deviation. Parametric statistics with advanced calibration were used to compare reference period flow datasets (pre-impact) with future climate change scenario flow datasets (post-impact). The advanced calibration will involve adjusting up to four parameters i) the high flow threshold ii) the low flow threshold iii) the high flow starts rate threshold and iv) the high flow end rate threshold whereas non-advanced calibration only a single flow parameter the high flow threshold (The Nature Conservancy, 2009). This software can calculate a total of 67 statistical parameters. These parameters are subdivided into 2 groups: the 33 IHA parameters (median and coefficient of dispersion) corresponding to 5 fundamental characteristics of the flow regime (magnitude, frequency, duration, timing, and rate of change) and 34 Environmental Flow Components (EFC) parameters corresponding to 5 fundamental characteristics of the flow regime (extreme low flow, low flows, high flow pulses, small floods, and large floods). As per the suggestion made by Wijngaard et al. (2017), high and low flow indices are used to evaluate changes in hydrological extremes. Thus, we used only two components of flow i) extreme low flow and ii) large flood (high flow) out of five characteristics as hydrological extremes. An extreme low flow was defined as a flow value less than or equal to the 10th percentile of the daily average flows of the period and a large flood event was defined as an initial high flow with a peak flow greater than 10 years return interval event. In other words, future changes in the 90th percentile of daily discharge levels, and the discharge levels of high flow events with a return period of 10 years (Wijngaard et al., 2017). The software finds the flow value equal to or less than the 10th percentile of all annual minimum flow as well as the 90th percentile of all annual maximum flood peaks (Bharati et al., 2019; The Nature Conservancy, 2009; Mathews and Richter, 2007). For in-depth parameters and characteristics of the flow regime, readers are suggested to refer to the Indicators of Hydrological Alterations User’s Manual (The Nature Conservancy, 2009). Overall, the method for a systematic approach for investigating climate change and its potential impact on the hydrological regime in the Koshi River basin is presented in Figure 3.2.

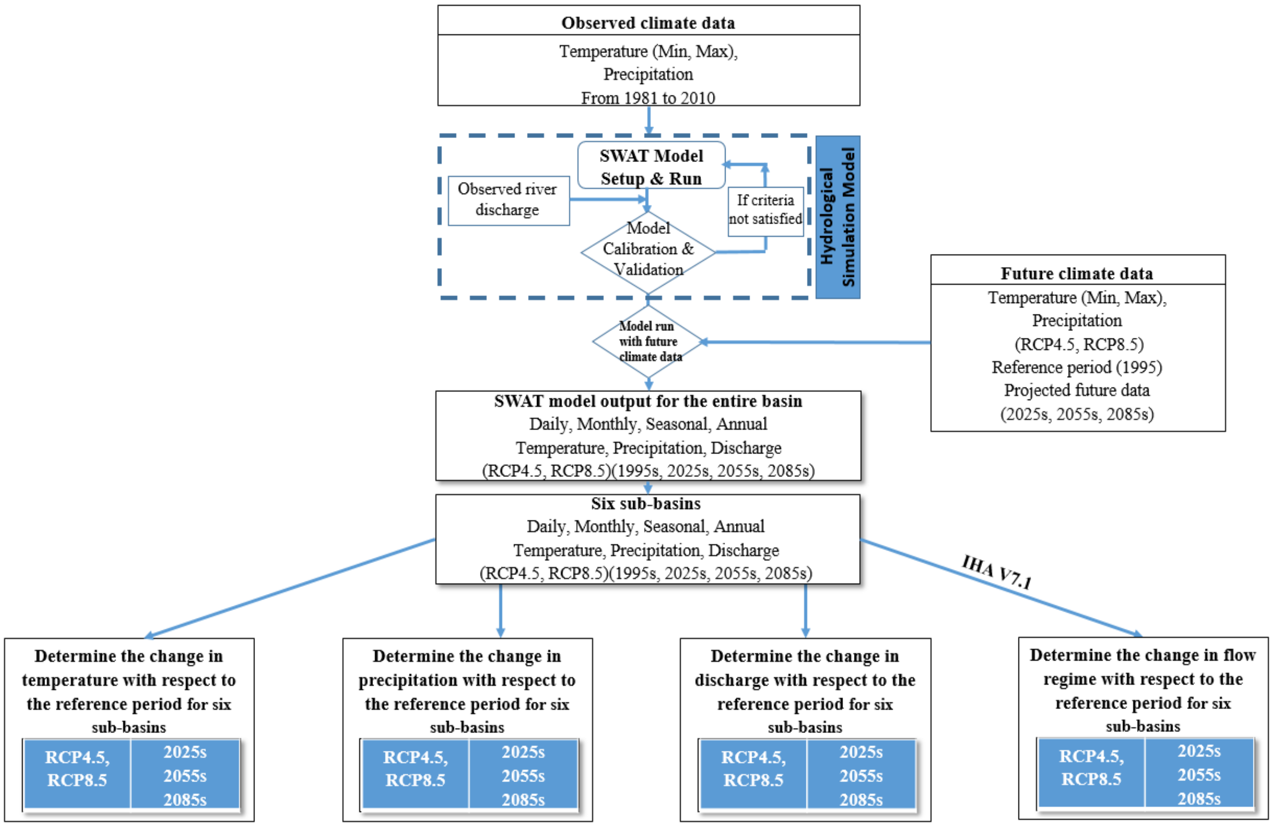


Figure 3. 2. Method for investigating climate change and its potential impact on the hydrological regime in the Koshi River basin.

3.4. Results and discussions

3.4.1. Calibration and validation of the SWAT model

The SWAT model result shows a good agreement between simulated and observed stream values at the two hydrological stations. The daily simulation results at Chatara showed that peaks matched for most of the years, however, they were underestimated for a few years between 1992 to 1995 for calibration. The model performance for the Chatara outlet is shown in Figure 3.3 (a, b). Based on hydrograph and statistical evaluations, the model was able to simulate the flow during calibration and validation and correlated well with the observed data. The goodness of fit statistics showed that both Nash-Sutcliffe Efficiency (NSE) and Coefficient of Determination (R^2) are above 0.75 and Percent Bias (PBIAS) is within ±15% in both stations, which makes the model a good representative of the Koshi River basin. This result is consistent with the findings of Shrestha et al. (2016) and Bharati et al. (2014). Therefore, it showed that the SWAT model was able to simulate the discharge at the outlet of the catchment with reasonably high accuracy. The calibration and validation output value of NSE, R^2 and PBIAS is provided in Table 3.2.

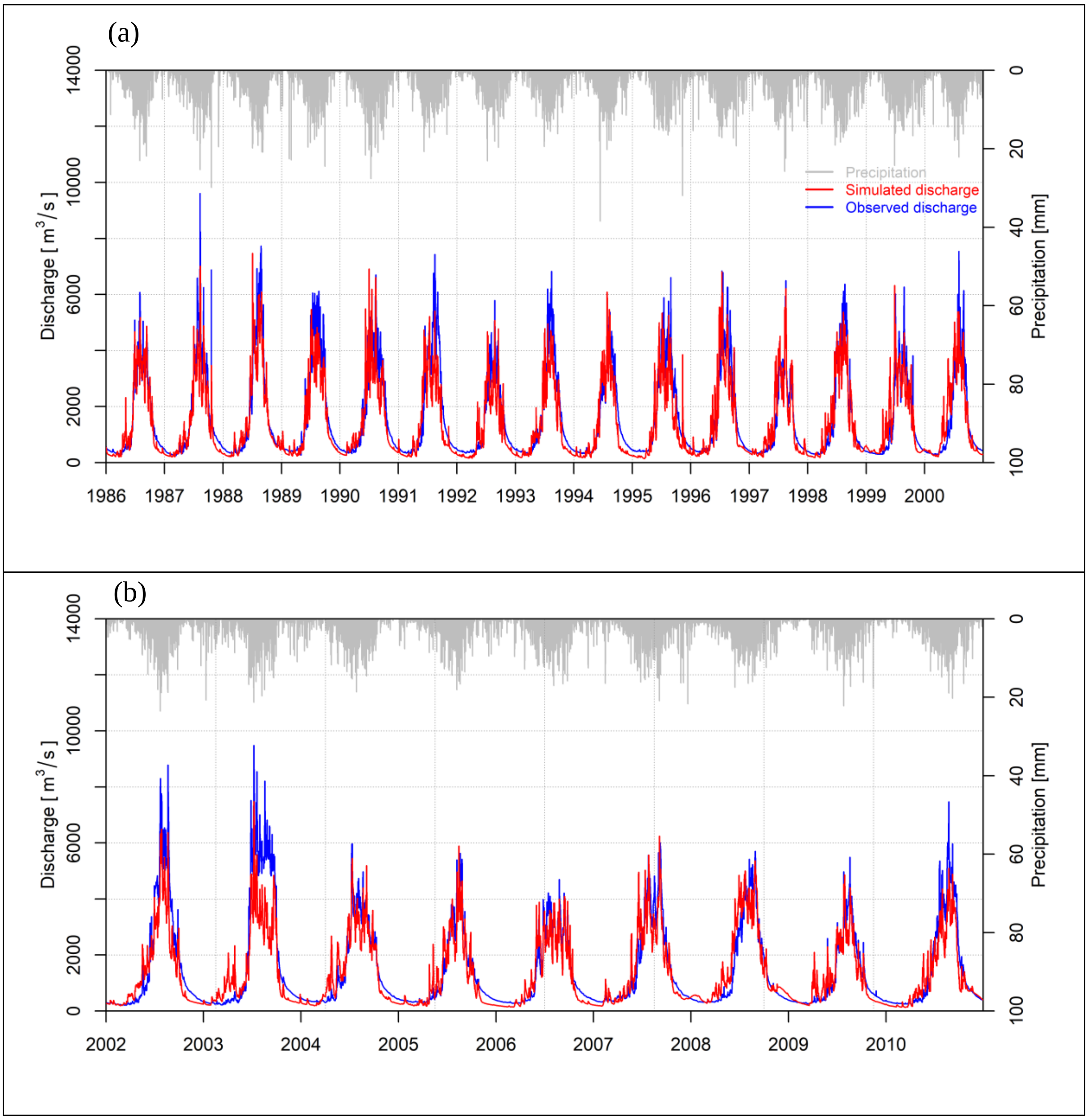


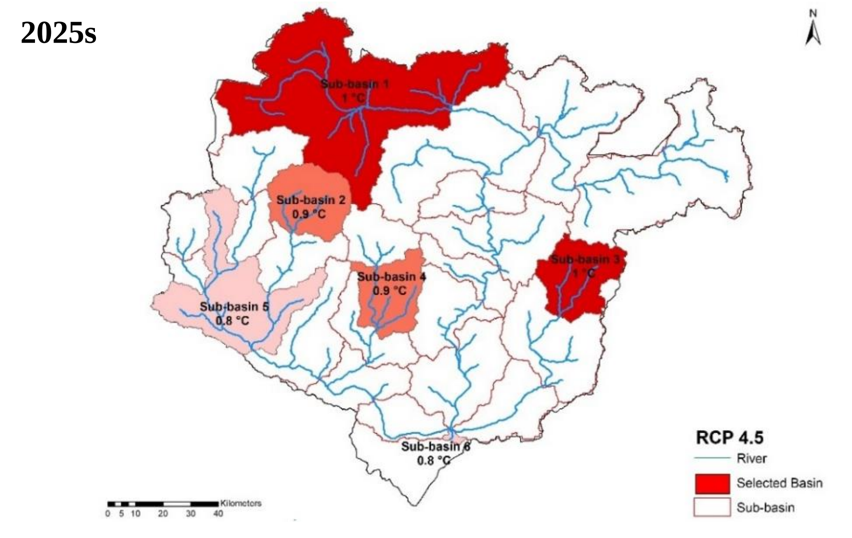
Figure 3. 3. (a) Calibration of the SWAT model of the Koshi Basin at Chatara hydrological station from 1986 to 2001; (b) Validation of the SWAT model of the Koshi Basin at Chatara hydrological station from 2002 to 2010.

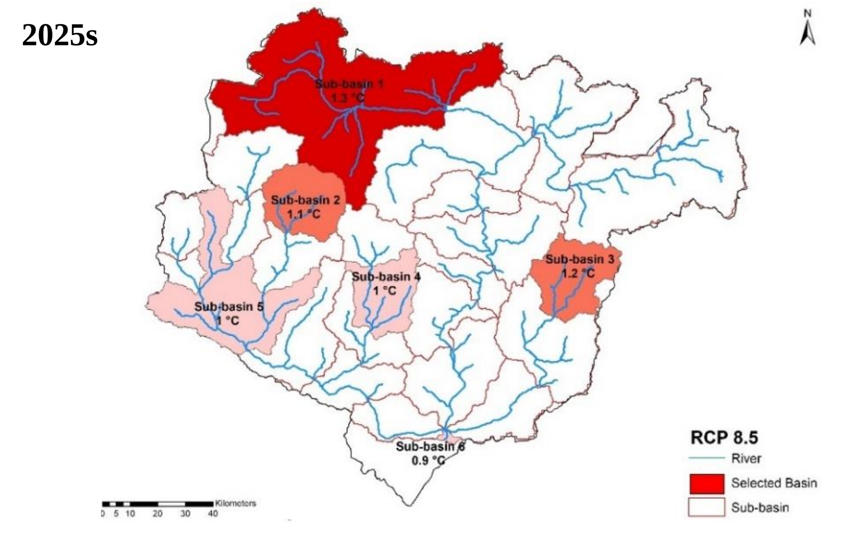
Table 3. 2. Model performance of daily river flow during calibration and validation at Chatara and Khurkot outlet.

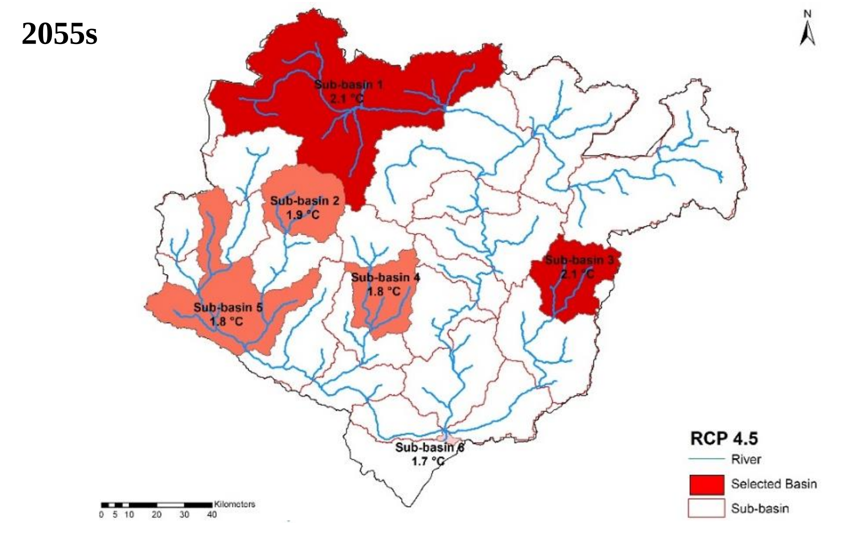
Station	Timeline	Evaluation Criteria		
		NSE	R^2	PBIAS
Chatara	Calibration Period (1986 – 2001)	0.87	0.87	-3.2
	Validation Period (2002 – 2010)	0.85	0.86	0.6
Khurkot	Calibration Period (1986 – 1994)	0.78	0.79	5.3
	Validation Period (2000 – 2008)	0.76	0.75	-4.6

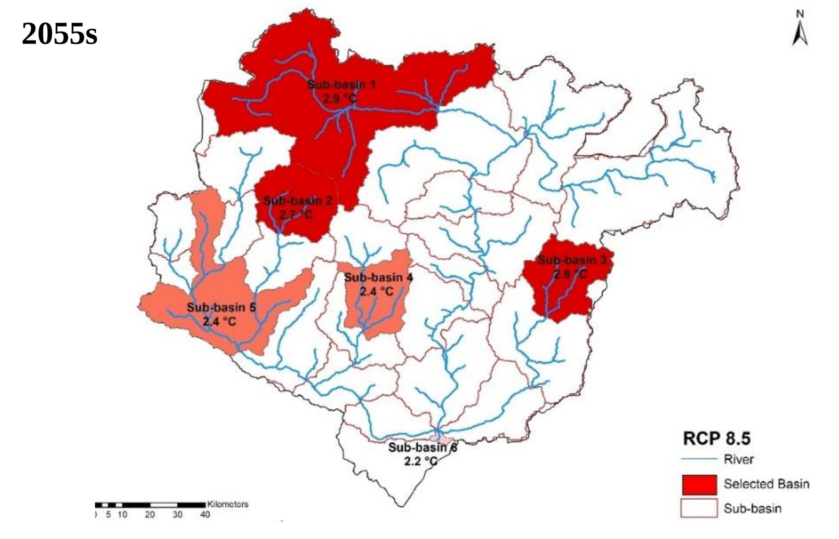
3.4.2. Projected changes in temperature

This study quantifies the change in future temperature concerning the reference period across the sub-basins over time under two projection scenarios. Our results indicate an increase in the average temperature across the sub-basins in the future timeline. Annual average temperatures are expected to increase over time across the six sub-basins and the increase will be greater under the RCP 8.5 climate scenario. For example, the temperature is likely to increase by 2.3°C to 2.7°C in sub-basins under RCP4.5 while by 3.8°C to 4.9°C in sub-basins under the RCP8.5 scenario by 2100. Increases in annual temperatures differ among the six sub-basins under both scenarios over time. The increase in temperature will be highest in sub-basin 1 followed by sub-basins 3, 2, 4, 5 and sub-basin 6 under both RCPs (Figure 3.4). Overall, the increase in average annual temperature will be greater in the northern sub-basins compared to the southern sub-basins which might most likely be attributed to elevation-dependent warming (Yao et al., 2019). This finding is consistent with the findings of Kaini et al. (2019), Shrestha et al. (2019), Shrestha et al. (2017), Rajbhandari et al. (2016), Bharati et al. (2014), Yao et al. (2019) and Wijngaard et al. (2018). The increasing temperature in the northern part means the upward shift of the snowline. As a result, the proportion of precipitation fall as rainfall instead of snowfall which decrease the accumulation and storage of snow at high altitude. In addition, increase temperature will accelerate the melting rate of remaining deposited snow and reduces the spatial extension of snow cover. Thus, a temperature change will change the snow cover area, as well as changes in the snowmelt rate which will impact the contribution of snowmelt, and the shift in discharge and flow regime.


2025s
N
Sub-basin 1
1 °C
Sub-basin 2
0.9 °C
Sub-basin 3
1 °C
Sub-basin 4
0.9 °C
Sub-basin 5
0.8 °C
Sub-basin 6
0.8 °C
RCP 4.5
River
Selected Basin
Sub-basin
0 5 10 20 30 40 Kilometers


2025s
N
Sub-basin 1
1.3 °C
Sub-basin 2
1.1 °C
Sub-basin 3
1.2 °C
Sub-basin 4
1 °C
Sub-basin 5
1 °C
Sub-basin 6
0.9 °C
RCP 8.5
River
Selected Basin
Sub-basin
0 5 10 20 30 40 Kilometers


2055s
N
Sub-basin 1
2.1 °C
Sub-basin 2
1.9 °C
Sub-basin 3
2.1 °C
Sub-basin 4
1.8 °C
Sub-basin 5
1.8 °C
Sub-basin 6
1.7 °C
RCP 4.5
River
Selected Basin
Sub-basin
0 5 10 20 30 40 Kilometers


2055s
N
Sub-basin 1
2.9 °C
Sub-basin 2
2.7 °C
Sub-basin 3
2.8 °C
Sub-basin 4
2.4 °C
Sub-basin 5
2.4 °C
Sub-basin 6
2.2 °C
RCP 8.5
River
Selected Basin
Sub-basin
5 10 20 30 40 Kilometers

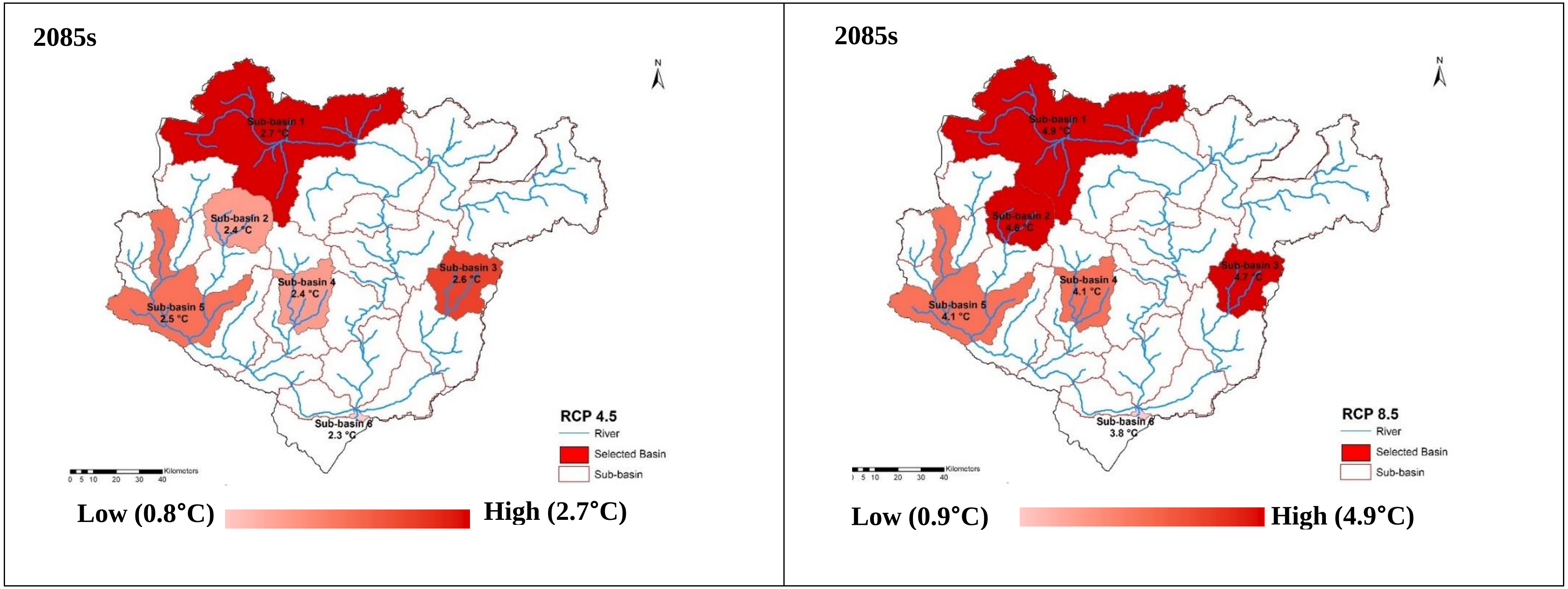


Figure 3. 4. Average annual temperature (°C) increases across the sub-basins in three time periods under both RCPs and the graduated colour ranges show the low (light) to high (dark) value.

Temperature increases will vary among the four seasons across the six sub-basins in both RCPs. The projected increases in temperature will likely be higher in the pre-monsoon and less during the monsoon season for all sub-basins and both scenarios. For example, temperature increases in sub-basin 1 will be greater in the pre-monsoon (3°C) compared to the winter (2.9°C), post-monsoon (2.4°C) and monsoon season (2.4°C) under the RCP4.5 scenario by 2100 (Table 3.3). This finding is consistent with the finding of Pandey et al. (2020a) in the Karnali-Mohana basin in western Nepal.

Table 3. 3. Average seasonal temperature increases across the sub-basins under both RCPs by 2100.

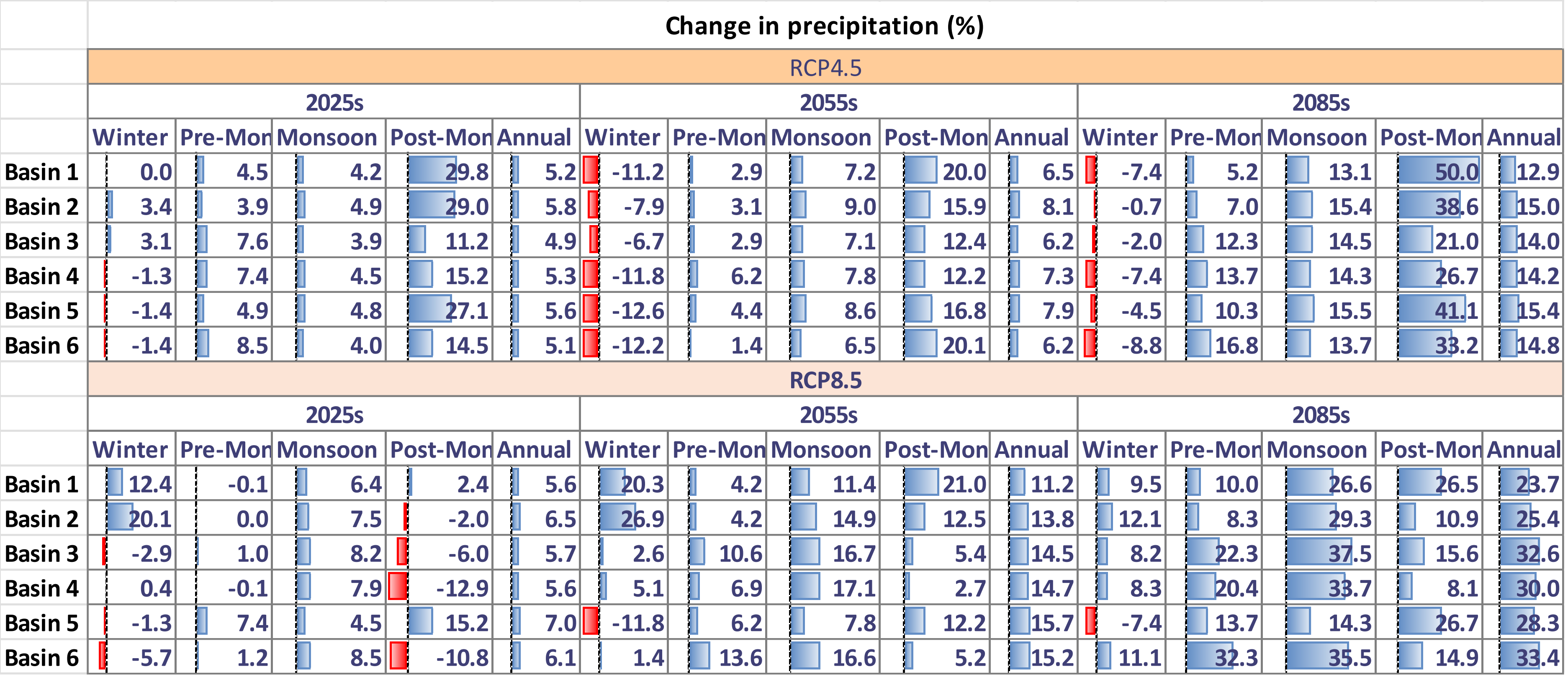
	RCP4.5				**RCP8.5**			
Basin	**Winter** (°C)	**Pre-Monsoon** (°C)	**Monsoon** (°C)	**Post-Monsoon** (°C)	**Winter** (°C)	**Pre-Monsoon** (°C)	**Monsoon** (°C)	**Post-Monsoon** (°C)
1	2.9	3.0	2.4	2.4	4.6	5.5	4.3	5.2
2	2.5	2.8	2.1	2.3	4.4	5.2	3.9	5.0
3	3.1	2.7	2.5	2.7	4.9	4.7	4.0	5.0
4	2.4	2.6	2.3	2.3	3.9	4.3	3.5	4.6
5	2.6	2.6	2.4	2.1	4.2	4.8	3.3	4.2
6	2.3	2.6	2.1	2.2	3.9	4.1	3.3	4.0

The rates of increase in temperature vary among time periods and sub-basins. For instance: annual temperature increases are projected to double between 2025s and 2055s for all sub-basins under the RCP4.5 scenario. However, for the RCP8.5 scenario, all sub-basins experience an approximate doubling of annual temperature increase between 2025s and 2055s as well as again between 2055s and 2085s (Figure 3.4). Furthermore, seasonal temperature increases are projected to be around double across all sub-basins under RCP8.5 compared to RCP4.5 by 2100.

3.4.3. Projected changes in precipitation

Precipitation increases vary among the sub-basins. For instance, overall precipitation is likely to increase by 12.9 % to 15.4% in sub-basins under RCP4.5 while increasing by 23.7% to 33.4% in sub-basins under the RCP8.5 scenario by 2100. The increase of annual precipitation will be highest in sub-basin 5 followed by sub-basins 2, 6, 4, 3 and sub-basin 1 under RCP4.5. In comparison, the increase of annual precipitation will be greatest in sub-basin 6 followed by sub-basins 3, 4, 5, 2 and finally sub-basin 1 under RCP8.5 (Figure 3.5). Those sub-basins in the southeast (sub-basins 3, and 6) will experience more precipitation than northwestern regions (sub-basin 1) which might be because sub-basins 3 and 6 are impacted by the monsoon season first.

The rate of increases in average annual precipitation in future across the six sub-basins for both climate scenarios increases greater in the RCP8.5 scenario. Annual and seasonal precipitations are projected to double between 2055s and 2085s for all sub-basins under the RCP4.5 scenario. However, for the RCP 8.5 scenario, all sub-basins will experience a doubling of annual and seasonal precipitations (except for dry season) between 2025s and 2055s as well as between 2055s and 2085s.



	Change in precipitation (%)														
	RCP4.5														
	2025s					2055s					2085s				
	Winter	Pre-Mon	Monsoon	Post-Mon	Annual	Winter	Pre-Mon	Monsoon	Post-Mon	Annual	Winter	Pre-Mon	Monsoon	Post-Mon	Annual
Basin 1	0.0	4.5	4.2	29.8	5.2	-11.2	2.9	7.2	20.0	6.5	-7.4	5.2	13.1	50.0	12.9
Basin 2	3.4	3.9	4.9	29.0	5.8	-7.9	3.1	9.0	15.9	8.1	-0.7	7.0	15.4	38.6	15.0
Basin 3	3.1	7.6	3.9	11.2	4.9	-6.7	2.9	7.1	12.4	6.2	-2.0	12.3	14.5	21.0	14.0
Basin 4	-1.3	7.4	4.5	15.2	5.3	-11.8	6.2	7.8	12.2	7.3	-7.4	13.7	14.3	26.7	14.2
Basin 5	-1.4	4.9	4.8	27.1	5.6	-12.6	4.4	8.6	16.8	7.9	-4.5	10.3	15.5	41.1	15.4
Basin 6	-1.4	8.5	4.0	14.5	5.1	-12.2	1.4	6.5	20.1	6.2	-8.8	16.8	13.7	33.2	14.8
	RCP8.5														
	2025s					2055s					2085s				
	Winter	Pre-Mon	Monsoon	Post-Mon	Annual	Winter	Pre-Mon	Monsoon	Post-Mon	Annual	Winter	Pre-Mon	Monsoon	Post-Mon	Annual
Basin 1	12.4	-0.1	6.4	2.4	5.6	20.3	4.2	11.4	21.0	11.2	9.5	10.0	26.6	26.5	23.7
Basin 2	20.1	0.0	7.5	-2.0	6.5	26.9	4.2	14.9	12.5	13.8	12.1	8.3	29.3	10.9	25.4
Basin 3	-2.9	1.0	8.2	-6.0	5.7	2.6	10.6	16.7	5.4	14.5	8.2	22.3	37.5	15.6	32.6
Basin 4	0.4	-0.1	7.9	-12.9	5.6	5.1	6.9	17.1	2.7	14.7	8.3	20.4	33.7	8.1	30.0
Basin 5	-1.3	7.4	4.5	15.2	7.0	-11.8	6.2	7.8	12.2	15.7	-7.4	13.7	14.3	26.7	28.3
Basin 6	-5.7	1.2	8.5	-10.8	6.1	1.4	13.6	16.6	5.2	15.2	11.1	32.3	35.5	14.9	33.4

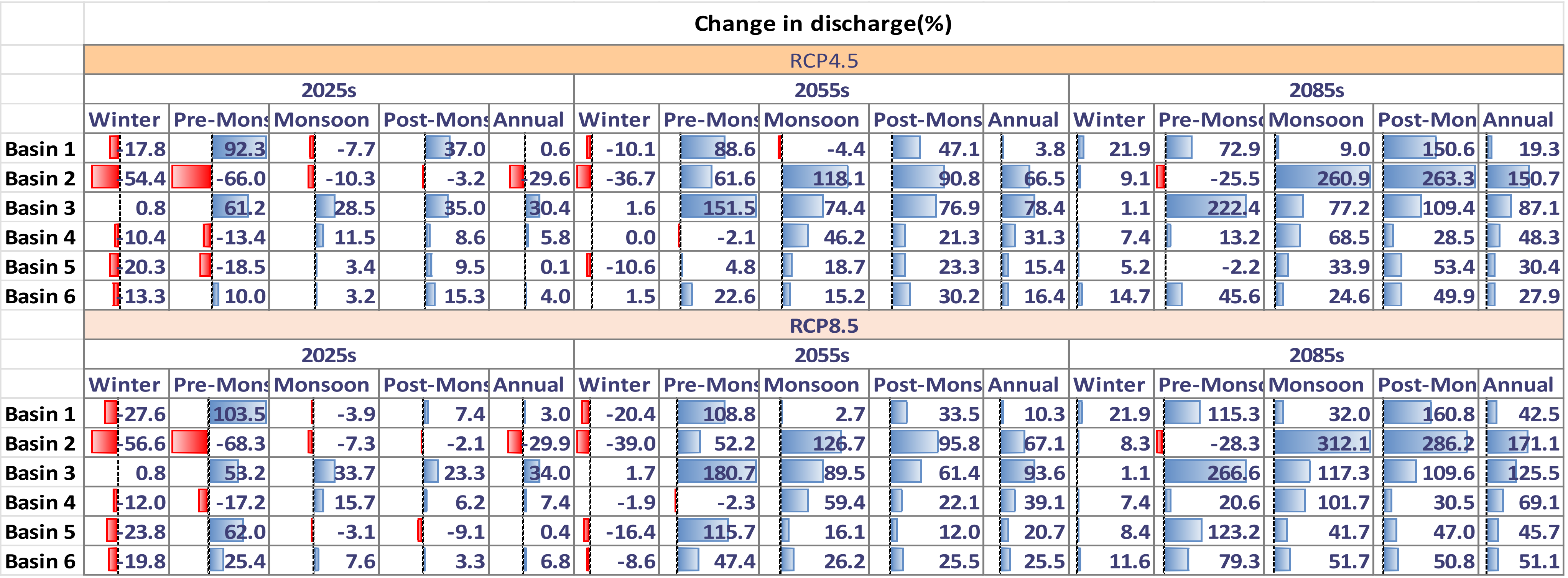
Figure 3. 5. The heat map of the percentage change in precipitation for selected sub-basins under two projection scenarios compared to the reference period (1995s) for three time periods. The color bar represents the percentage change in precipitation for the given period. The blue color indicates an increase, and the red color indicates a decrease in precipitation.

The projected precipitation changes show larger variations in seasons than on an annual basis for both scenarios. Winter season precipitation is expected to decrease under RCP4.5 but increase for RCP8.5 for most of the basin. The precipitation during the monsoon is projected to increase in all sub-basins for all time periods under both RCPs. Post-monsoon precipitation is expected to increase for all time periods except for RCP8.5 in 2025s when four out of six sub-basins show a decrease. The projected changes in precipitation during monsoon and post-monsoon are in line with the finding by Rajbhandari et al. (2017) across the Koshi Basin.

Overall, results show that it is likely to be a potential decline in precipitation in winter and an increase in other seasons, especially the rainy season. Therefore, it can be predicted that the dry season is likely to be drier and the wet season is likely to be wetter under RCP4.5. In contrast, there is likely to increase precipitation in all seasons under RCP8.5. Therefore, all seasons are likely to be wetter in the mid and end of the twenty-first century under RCP8.5, except for sub-basin 5 in the winter season. The projections for precipitation show an annual increasing trend for both scenarios by 2100; this could positively have an effect on the riverine landscape ecosystem services. However, climate change is likely to disrupt precipitation regimes with alternating erratic rainfall and droughts, resulting in more repeated floods and droughts. For instance, the number of rainy days and consecutive wet days was projected to decrease whereas consecutive dry days were projected to increase in the Koshi Basin. Furthermore, the number of very wet days was projected to increase in Koshi Basin (Kaini et al., 2019; Rajbhandari et al., 2017). Changes in the frequencies of extreme rainfall events might impact land degradation processes such as mass movements, soil erosions, and removal of top fertile soil, which might reduce fertile land. Ultimately, change will impact the lives and livelihood of the people depending on agriculture in the Koshi Basin.

3.4.4. Potential impact of climate change on river discharge

Increases in annual discharge are projected across all sub-basins and these will be greater under RCP8.5 (84%) compared to RCP4.5 (61%) by 2100. The annual discharge is likely to increase by 19 % to 151% in sub-basins under RCP4.5, while by 43% to 171% in sub-basins under the RCP8.5 scenario by 2100. The increase in annual discharge is projected to be highest in sub-basin 2 followed by sub-basins 3, 4, 5, 6 and sub-basin 1 under RCP4.5. In comparison, the increase in annual discharge is projected to be greater in sub-basin 2, followed by sub-basins 3, 4, 6, 5 and sub-basin 1 under RCP8.5 by 2100 (Figure 3.6). Overall, there is a slight east-west spatial trend in annual discharge with an increase to the east to a decrease to the west. In terms of the future change in discharge, sub-basin 3 and sub-basin 2 dominate all other sub-basins in the degree of change under both RCPs. The discharge in sub-basin 2 is relatively low during the reference period (13.26 m^3/s annual mean discharge) but is projected to increase up to 150% (171%) by 2100 under RCP4.5 (RCP8.5). Sub-basin 2 shows a higher projected discharge than other sub-basins. It reflects that small absolute increases in sub-basin 2 can result in large relative increases. Sub-basin 3 also shows high relative increases in discharge under both RCPs. It might be a reason that around 24% of the sub-basin 3 area is covered by snow and glacier, being higher than the other sub-basins (Khadka et al., 2020; Khadka et al., 2016). For instance, sub-basin 3 (upper part of Tamor Basin) consists of 358 sq. km of glacier area (Khadka et al., 2020) and 784 sq km of snow cover area (Khadka et al., 2016). Due to an increase in temperature, the contribution of snow and glacier melt combined with monsoon rainfall will increase surface discharge. Thus, sub-basin 3 is the only basin that does not show any decrease in discharge in annual and seasonal intervals for all time periods up to 2100 compared to the reference period under both RCPs.



	Change in discharge(%)														
	RCP4.5														
	2025s					2055s					2085s				
	Winter	Pre-Mons	Monsoon	Post-Mons	Annual	Winter	Pre-Mons	Monsoon	Post-Mons	Annual	Winter	Pre-Mons	Monsoon	Post-Mon	Annual
Basin 1	-17.8	92.3	-7.7	37.0	0.6	-10.1	88.6	-4.4	47.1	3.8	21.9	72.9	9.0	150.6	19.3
Basin 2	-54.4	-66.0	-10.3	-3.2	-29.6	-36.7	61.6	118.1	90.8	66.5	9.1	-25.5	260.9	263.3	150.7
Basin 3	0.8	61.2	28.5	35.0	30.4	1.6	151.5	74.4	76.9	78.4	1.1	222.4	77.2	109.4	87.1
Basin 4	-10.4	-13.4	11.5	8.6	5.8	0.0	-2.1	46.2	21.3	31.3	7.4	13.2	68.5	28.5	48.3
Basin 5	-20.3	-18.5	3.4	9.5	0.1	-10.6	4.8	18.7	23.3	15.4	5.2	-2.2	33.9	53.4	30.4
Basin 6	-13.3	10.0	3.2	15.3	4.0	1.5	22.6	15.2	30.2	16.4	14.7	45.6	24.6	49.9	27.9
	RCP8.5														
	2025s					2055s					2085s				
	Winter	Pre-Mons	Monsoon	Post-Mons	Annual	Winter	Pre-Mons	Monsoon	Post-Mons	Annual	Winter	Pre-Mons	Monsoon	Post-Mon	Annual
Basin 1	-27.6	103.5	-3.9	7.4	3.0	-20.4	108.8	2.7	33.5	10.3	21.9	115.3	32.0	160.8	42.5
Basin 2	-56.6	-68.3	-7.3	-2.1	-29.9	-39.0	52.2	126.7	95.8	67.1	8.3	-28.3	312.1	286.2	171.1
Basin 3	0.8	53.2	33.7	23.3	34.0	1.7	180.7	89.5	61.4	93.6	1.1	266.6	117.3	109.6	125.5
Basin 4	-12.0	-17.2	15.7	6.2	7.4	-1.9	-2.3	59.4	22.1	39.1	7.4	20.6	101.7	30.5	69.1
Basin 5	-23.8	62.0	-3.1	-9.1	0.4	-16.4	115.7	16.1	12.0	20.7	8.4	123.2	41.7	47.0	45.7
Basin 6	-19.8	25.4	7.6	3.3	6.8	-8.6	47.4	26.2	25.5	25.5	11.6	79.3	51.7	50.8	51.1

Figure 3. 6. The heat map of the percentage change in discharge for all sub-basins and time periods under both scenarios compared to the reference period.

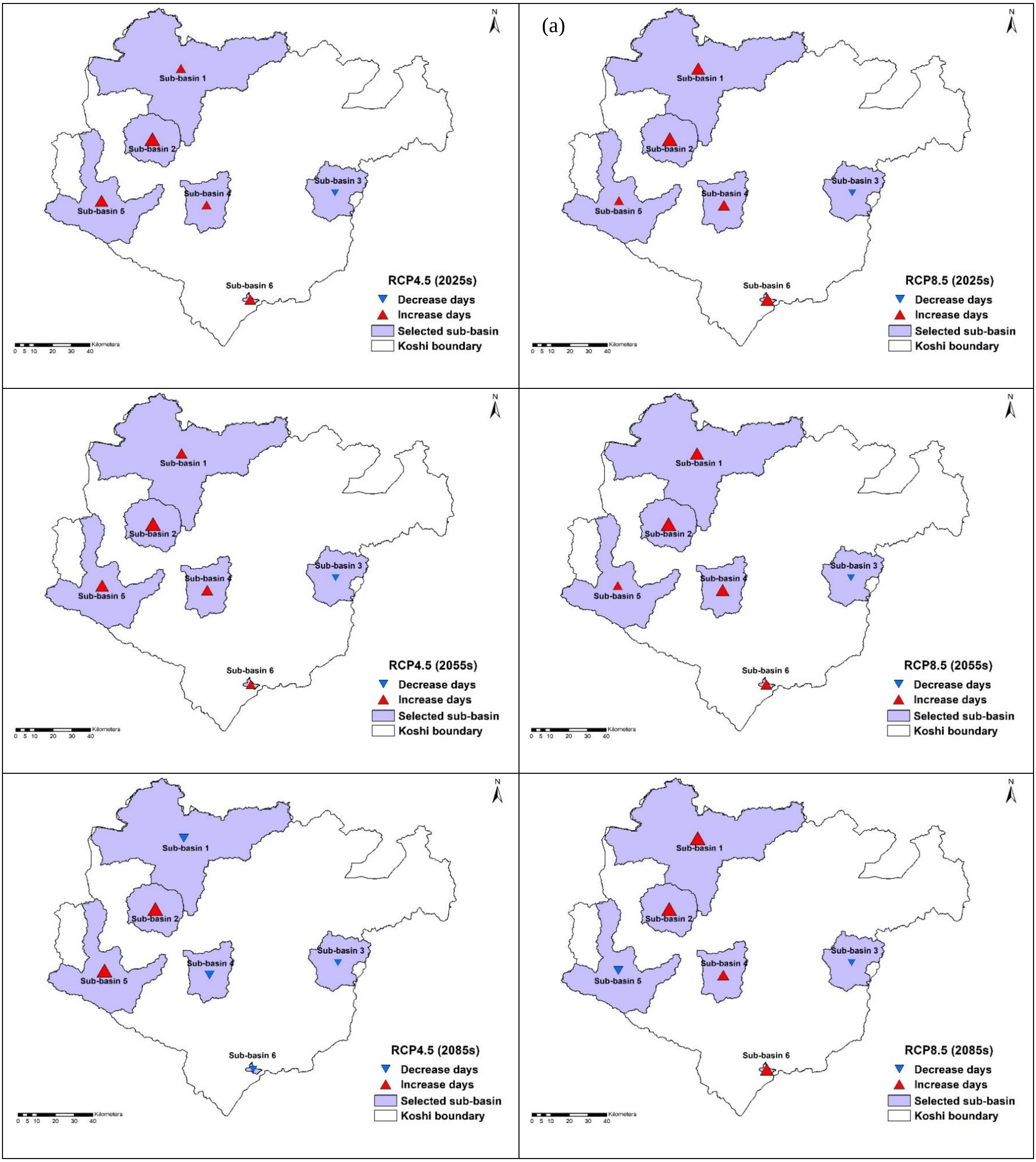
Seasonal changes in discharge will differ among the four seasons. The winter discharge is projected to decrease under RCP4.5 in 2025s and 2055s, as well as under RCP8.5 in 2025s, for all sub-basins except for sub-basin 3. Pre-monsoon discharge is projected to increase in most sub-basins except in sub-basin 2 under both RCPs in 2025s and 2085s. In addition, discharge in sub-basin 4 is projected to decrease during pre-monsoon under both RCPs in 2055s, as well as under RCP4.5 in 2025s. There is a marked increase in discharge in monsoon and post-monsoon seasons under both RCPs where the highest increase is in the post-monsoon season under RCP4.5 and in the monsoon season under RCP8.5.

The rate of change of annual discharges is projected to increase by 2100. For instance, the annual discharge between 2025s and 2055s in all sub-basins is projected to at least double whereas the annual discharge in three sub-basins (1, 2 and 5) is projected to more than double between 2055s and 2085s under RCP4.5. Seasonal discharge change is more variable for both time periods under RCP4.5. However, for the RCP 8.5 scenario, all sub-basins will experience significant increases in annual and seasonal discharges between 2025s and 2055s as well as between 2055s and 2085s. The rate of increase of discharge in monsoon might be an increase in monsoon precipitation combined with an increase in meltwater after mid-century in the Koshi Basin (Khadka et al., 2020; Wijngaard et al., 2018)

Overall, the result shows that there is an increase in annual discharge, albeit with a large variation in seasonal discharge. There might be water stress during the winter season but surplus water during the monsoon season. Simulated flow results show that the annual flow is still dominated by monsoon flow in the future even under the impact of climate change (Figure 3.6). Furthermore, most sub-basins show an increase in average seasonal flow except during the winter season. The decrease in winter river flow might be due to decreases in winter precipitation. This decrease in winter river flow and precipitation might impact highly winter cultivation.

3.4.5. Potential impact of climate change on flow extremes

Climate change is projected to influence components of the flow regime in each sub-basin. The response of flow alteration varies according to sub-basins and season for the different periods under both RCPs. The flow alteration results show that the magnitude and frequency of peak discharge in all sub-basins are projected to increase under both RCPs over all periods except for sub-basins 2 and 5 in 2025s under RCP8.5. Furthermore, the duration of low flow, as well as high flow, are likely to increase under both RCPs for all periods, except for sub-basin 3 in terms of low flows (Figure 3.7a). In other words, hydrological extremes (high flow and low flow) are projected to occur more frequently in all sub-basins in the Koshi Basin. The change in the number of extremely low flow days varies from -15 to 100 days under RCP4.5 and -8 to 60 days under RCP8.5 across sub-basins by 2100. Similarly, the change in the number of large flood days varies from 5 to 18 days under RCP4.5 and 7 to 28 days under RCP8.5 across sub-basins by 2100. The spatial change in hydrological extremes across the sub-basins is shown in Figure 3.7 (a,b). The increase in the duration of low flow is greater than the high flow. The projected changes in flow extremes are in line with the findings by Nie et al. (2021) in the Himalayas, Wijngaard et al. (2018) for the Upper IGB River basins, Wijngaard et al. (2017) for the upper Ganges and Bharati et al. (2019; 2016) and Khadka et al. (2016) for Koshi. However, at the beginning of climate change (in the 2025s), there will most likely be influence on low flow than high flow, but it will then reverse as time passes. Low flow duration will be shortened whereas high flow duration will be extended. During the low flow season, the surface water availability will be low which is likely to affect the environmental flow requirement and lead to high water demand, resulting in high competition between water users (Wijngaard et al., 2018). This would impact people who rely on water-dependent ecosystem services.


(a)
N
Sub-basin 1
Sub-basin 2
Sub-basin 3
Sub-basin 4
Sub-basin 5
Sub-basin 6
RCP4.5 (2025s)
RCP8.5 (2025s)
RCP4.5 (2055s)
RCP8.5 (2055s)
RCP4.5 (2085s)
RCP8.5 (2085s)
Decrease days
Increase days
Selected sub-basin
Koshi boundary
0 5 10 20 30 40 Kilometers

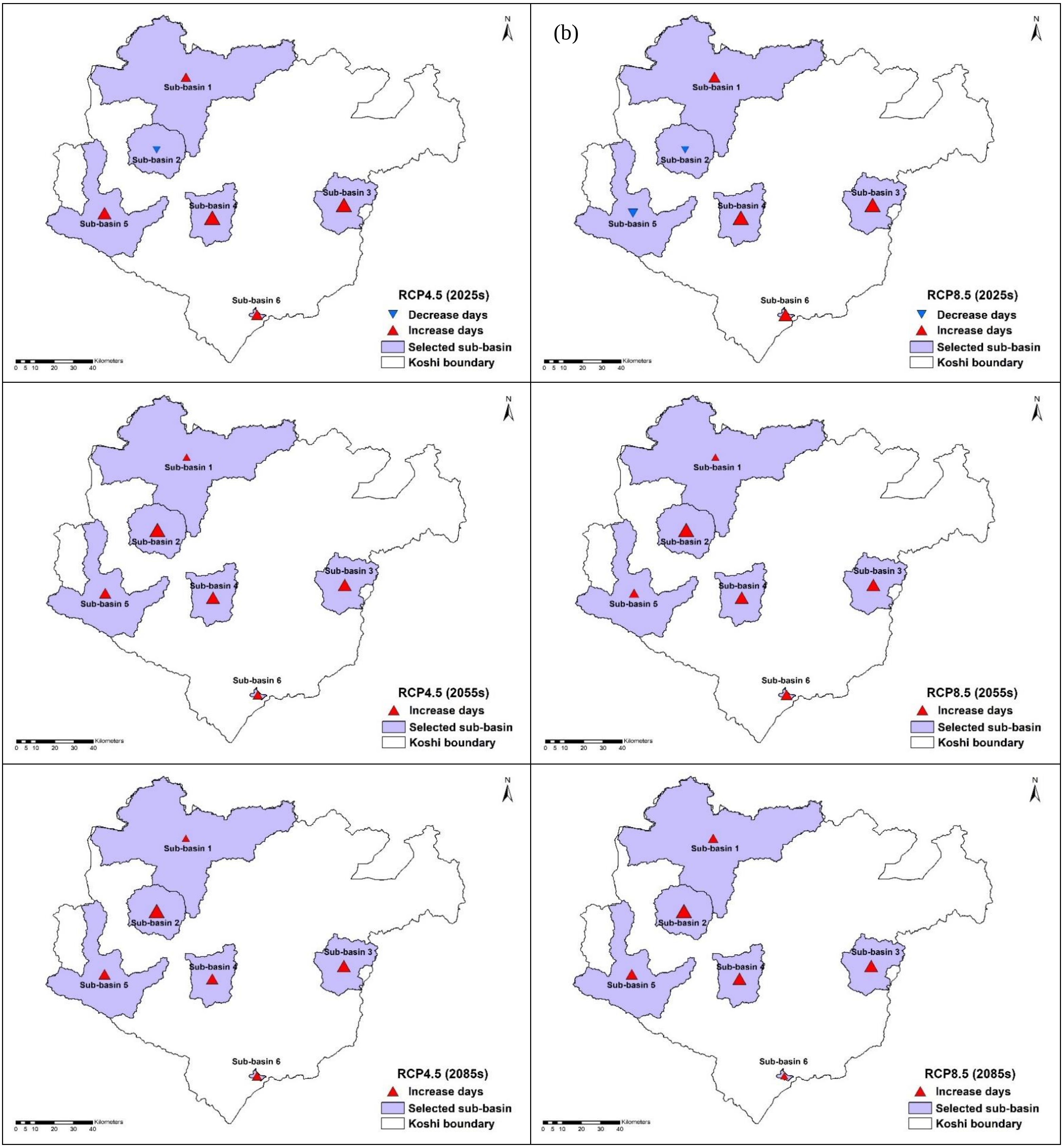


Figure 3. 7. a) The map of the change in extreme low flow days for all sub-basins under both scenarios according to time compared to the reference period. The symbol size represents the number of days; b) the map of the change in large flood days for all sub-

basins under both scenarios according to time compared to the reference period. The symbol size represents the number of days.

Furthermore, the timing of the projected average monthly discharge will also change. For instance, the most flow-generating month may shift for one month, from July to August in 2085s in sub-basin 4 and 5 under RCP8.5 (Figure 3.8) whereas for the other remaining sub-basins, the projected average monthly discharge period timing remains the same. This finding is supported by studies by Bajracharya et al. (2018) of the Kaligandaki basin adjacent to the Koshi Basin, and by Khadka et al. (2016) of the Koshi Basin.

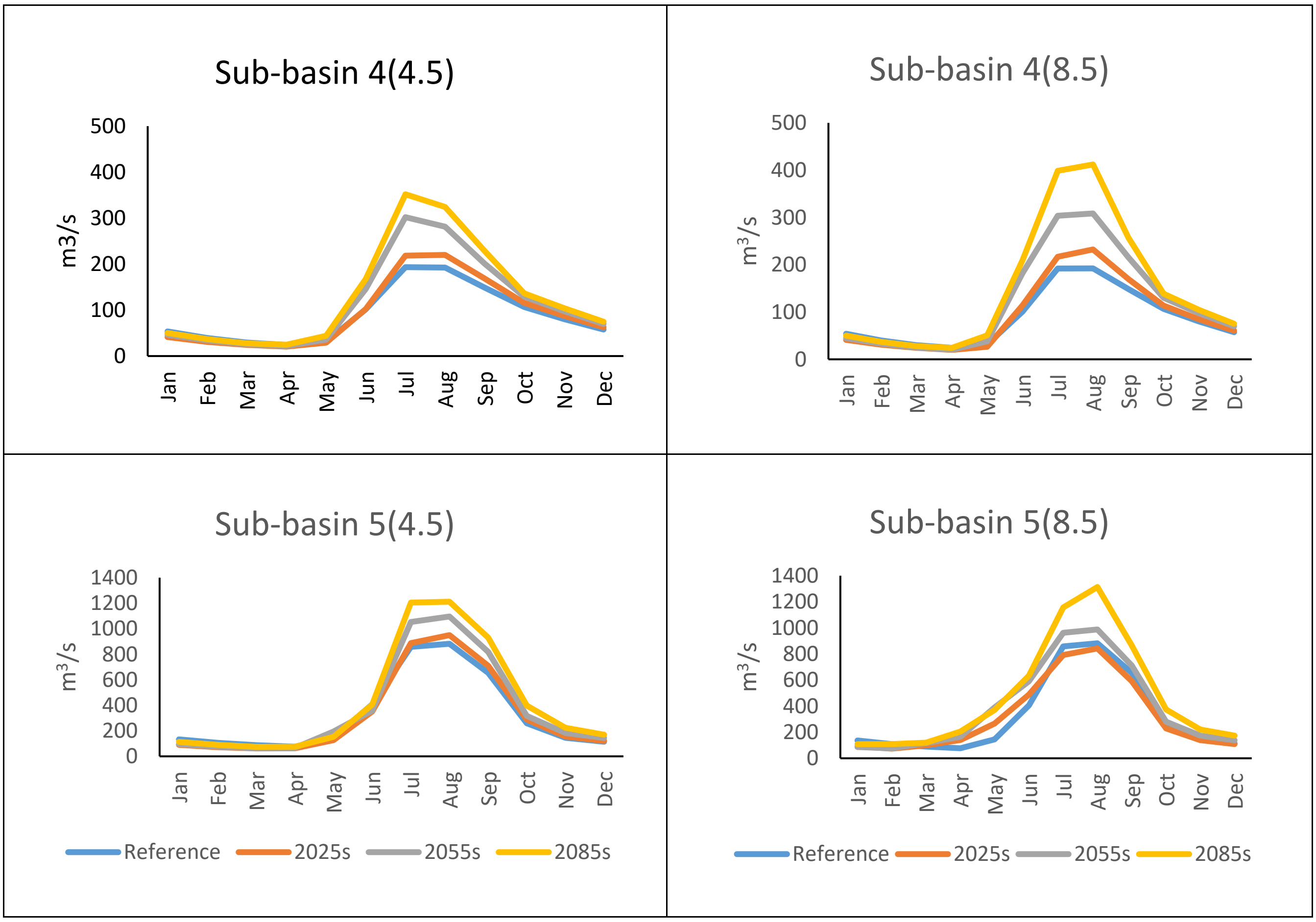


Figure 3. 8. Projected average monthly discharge for sub-basin 4 and 5 under RCP4.5 and RCP8.5 in 2085s compared to the reference period.

Overall, the flow regime in the Koshi Basin is projected to be significantly impacted by climate change. The frequency in occurrence of high and extremely low flow events demonstrates the “too much or too little water” problem. This means the basin is vulnerable to both floods and drought, resulting in a high risk to people and their livelihood. Furthermore, the change in flow regime will in all probability change the biological and physical processes of the river which will have an effect on quality, quantity, hydro-geomorphology and biodiversity in riverine ecosystems (Bharati et al., 2016).

3.4.6. Uncertainties in climate projection

We used the robust HI-AWARE datasets of maximum and minimum temperature, and precipitation of 8 GCMs (4 each for RCP4.5 and RCP8.5) as input data for the SWAT model to simulate the future scenarios for the study basin. However, there is uncertainty in the climate data as these trajectories are dependent upon many factors including human intervention, atmospheric processes as well as international climate negotiations. To account for these uncertainties, the models were selected based on simulating the four corners of the projection spectrum, i.e. one each for cold-dry, cold-wet, warm-dry and warm-wet condition of the future for each RCP and their ensemble was used as representative of the future states. However, there are significant uncertainties within the projections in the study area for RCP4.5 and RCP8.5 scenarios. Cui et al. (2018) reported that the uncertainties from climate models together with the uncertainty from a hydrological model pose a great challenge to the accurate projection of hydrological regime alteration. Therefore, we should cautiously use the output of the model results considering the uncertainty range given by all datasets.

These uncertainties can be understood from the ensemble plot in Figure 3.9a where it can be seen that even though the projection for both precipitation and temperature increases, the response of models has higher variability for precipitation than for temperature for both

RCPs. Also, Figure 3.9b suggests that there is more variability in projection for 2085s than for 2025s or 2055s. The future projection for precipitation shows higher uncertainties in RCP4.5 than in RCP8.5. However, for temperature, the uncertainties are similar for both RCPs, although lower than those for precipitation. This can be understood by the higher value of the coefficient of variation in precipitation than in temperature in Table 3.4. For example, the coefficient of variation for precipitation is 0.11 (0.18) for RCP4.5 (RCP8.5) in 2085s - suggesting the range of projected change in precipitation is large. In the case of temperature, the coefficient of variation is 0.05 (0.07) for RCP4.5 (RCP8.5) in the 2085s.

Table 3. 4. Quantitative estimates of uncertainties for the entire Koshi Basin.

	Variable	**Statistics**	**RCP4.5**			**RCP8.5**		
			2025s	**2055s**	**2085s**	**2025s**	**2055s**	**2085s**
Multi-model ensemble for Koshi basin	Precipitation (mm)	Mean	1884	1911	2053	1921	2072	2317
		Standard deviation	129	124	222	139	155	405
		Co-efficient of variation	0.07	0.07	0.11	0.07	0.08	0.18
	Temperature (°C)	Mean	11.5	12.3	12.8	11.6	12.7	14.2
		Standard deviation	0.30	0.50	0.70	0.30	0.60	1.00
		Co-efficient of variation	0.02	0.04	0.05	0.03	0.05	0.07

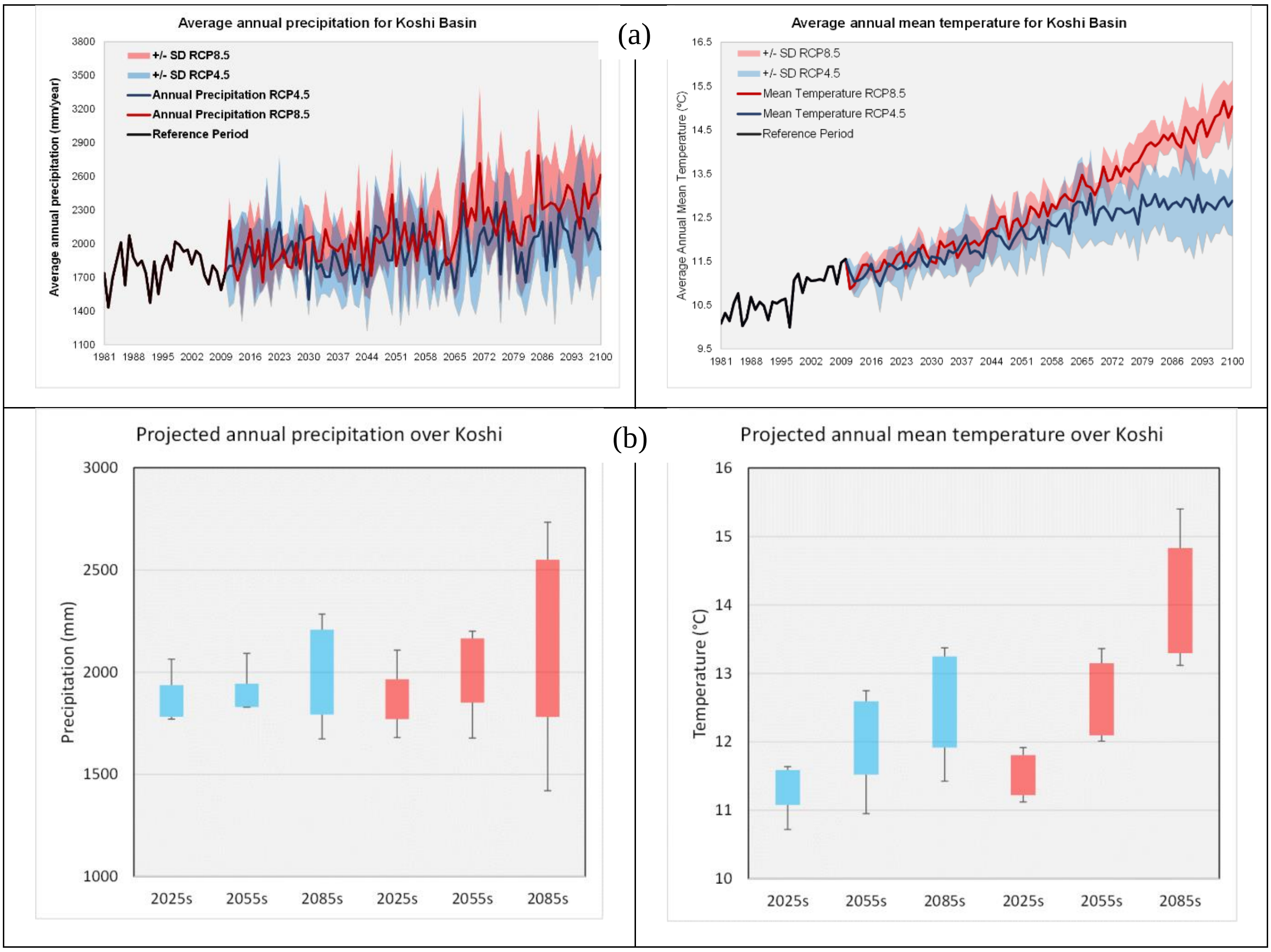


Figure 3. 9. a) Ensemble plot of precipitation and temperature under RCP4.5 (blue) and RCP8.5 (red) for the period of 1981-2100. The coloured band represents the standard deviation from the select GCMs. The black line represents the reference period; b) Projected annual precipitation (mm) and temperature (ºC) for three-time periods for RCP4.5 (blue) and RCP8.5 (red).

Projections of mean air temperature indicate an increase ranging from 1.3 °C to 4.9 °C between 1995s and 2085s, with stronger warming at higher altitudes. The maximum range of uncertainty in the change of temperature is observed during the 2085s under the RCP8.5 scenario, whereas it is the least during the 2025s under the RCP4.5 scenario. The uncertainty in future precipitation is also large, with projections ranging from −7% to +33% between 1995s and 2085s. The uncertainty range is expected to be small in the winter season and more during the monsoon season because during winter basin receives only around 2-5 % of total rainfall. The range is expected to be highest during the 2085s under both scenarios. The range of uncertainty in temperature is not expected to vary much, unlike precipitation, but is expected to increase towards the 2085s. The finding of our result is consistent with the findings of Kaini et al. (2019), MoFE (2019), Bajracharya et al. (2018) and Lutz et al. (2016a).

3.5. Conclusion

This study assessed changes in the future climate and their influence on hydrology in six sub-basins in the Koshi Basin. We use the SWAT model to simulate the surface hydrology of the Koshi Basin up to the Chatara hydrological station and the IHA V7.1 tool to assess the characteristics of the flow regime as hydrological extremes. The hydrological model is forced with an ensemble of downscaled GCMs – representing a wide range of regional RCP4.5 and 8.5 climate conditions for 2025s, 2055s and 2085s. The model output was analysed in terms of projected change in temperature, precipitation, and river discharge and flow extremes. Overall, the results show the sub-basins are likely to be markedly affected by changing temperature and precipitation, as well as the response of river flow in the three-time periods under both scenarios. Furthermore, the responses are varied among sub-basins with impacts being more noticeable at local and seasonal scales. The impacts strongly accelerate with increasing annual mean temperature, and precipitation will result in an altered flow regime up to 2100 with the largest projected increases for RCP8.5 scenarios.

Temperature rise showed differences among the sub-basins, with the greatest increase in the northern sub-basin (sub-basin 1) and the least increase in the southern sub-basin (sub-basin 6) under both scenarios by 2085s. The increase in temperature clearly showed a north-south trend. Regarding the seasonal warming, most sub-basins showed that pre-monsoon is most likely to increase temperature faster than the rest of the seasons under both scenarios. An increase in temperature is likely to be lower in the monsoon season compared to other seasons under both RCPs. Furthermore, among all sub-basins and seasons, the eastern sub-basin (sub-basin 3) showed the highest warming during winter.

Annual precipitation showed an increasing trend among all basins under both RCP4.5 and RCP8.5. The south-western sub-basin (sub-basin 5) is likely to get more precipitation at the end of the century compared to other basins under RCP4.5 whereas the southern sub-basin is likely to get more precipitation under RCP8.5. However, the seasonal breakdown of the precipitation showed different aspects. The dry season is drying more, and the wet season is becoming wetter under RCP4.5, whereas all seasons are becoming wetter under RCP8.5, except for pre-monsoon and post-monsoon in 2025s.

In both RCPs, the annual flow at the outlet of the sub-basins is expected to increase significantly in the 2055s and 2085s compared to the 2025s. But there is high variability in seasonal discharge among sub-basins. Most sub-basins show a decrease in flow during the winter season in all time periods except in 2085s under both RCPs. The western sub-basin (sub-basins 2) and eastern sub-basin are most likely to get surplus water under both scenarios compared to other basins in the 2085s. As the discharge in the western sub-basin is projected to be a significant increase in some seasons as well as a significant decrease in other seasons under both RCPs, it will most likely face the issue of too much or too little water scenario. The western sub-basin will most likely be more vulnerable to climate change than other sub-basins. Furthermore, the eastern sub-basin is likely to have a surplus of water under both scenarios by 2085s. There is a shift in average monthly flow in the central sub-basin (sub-basin 4) and the south-western sub-basin during the 2085s under RCP8.5. Our findings also show that there will be an increase in extreme events i.e. extremely low flows and large floods in future for all sub-basins.

Finally, our findings show that water availability during the century is likely to increase in sub-basins at an annual scale but water availability within inter-annual and seasonal periods will become highly variable. It seems climate change is expected to have greater effects seasonally rather than annually. This change in hydrology could affect water distribution (timing and quantity) in the basin. For instance, a month shift of the average monthly discharge will impact the riverine ecosystem functions that rely on appropriately timed high flows, thus affecting the dispersal of seeds onto the floodplain, survival of certain fish species, and water demand of crops etc. are likely to heavily impact. Our results suggest that the impacts of climate change are scale-dependent in terms of temperature, precipitation, and river flow response. However, there are still large uncertainties associated with the quantitative estimates for future time periods. Thus, the impact of climate change can only be understood if uncertainties are also considered.

The finding of this study will be valuable in identifying how sub-basins are likely to be impacted by climate change and in stipulating effective planning and management of water resources in the future decades. Given the lack of meteorological observation networks, high resolution metrological modelling of the regional climate, this analysis still represents the state of the art for the region.

3.5.1. Limitations

The major limitations of the present study lie with the spatial coverage of ground-based monitoring stations as well as the availability of time series observed hydrometeorological data. In the Koshi Basin, the network of hydrometeorological stations is sparse (Figure 3.1), for instance, most parts of the northern basin do not have meteorological stations even though on the Nepal side the stations are extremely uneven and the number of gauge stations is also small. This is indeed a limitation for understanding the larger variability of the precipitation patterns as well as it is difficult to infer the high-altitude precipitation in rugged topography. Furthermore, limitations for understanding the snow and glacier hydrology of a river basin in mountainous terrain as well as difficulty for model calibration and validation. Thus, we took only two stations (Figure 3.1) for calibration and validation of the hydrological model. It is well known that the more observed data is available, the chance of developing a more accurate model is increased.

3.6.References

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Chapter 4: The response of flow-dependent ecosystem services to climate change within the lateral position of the riverine landscape in the Sunkoshi Basin, Nepal

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Riverine landscape in Tamakoshi River Basin near the confluence of Sunkoshi and Tamakoshi Rivers.

MANUSCRIPT INFORMATION PAGE

The response of flow-dependent ecosystem services to climate change within the lateral position of the riverine landscape in the Sunkoshi Basin, Nepal.

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STATEMENT OF ORIGINALITY

We, the Research PhD candidate and the candidate's Principal Supervisor, certify the following text, tables and figures are the candidate's original work.

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Tables 4.1 – 4.3	207, 215, 222
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STATEMENT OF AUTHORS' CONTRIBUTION

We, the Research PhD candidate and the candidate's Principal Supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the candidate's contribution as indicated in the *Statement of Originality*.

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4.1.Abstract

Flow-dependent ecosystem services are the benefits people obtain from riverine ecosystem functions. These ecosystem services vary according to the physical template of the river system. Climate change will influence the flow regime of rivers and, change the biophysical template of the riverine landscape. The influence of altered flow regimes will vary spatially within riverine landscapes and thus, will drive a spatially heterogeneous response on flow-dependent ecosystem services. In this study, we examine the spatial patterns in the likely response of flow-dependent ecosystem services to climate change with respect to lateral position within the riverine landscape. This study focuses on the Sunkoshi Basin, Nepal, and uses the Soil and Water Assessment Tool (SWAT) and Indicators of Hydrological Alteration (IHA) to assess change under medium (RCP4.5) and high (RCP8.5) emissions future climate scenarios. The results show the distribution of flow-dependent ecosystem services varies laterally across the riverine landscape and the flow regime will likely change and drive different responses in flow-dependent ecosystem services based on lateral position, the two climate scenarios over time. Specifically, there is greater potential for flow-dependent ecosystem services to change in the riparian zone compared to the floodplain and the river channel across the three time periods (2025s, 2055s, and 2085s) under both climate change scenarios. Thus, the response of flow-dependent ecosystem services to climate change is not uniform. Overall, most flow-dependent ecosystem services are projected to be enhanced by the end of the century, suggesting a net benefit to communities in the basin due to increases in the availability of resources.

Keywords: Flow-dependent ecosystem services, riverine landscape, climate change, flow regime, Sunkoshi Basin

4.2.Introduction

Ecosystem services provided by the riverine landscapes are those ecosystem functions from which people derive benefits (Brauman et al., 2007). Benefits are commonly separated into 'supporting services' (e.g., biogeochemical cycling, biodiversity, habitat, refugia), 'regulating services' (e.g., biological processes, climate regulation, erosion, and flood control, regulation of water quality,), 'provisioning services' (e.g., direct or indirect food for humans, fiber, freshwater, power generation, wood), and 'cultural services' (e.g., aesthetic, educational, recreational, spiritual, cremations). Monetary values have been assigned to these services (e.g., Costanza et al., 1997) to illustrate the importance of riverine landscapes to society. Floodplains (US\$25,681 ha^{-1}) and their associated river channels (\$12,512 ha^{-1}) are recognized among the world's most valuable landscapes in terms of ecosystem services (Costanza et al., 2014). Ecosystem services connect or bridge natural and human systems (Biggs et al., 2015). The concept of riverine ecosystem services has been promoted as a means to enhance river-ecosystem management because it frames rivers as social-ecological systems in which there is mutual interdependence between ecosystems and human societies (Biggs et al., 2015).

River floodplains are hotspots for many ecosystem services (cf. Thoms et al., 2016; Tomscha et al., 2017). Floodplains contribute to the provision of more than 25 percent of terrestrial ecosystem services (Tockner and Stanford, 2002), and are significant global agroecosystems (Power, 2010). Variations in local floodplain land-use types result in ecosystem service differences between catchments and even within reaches (cf. Felipe-Lucia et al., 2014; Castro et al., 2018). Applying principles of river science Thorp et al. (2010) and Tomscha et al. (2017) show the capacity of rivers to deliver ecosystem services varies with longitudinal position within a river network, and that this capacity is driven by the physical characteristics of the network (Thorp et al., 2010). In particular, the river reaches with floodplains have an enhanced capacity for supporting, provisioning, and regulating services (Tomscha et al., 2017). However, riverine landscapes also display significant lateral complexity in biophysical character (Thorp et al., 2006) from the river channel (riverscape), through the riparian zone and across the floodplain or floodscape, and this complexity likely translates into complexity in the capacity of the system to provide ecosystem services. Moreover, this complexity is compounded by variations in hydrological connections across the riverine landscape. Flow is the critical driver that maintains ecological processes and ecological integrity (Poff, 2002). Thus, the nature and spatial distribution of ecosystem services also vary laterally within riverine landscapes.

Climate change and its impact on ecosystem services are primary global concerns and challenges for the 21st century (Locatelli, 2016). Landscapes and ecosystems are vulnerable to climate change, even under low- and medium-range scenarios of global warming (Settele et al., 2014). In rivers, alterations to temperature, rainfall and flow regimes, and changes to regional water budgets are commonly projected to occur as a result of global climate change (Yeakley et al., 2016). Projected hydrological changes include increased variability and unpredictability in the character of flow events, with a greater prominence of extreme events; changes in the seasonality of flows, which can result from early snowmelt or no snowfall; and, increases or reductions in annual flow volumes (Gilvear et al., 2016). Given flow is the master variable that shapes the structure and function of riverine landscapes (Walker et al., 1995), sustained hydrological alterations, as a result of climate change, will affect the ecosystem service capacity of riverine landscapes (Stagl and Hattermann, 2016). In the Koshi River Basin, Nepal, climate change is forecast to significantly increase the frequency and duration of bankfull discharges (Doody et al., 2016), providing greater in-channel aquatic habitat for culturally important native water buffaloes. Moreover, projected changes in the timing of early monsoon rainfalls are expected to reduce crop yields from floodplain areas in eastern Nepal by 12.5%, and up to 30% in western Nepal by 2025 (Regmi, 2007).

Changes in streamflows have important implications for water-dependent ecosystems and their associated services (Bharati et al., 2016). Thus, the effect of these projected hydrological changes on ecosystem services is of concern because of the direct link to the livelihoods of the people residing within the riverine landscapes of the region. Combined with the provision of ecosystem services in different parts of riverine landscapes, climate change may also have a differential impact on the provision of ecosystem services within different parts of river landscapes in the Himalayas. Given the importance of riverine landscapes to the region and the impending threat of climate change, well-focused and comprehensive studies are needed for climate change impacts on riverine landscapes in the region.

Retrospective studies on climate change effects on riverine ecosystem services focus on effects at a single site or on longitudinal patterns within the river network (Thoms et al., 2016). Exploration of the potential effect of climate change on ecosystem service capacity in other dimensions of the riverine landscape – the lateral, and time dimensions – are not as common. Given the importance of lateral gradients and connections in riverine landscapes, especially those that include floodplains, we suggest that the impact of climate change on ecosystem services will vary laterally and temporally across riverine landscapes. Therefore, we hypothesise that climate change will have a differential effect on ecosystem services depending on the lateral position within the riverine landscape and over time.

This paper examines the response of ecosystem services to climate change across the riverine landscape (river channel, riparian zone, floodplain) of the Sunkoshi Basin, Nepal. The floodplain of the Sunkoshi Basin contributes to the provision of ecosystem services to more than 80% of the people who reside in the basin. It is an important river corridor connecting the High Himalayas to the lowland regions of Nepal and China; and is a regional biodiversity hotspot. This assessment of the impact of climate change will: 1) provide an outline of ecosystem services across the riverine landscape; 2) determine the hydrological character of the Sunkoshi under different climate scenarios over time; and 3) determine the potential response of ecosystem services to these hydrological alterations across the riverine landscape. This study aims to determine the spatial distribution of ecosystem services across different components of the riverine landscape and, determine the response of flow-dependant ecosystem services to changes in the flow regimes brought about by climate change.

4.3.Study area

The Sunkoshi River drains 3,633 km^2 of the Himalayas in Nepal. It is a sub-catchment of the Koshi River Basin, and elevations within it range from 203 to 6,851 m a.s.l. (Figure 4.1). There are four physiographic regions within the Sunkoshi: the High Himalaya region (19.28% of the catchment), the Middle Mountain region (62.17%), the High Mountain region (14.95%), and the Siwalik region (3.5%) (Figure 4.1). These physiographic regions have different elevations, rainfall, soil, and native vegetation. The Sunkoshi and Tamakoshi are the two principal river systems that drain the Sunkoshi catchment, and the confluence of these two river systems is at the Khurkhot hydrological station. The climate of the Sunkoshi varies across the catchment in association with elevation changes. Mean annual precipitation decreases from >1,100mm in the southern regions of the catchment to <700mm in the northern regions (Khadka et al., 2016). In addition, there is a marked temperature gradient across the catchment also associated with elevation; mean daily temperatures decrease by 5.6°C/km from south to north (Bajracharya et al., 2018).

The primary land uses of the Sunkoshi are diverse across the Basin. There is a clear dominance of forests (47.31%), followed by agriculture (41.61%), and then grasslands (5.72%). Other land-use types include barren land (1.86 %), snow and glaciers (2.34 %), shrubland (0.85%), natural water bodies (0.21%), and urban areas (0.1%). In addition, there are five regional government districts within the Sunkoshi, which administer a population of 13, 88,000 (CBS, 2011). Population densities across the catchment range from 94 persons per km^2 in the Dolkha District to 269 persons per km^2 in the Kavre District. In the productive floodplains of the Kavre District population densities can be >400 persons per km^2. There are 102 km^2 of floodplains in the Sunkoshi Basin, which represents 2.86% of the total basin area.

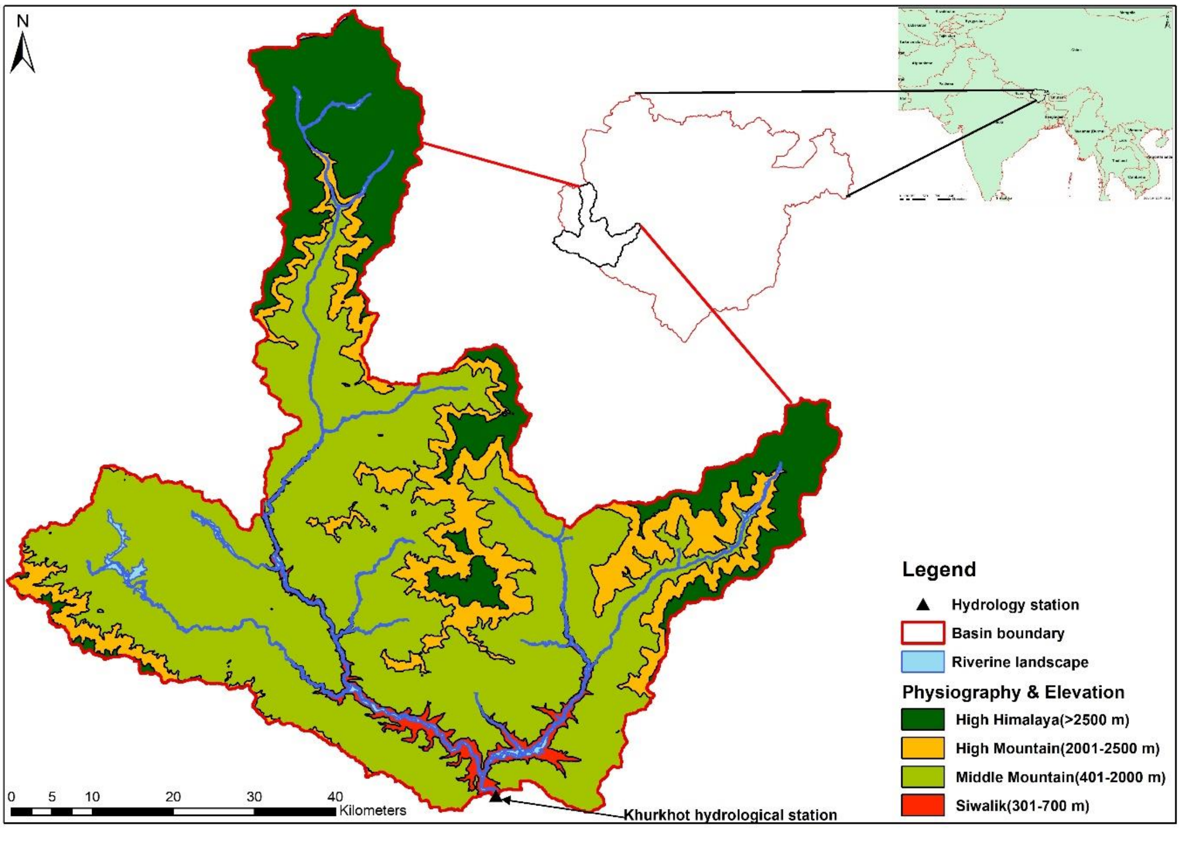


Figure 4. 1. Location map of the Sunkoshi Basin within the greater Koshi River Basin.

The Sunkoshi is a perennial river fed by snow and glacier melt but the hydrological character of river systems in the Sunkoshi is also strongly influenced by monsoonal activity. The monsoon dominates the annual flow of the basin and around 80% of the annual flow occurs during the monsoon. The mean annual discharge (1984-2009) at the Khurkot gauging station is 460 m^3s^{-1}, while Q50 = 172 m^3s^{-1} and Q25 = 737 m^3s^{-1}. The flow regime of the Sunkoshi and Tama Koshi is also influenced by the presence of glacial lakes in the mountain regions of the catchment. Several of these glacial lakes are categorized as potentially hazardous because of their risk of glacial lake outbursts. The water surface area of Lumi Chimi Lake, for example, has increased from 1.67 km^2 to 3.84 km^2 from 1977 to 2004 and is approaching levels of potential instability (Shrestha et al., 2010). Overall, the basin has a high potential for hydropower development, with five hydropower dams currently in operation, and four more planned.

4.4.Method

The response of flow-dependent ecosystem services to climate change in the riverine landscape of the Sunkoshi Basin was determined using five steps. These steps are illustrated in Figure 4.2 and explained in detail in subsequent sections. In brief, first, a Soil and Water Assessment Tool (SWAT) model was used to model future flows for different climate scenarios and time periods. These modeled flows were used to derive Indicators of Hydrological Alteration (IHA) values based on a range of flow regime variables which were applied to the river channel, riparian zone, and floodplain of the Sunkoshi. Second, the response in key riverine ecosystem functions to changes in flow regime was determined. Third, the riverine landscape units were determined, and the ecosystem services of the riverine landscape were collated via a search of relevant studies in Nepalese rivers, field observation, surveying residents, and Nepal census data in the Sunkoshi Basin. These services were then allocated to the three zones of the riverine landscape. Fourth, the direction of the functional response of ecosystem services due to flow regime change in the riverine landscape was determined. Fifth, a matrix on the potential response of ecosystem services in the Sunkoshi riverine landscape was determined and calculated.

4.4.1. Step 1: Determine the flow regimes change for different climate change scenarios.

For this study, we utilised the SWAT hydrological character of the Sunkoshi under various climate change scenarios. SWAT is a flexible and comprehensive simulation tool designed to quantify water provisions at multiple scales (Gassman et al., 2014). The SWAT model has been successfully tested and applied in many Himalayan river basins in Nepal (Bharati et al., 2014, 2016, 2019; Devkota and Gyawali, 2015; Kaini et al., 2021). The SWAT model built for this study of the Sunkoshi used long-term observed daily (1981-2010) climate data (precipitation and temperature), collected at five Department of Hydrology and Meteorology (DHM) stations, and flow data from 1 gauging station throughout the basin as input. To derive the watershed model we used a 90m×90m resolution Shuttle Radar Topography Mission (SRTM) with 2010 land use data at a 30m resolution, obtained from the International Centre for Integrated Mountain Development (ICIMOD), along with soil data obtained via the Soil and Terrain Database Programme (SOTER).

Model evaluation is essential to measure the consistency of its output. It is considered reliable if the evaluation statistics fall within an acceptable limit (Moriasi et al., 2007). According to Moriasi et al. (2007), a model is deemed suitable for stream flow simulation, if PBIAS is within ±15% and NSE is above 0.75. We calculated the PBIAS, NSE, and Coefficient of Determination (R^2) to verify our SWAT results. The SWAT model was calibrated and validated at the Khurkot hydrological station. This hydrological station is operated by DHM and there is no effect of hydropower dams on river discharge. Observed daily discharge data (1986 to 2008) for the Khurkot gauging station (Figure 4.1) were used to calibrate (1986 to 1994) and validate (2000 to 2008) the SWAT model. Model calibration was done via SWAT-

CUP, and the validation was done by comparing or visually matching the simulated flows with observed flows. I did not use the data from 1995 to 1999 for both calibration and validation due to data gaps and data errors. Once the SWAT model was calibrated and validated from observed data and able to simulate the discharge at the outlet of the catchment realistically, the validated SWAT model is ready to run with the future climate scenario data.

Two future climate scenarios generated for the Sunkoshi were downloaded from ICIMOD (http://rds.icimod.org/clim) the previous datasets generated by Lutz et al. (2016). This data was prepared based on selected the Coupled Model Intercomparison Project 5 (CMIP5) General Circulation Model (GCM) and downscaled to a 10x10 km spatial resolution and daily time steps (Lutz et al., 2016). The GCMs were selected for the region using the 'Envelope' approach and bias-corrected using Quantile mapping. In the envelope approach, the projected climate covers the full possible range of future situations ranging from dry and cold projections to wet and warm projections. The approach also looks at past performance. Table 4.1 shows the chosen climate models used for this study.

Table 4. 1. Selected climate models and scenarios as part of a study by Lutz et al. (2016).

RCP	Projected Climate Conditions	Selected GCM
RCP4.5	Warm, dry	CMCC_CMS_r1i1p1
	Warm, wet	CSIRO-MK3-6.0_r4i1p1
	Cold, wet	BNU_ESM_r1i1p1
	Cold, dry	inmcm4_r1i1p1
RCP8.5	Warm, dry	CMCC_CMS_r1i1p1
	Warm, wet	CanESM2_r3i1p1
	Cold, wet	bcc-csm1-1_r1i1p1
	Cold, dry	inmcm4_r1i1p1

Source: http://rds.icimod.org/clim

The download data was averaged from the four selected GCMs for RCP4.5 and four selected GCMs for RCP8.5. In other words, the four selected GCMs for RCP4.5 were averaged to make one ensemble average of RCP4.5, and four selected GCMs for RCP8.5 were averaged to make one ensemble average of RCP8.5. These ensemble average datasets (RCP4.5 and RCP8.5) were used for running the validated SWAT model. For this study, we used 30 (1981 - 2010) years of average annual climate variable (Temperature and Precipitation) as a reference period whereas 2025s (2011 - 2040), 2055s (2041 - 2070), and 2085s (2071 - 2100) as a projected future data to see the change in climate and flow regime between the reference and future projection in the Sunkoshi Basin.

The validated SWAT model was forced with reference and future climate datasets under two scenarios (RCP4.5 and RCP8.5). Altogether, the validated SWAT model was run seven times, first for the reference period, and then for the two climate scenarios (RCP4.5 and 8.5) and three future periods of 2025s, 2055s, and 2085s. The simulated SWAT model thus provided seven outputs (reference and six future projected) for daily temperature, precipitation, and discharge across the Sunkoshi Basin. The discharge obtained from the simulating reference dataset was treated as baseline data. These reference period simulated discharges were compared with future simulated discharges from the future change in flow regime.

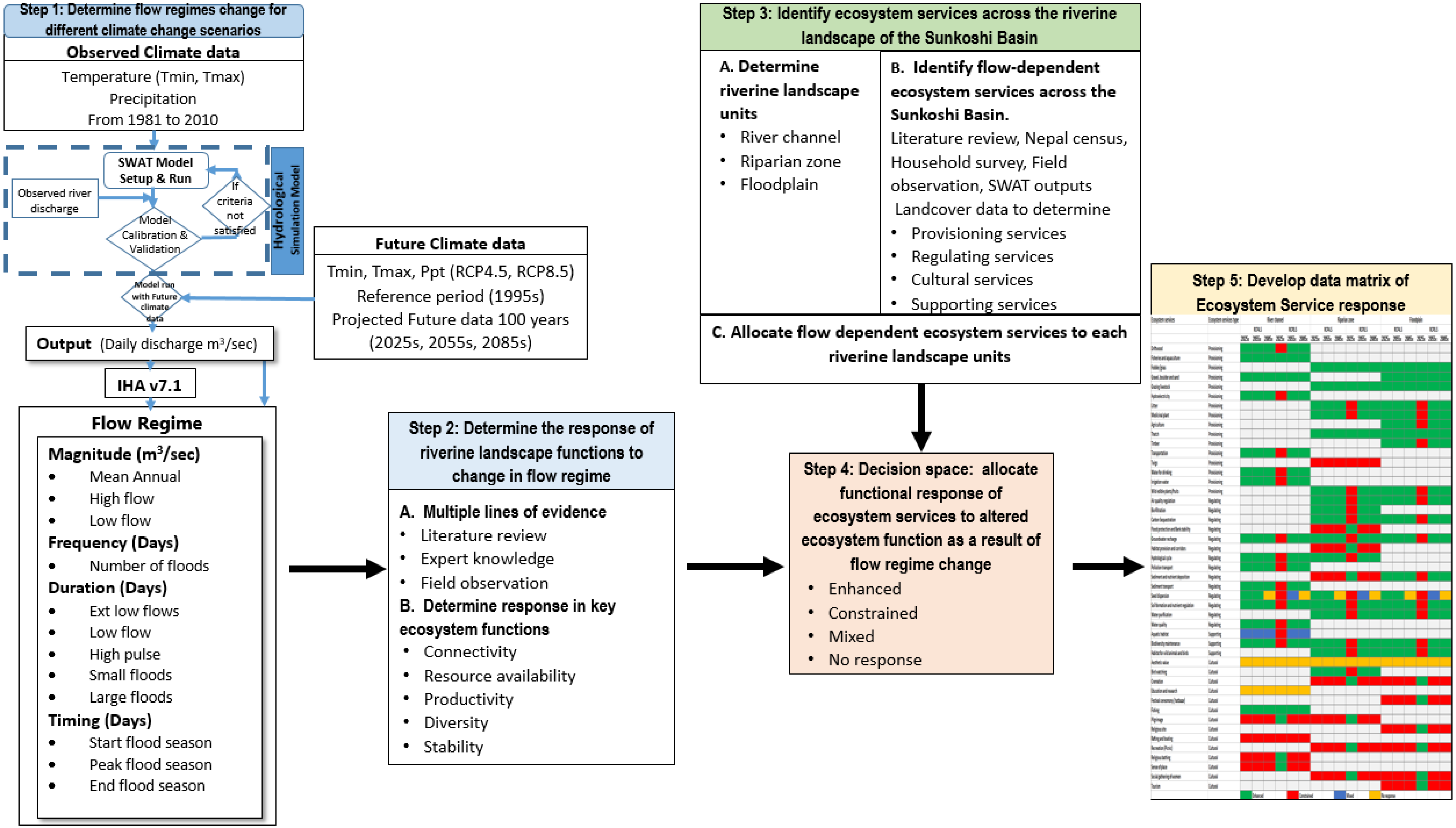


Figure 4. 2. Determining the response of flow-dependent ecosystem services to potential climate change across the riverine landscape of the Sunkoshi Basin, Nepal. For each climate scenario, 100 years of daily data were generated, and these were grouped into three time periods; the present to 2040 (2025s), 2041 to 2070 (2055s), and 2071 to 2100 (2085s). The Household survey data was obtained from the ICIMOD Poverty and Vulnerability Assessment (PVA) data. The Nepal Census data was from the Nepal National Census of 2011. SWAT - Soil and Water Assessment Tool.

The simulated daily discharge from SWAT was input for the Indicators of Hydrological Alteration (IHA) to generate characteristics of the flow regime. Four elements of the flow regime were examined: magnitude, frequency, duration, and timing. The fifth element of the flow regime – the rate of change – was not examined in this study. Three magnitude variables (annual discharge, high/peak discharge, low discharge), one frequency variable (frequency of flood), five duration variables (large flood duration, small flood duration, high pulse duration, low flow duration, extreme low flow duration), and three timing variables (start of wet season, finish of wet season, peak discharge timing) were calculated using the Indicators of Hydrological Alteration (IHA) tool Version 7 (The Nature Conservancy, 2009). Individual data sets of daily discharge for two climate scenarios and three-time slices were run through the IHA tool to generate the 12 variables characterising the flow regime in the Sunkoshi Basin.

An extreme low flow was defined as an initial low flow below Q90 (10th percentile of all low flows) of the daily flows of the period. Flows exceeding Q25 of daily flows for the period were classified as high flows and those below Q50 of daily flows for the period were classified as low flows. A small flood was defined as an initial high peak flow of 2 to 10 years return interval. In addition, a large flood event was defined as an initial high flow with a peak flow greater than 10 years return interval event (Mathews & Richter, 2007; Indicator of Hydrological Alteration, User Manual, 2009). The five flow components provide a heuristic framework for describing how an organism experiences river flow variability (c.f Mathews & Richter, 2007). For instance, low flows determine the quantity and quality (e.g., flow velocity, connectivity, temperature, etc.) of aquatic habitat that is available for most of the year. The flow variables used in this study reflect the full range of naturally varying river flows.

4.4.2. Step 2: Determine the response of riverine landscape functions to changes in flow

Multiple lines of evidence approach were taken to determine the response of riverine landscape functions to changes in the flow regime. Potential changes in five ecosystem functions of connectivity, resource availability, productivity, diversity, and stability (cf. Thorp et al., 2008) were derived for the Sunkoshi River. The scientific literature (Bharati et al, 2019; Mathews and Richter, 2007; Indicator of Hydrological Alteration, User Manual, 2009; Rai et al., 2019; Datry et al., 2017) was used to determine the link between flow regime changes and ecosystem function changes.

For instance, changes to the duration variables of extreme low flows, low flow, high flow pulses, small floods, and large floods all have the potential to influence the five functions. Low flows and extreme low flows reduce connectivity that might result in locally increased productivity within the channel while reducing the productivity of the riparian zone and floodplain due to water limitations. High flow pulse will increase riparian connectivity, which might increase resource availability and diversity in the riparian zone but reduce in-channel productivity. Small floods will increase connectivity and increase floodplain and riparian productivity and resource availability etc. Large floods occur rarely but play a critical role in a river ecosystem by typically re-arranging both the biological and physical structure of a river and its floodplain. It is important in forming key habitats in the riverine landscape and influencing resource availability, productivity, and diversity function, for instance by flushing organic materials and woody debris into the channel and depositing gravel and cobbles in the floodplain. During large floods, there will be lateral connectivity between the channel, riparian zone, and floodplain.

Changes to the frequency of the number of floods will increase the connection among the three riverine landscape units and increase productivity, resource availability, and diversity within a floodplain and riparian zone. Changes to the magnitude of the mean annual, high flow, and low flow all have the potential to influence the key ecosystem functions. In terms of annual flow (magnitude), and the start and end of the flood season (timing), there will be no influence at all on lateral connectivity. However, changes to the duration of the peak flood season will have implications for lateral connectivity and influence resource, productivity, and habitat ecosystem functions. However, annual flow represents the surface water availability in the river and provides an overview of habitat and resource availability in the riverine landscape. This understanding of the relationships between flow regime variables and river ecosystem function was used to infer the response of these functions to flow change in the Sunkoshi Basin. Finally, based on these relationships, the matrix table (Figure 4.4) was prepared to set out the response of riverine landscape functions to changes in flow regime. The main analysis is based on the logic that climate change will change the flow regime, and this will affect ecosystem function via the effects on the various flow regime components. As outlined above, these effects will vary depending on the lateral position of the different riverine landscape units.

4.4.3. Step 3: Identify flow-dependent ecosystem services associated with riverine landscape units

4.4.3.1. Determine the riverine landscape units of the Sunkoshi Basin

The riverine landscape can be divided into riverine landscape units, which are structurally and functionally distinct components of the riverine landscape arranged laterally, the river channel, the riparian zone, and the floodplain. These riverine landscape units were delineated as follows. The drainage network (river channel), watershed boundary, flow direction, and flow accumulation of the Sunkoshi Basin were prepared from a 90 m SRTM Digital Elevation Model from Arc Hydro tool in ArcGIS. These outputs were inputs for running the Floodplain Model (FLDPLN, Kastens 2008) to determine floodplain extent as a function of floodwater depth. This output was input to the Valley Floor Mapper model to delineate the valley floor area. The valley floor area was used as a surrogate for potential floodplain areas. The river channel was used to generate the riparian zone assuming the width of the riparian zone is 30 meters from the river channel. Then, it was buffered 30 meters from the river channel via ArcGIS.

4.4.3.2. Identify the flow-dependent ecosystem services across the Sunkoshi Basin

We used three approaches to identify the distribution of ecosystem services in the riverine landscape. First, the literature was reviewed focusing on the ecosystem services of riverine landscapes in Nepal. Second, ecosystem services data was gathered from the survey data of ICIMOD (Poverty and Vulnerability Assessment data) carried out in the Sunkoshi basin as well as from the Nepal census data. Third, ecosystem services were identified from field observation. From the literature review, surveys, and field observation, a list of the ecosystem's goods and services was prepared (Table 4.2). The list was then categorized into provisioning, regulating, cultural, and supporting services following the MEA framework, 2005. Next, the provisioning, regulating, cultural, and supporting ecosystem services associated with the riverine landscape of the Sunkoshi were partitioned into the three riverine landscape units of the river channel, riparian zone, and broader floodplain. Here, and through the remainder of the paper, the ecosystem services denote the flow-dependent ecosystem services.

4.4.4. Step 4: Response of flow-dependent ecosystem services to a change in ecosystem function as a result of flow regime change

Connectivity is a key determiner of the inferred response of flow-dependent ecosystem services to climate change. The combination of steps 2 (response of ecosystem function to flow regime) and 3 (list of flow-dependent ecosystem services and where they are) provide the knowledge to determine the functional response of flow-dependent ecosystem services to a change in riverine ecosystem function and helps to make reasoned decisions in step 4. Multiple lines of evidence, including literature review (Rai et al., 2019; Datry et al., 2018; Poff, 2002; Gibson et al., 2005; Palmer et al., 2009; Poff and Zimmerman, 2010; Grizzetti et al., 2016; Papadaki et al., 2016; Carolli et al., 2017; Cui et al., 2018; Schneider et al., 2013; Vaughn et al., 2015; Shrestha and Aryal, 2010; Bunn and Arthington, 2002; Chang and Bonnette, 2016; Sesana et al., 2021; Davis, 2018; Campagne et al., 2017; Talbot et al., 2018) expert opinion and knowledge and field observation were used to determine the response (enhanced, constrained, mixed and no response) of flow-dependent ecosystem services due to changes in ecosystem function. The field observation photo and literature used to determine the direction of response are listed in Annex I and II. A similar approach was used by Schneider et al. (2014); and Hornung et al. (2019) to link the impact of measures and human activities to ecosystem services.

For instance, if there is a high flow, it will increase lateral connectivity, allow access to new habitats, resources, and thus enhance the fish productivity means the provisioning system is enhanced. If the duration of extreme low flow increases then habitat availability in the floodplain will decrease due to disconnection to the floodplain. Low flows will always influence the river channel due to limited water as well as during the low flow there will be potential for fragmentation of aquatic habitats and organisms.

Table 4. 2. Riverine landscape and ecosystem goods and services in the study area.

Riverine landscape	Ecosystem goods and services			
	Provisioning Services	Regulating Services	Cultural Services	Supporting Services
River channel (Rc)	Fisheries and aquaculture, water for drinking, hydroelectricity, water for non–drinking, driftwood, gravel, boulder, and sand, transportation	Sediment transport, seed dispersion, pollution transport, hydrological cycle, water quality, soil formation and nutrient regulation, groundwater recharge	Aesthetic value, education and research, rafting and boating, pilgrimage, religious bathing, sense of place, fishing	Biodiversity maintenance, aquatic habitat
Riparian zone (Rz)	Twigs, medicinal plants, fodder/grass, thatch, grazing livestock, litter, wild edible fruits/plants	Bio-filtration, flood protection and erosion prevention, carbon sequestration, hydrological cycle, seed dispersion, soil formation and nutrient regulation, air quality regulation, water purification, groundwater recharge, habitat provision and corridors, sediment and nutrient deposition	Aesthetic value, recreation, pilgrimage, bird watching, cremation, social gathering of women while washing their household stuff	Biodiversity maintenance, habitat for mammals, birds, reptiles and amphibians
Floodplain (Fp)	Sand and gravel for building, fodder/grass, thatch, timber, grazing livestock, wild edible plants/fruits, litter, sustain agricultural productivity, medicinal plants	Water purification, groundwater recharge, sediment and nutrient deposition, air quality regulation’ carbon sequestration, seed dispersion, soil formation and nutrient regulation	Aesthetic value, festival ceremony (Hat-bazar), presence of temple and religious site, social gathering of women while washing their household stuff, recreation, cremation, tourism	Biodiversity maintenance, habitat for wild animals and birds

4.4.5. Step 5: Response of flow-dependent ecosystem services to climate change

To determine the response of 47 flow-dependent ecosystem services to climate change, a matrix model method was used. The model consists of a relatively simple matrix with the 47 ecosystem services (Figure 4.6a) forming the rows and the three zones of riverine landscapes (Rc, Rz, and Fp), two climate scenarios (RCP4.5 and 8.5), three-time periods (2025s, 2055s and 2085s) forming columns (Figure 4.2, 4.5a). Finally, the derived responses of flow-dependent ecosystem services to climate change were tallied to determine the total impact of climate change on the three riverine landscape components (river channel, riparian zone, and floodplain) such that the flow-dependent ecosystem services were determined to be enhanced, constrained, to experience a mixed and no response. A similar matrix approach was used by Burkhard et al. (2009); Burkhard et al. (2012); Schneider et al. (2013); Burkhard et al. (2014); Sohel et al. (2015); Jacobs et al. (2015) to assess the capacities of different land cover classes to supply of ecosystem services.

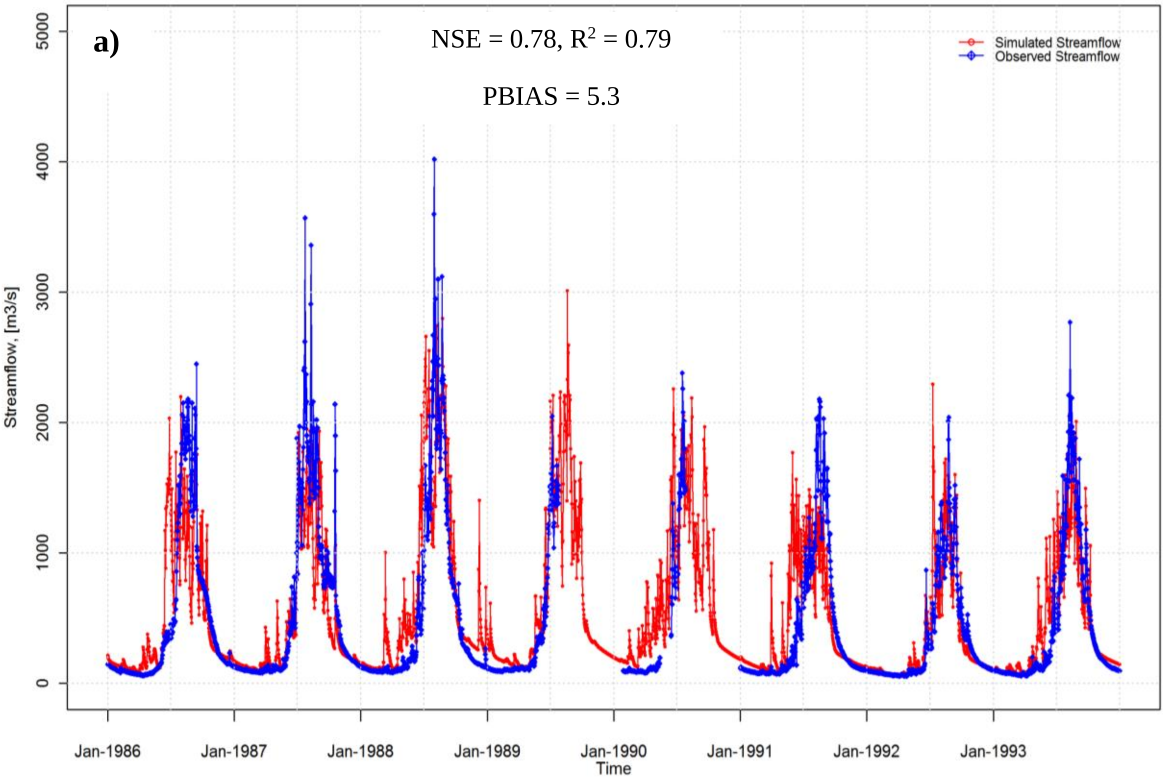
4.4.6. Limitations of the study

The major limitations of the present study lie in the limited household and ecosystem services data availability and accurate information in the high Himalayan areas (The northern part of our study area). These areas are very remote and have less accessibility. Due to the unavailability of ecosystem services data, we used landcover and SWAT outputs as proxy ecosystem services to fulfill those gaps. Furthermore, changes in vegetation due to climate change is unavoidable, but land use change scenarios data are unavailable. Thus, the model was run with static land use data assuming no change in vegetation.

4.5. Results

4.5.1. Calibration and validation of the SWAT model.

The SWAT model result shows a good agreement between simulated and observed stream flow at the Khurkot hydrological station (Figure 4.3 a, b). Calibration output values for the Sunkoshi SWAT were NSE (0.78), R^2 (0.79), and PBIAS (5.3). The validation values of NSE (0.76), R^2 (0.75), and PBIAS (-4.6). These values are all high, representing the robust highly predictive capacity of the Sunkoshi SWAT model. Therefore, it showed that the SWAT model was able to simulate the discharge at the catchment with reasonably high accuracy.



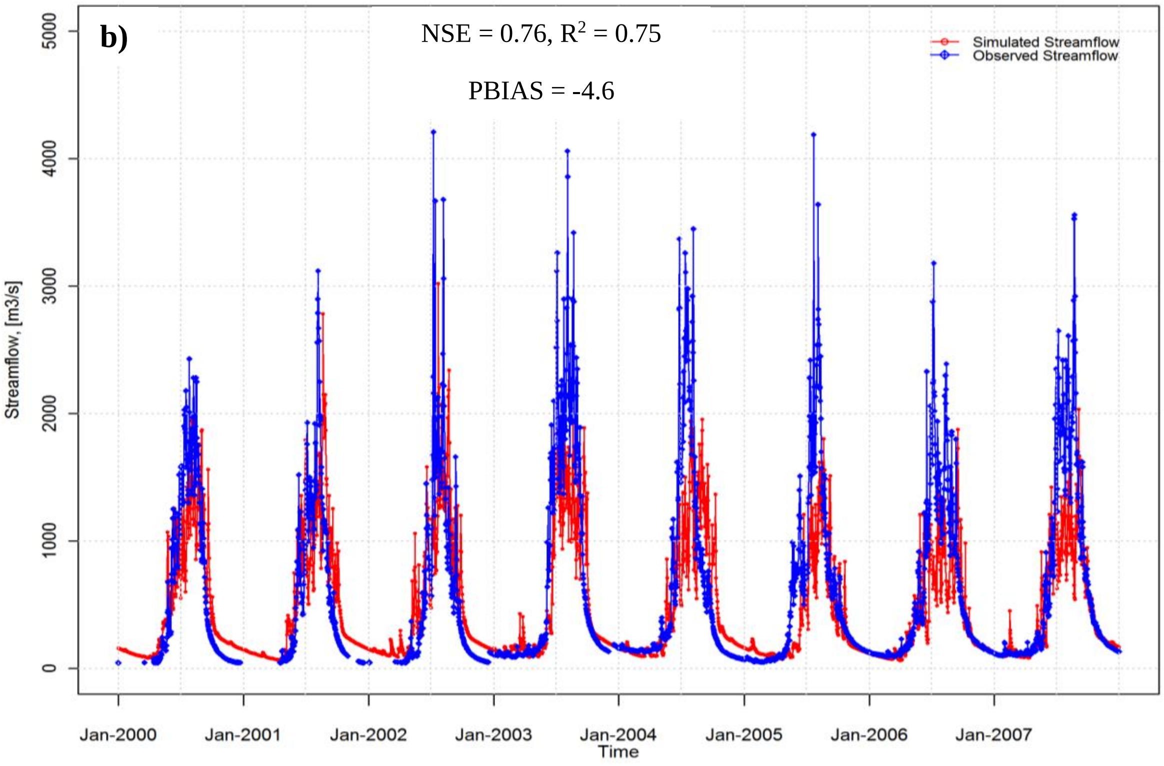
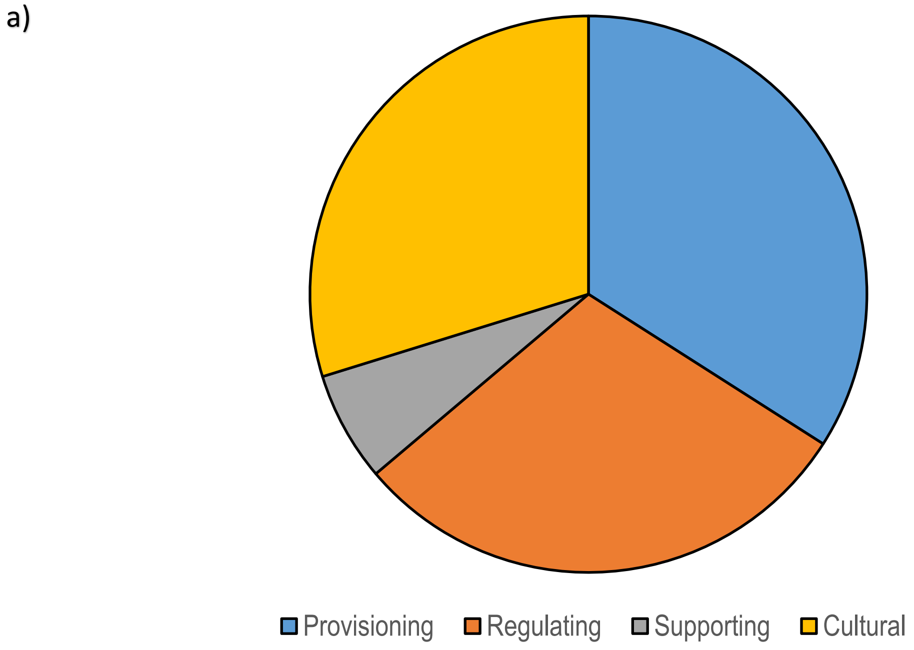
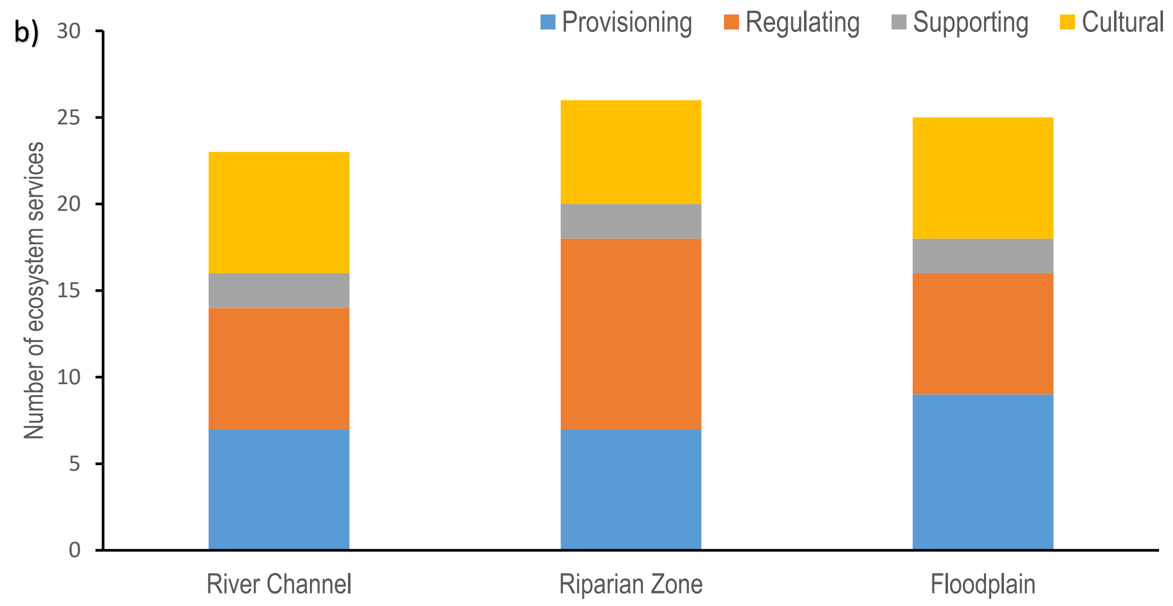


Figure 4. 3. a) Calibration of the SWAT model of the Sunkoshi Basin at Khurkot hydrological station from 1986 to 1994, b) Validation of the SWAT model of the Sunkoshi Basin at Khurkot hydrological station from 2000 to 2008.

4.5.2. Flow-dependent ecosystem services in the Sunkoshi riverine landscape

A total of 47 flow-dependent ecosystem services were observed across the Sunkoshi riverine landscape, of which there were more provisioning services (16) than regulating (14), cultural (14), and supporting services (3) (Figure 4.4a). Although most were present in all three riverine landscape zones, there was a significant difference in the distribution of flow-dependent ecosystem services between the river channel, riparian zone, and floodplain zones (Kolmogorov Smirnov test: $p<0.01$). There were more flow-dependent ecosystem services in the riparian zone compared to the floodplain and the river channel zones (Figure 4.4b). Overall, provisioning services were dominant in the floodplain, whereas regulating services were dominant in the riparian zone. By comparison, supporting services were equally distributed among all three riverine landscape zones (Figure 4.4b) while cultural services were evenly distributed between the river channel and floodplain zones only (7). Thus, a complex pattern of ecosystem services emerged among the three zones. Of the 47 flow-dependent ecosystem services, 15 flow-dependent ecosystem services (e.g. Hydroelectricity, transportation) were only found in the river channel, whereas five were unique to the riparian zone (e.g. flood protection and bank erosion, biofiltration, etc), and five (e.g. Agriculture, festival ceremony) were only found in the floodplain. In contrast, 14 flow-dependent ecosystem services were found in both the riparian, floodplain zones and three of which were regulating services (Figure 4.4c).





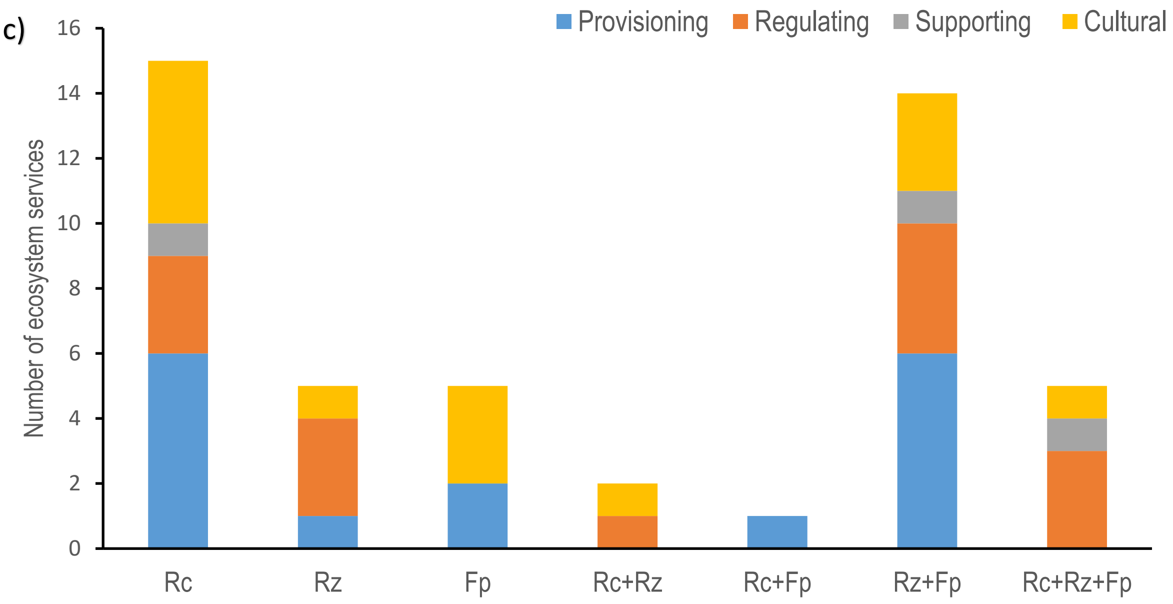


Figure 4. 4. a) Number of flow-dependent ecosystem services in the Sunkoshi Basin; b) The distribution of ecosystem services across the riverine landscape of the Sunkoshi Basin; c) Unique and shared ecosystem services in the riverine landscape in the Sunkoshi Basin. Where Rc= River channel, Rz= Riparian zone, Fp= Floodplain.

4.5.3. Expected flow regime changes in the Sunkoshi Basin

4.5.3.1. Potential flow alteration in the Sunkoshi Basin with climate change

Significant alterations to the flow regime of the Sunkoshi Basin are expected to occur as a result of climate change. The magnitude, frequency, duration, and timing of flows will all potentially change but these changes will differ among the three riverine landscape zones, as well as the two climate scenarios and over time for each scenario (Figure 4.5a). The river channel will experience changes to all components of the flow regime (magnitude, frequency, duration, and timing of flows) whereas low flow changes (magnitude, duration) within channel flows will not be relevant to the riparian zone or floodplain zones. Potential flow changes in the riparian and floodplain zones are dominated by changes in the magnitude, duration, and timing of overbank flows.

Increases in flood activity will be a prominent change to the flow regime of the Sunkoshi Basin (Figure 4.5 a, b). The magnitude, frequency, and duration of flood events will increase as will the duration of extremely low flows, compared to the reference period. The timing of the flood season in the Sunkoshi Basin will also change. On average, the onset of the flood season will be delayed by up to 7 days and the finish of the flood season will be extended by 8 days.

4.5.3.2. Potential flow alteration between two climate scenarios

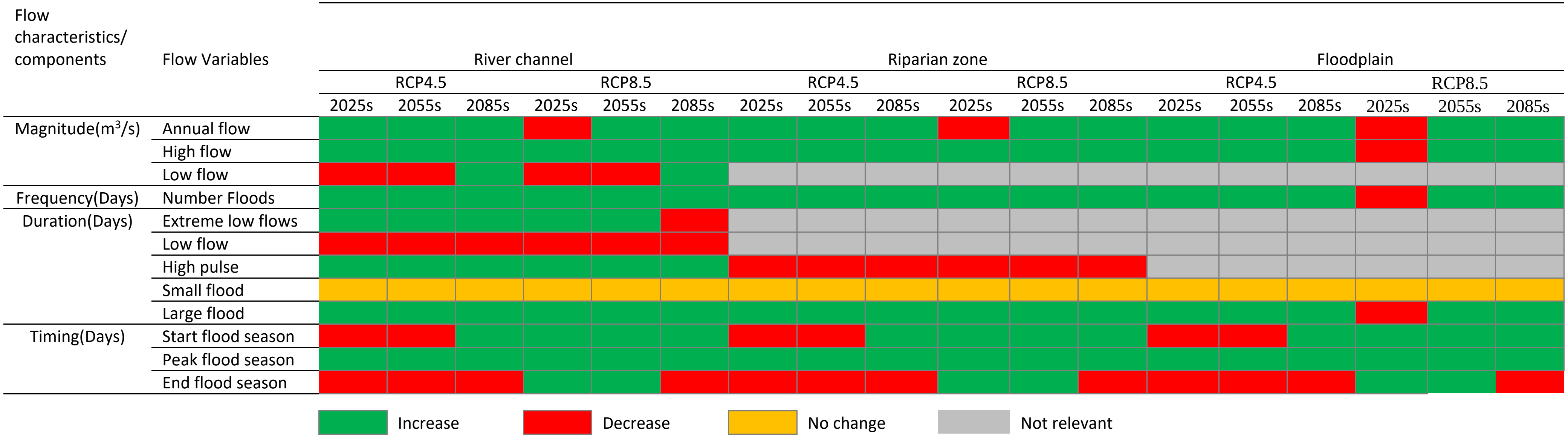
Expected flow regime changes will differ between the two climate scenarios, especially in terms of the magnitude, duration, and timing of flows (Table 4.5a). The flood season under the RCP4.5 scenario will be shorter compared to that under the RCP8.5 scenario. A similar is also evident over time. For example, under the RCP8.5 scenario both the start and finish of the flood season are projected to be delayed. Furthermore, high flow, the number of floods, and large floods are projected to increase for all three future periods under both climate change scenarios, except for the floodplain in the 2025s under RCP8.5 where a decrease is projected. The duration of low flows is projected to decrease under both scenarios and all future time periods. In contrast, the duration of extremely low flows is projected to increase in all time periods and both scenarios except for the 2085s under RCP8.5 in the river channel.

Table 4. 3. The percentage change in discharge for Sunkoshi Basin and time periods under both scenarios compared to the reference period.

	Change in discharge (%)					
	RCP4.5			RCP8.5		
	2025s	2055s	2085s	2025s	2055s	2085s
Winter	-20.3	-10.6	5.2	-23.8	-16.4	8.4
Pre-Monsoon	-18.5	4.8	-2.2	62.0	115.7	123.2
Monsoon	3.4	18.7	33.9	-3.1	16.1	41.7
Post-Monsoon	9.5	23.3	53.4	-9.1	12.0	47.0
Annual	0.1	15.4	30.4	-0.4	20.7	45.7

Projected discharges in the Sunkoshi Basin are expected to increase by the end of the century under both climate scenarios. The average annual discharge is likely to increase by 15 to 30% under the RCP 4.5 scenario and 20 to 45% under the RCP 8.5 scenario in the 2055s and 2085s but is likely to decrease in 2025s under both RCPs (table 4.3). Overall, flows are projected to increase more under RCP8.5 compared to RCP4.5. Seasonal increases in discharge are projected to be maximal during the post-monsoon under RCP 4.5 (53%) and during the pre-monsoon under RCP 8.5 (123%) in the 2085s. However, during the dry/winter and pre-monsoon seasons decreases in discharge are projected for 2025s under RCP4.5. Similarly, discharge is expected to decrease during dry, monsoon, and post-monsoon in 2025s under RCP8.5.

a)



Flow characteristics/ components	Flow Variables	River channel						Riparian zone						Floodplain					
		RCP4.5			RCP8.5			RCP4.5			RCP8.5			RCP4.5			RCP8.5		
		2025s	2055s	2085s	2025s	2055s	2085s	2025s	2055s	2085s	2025s	2055s	2085s	2025s	2055s	2085s	2025s	2055s	2085s
Magnitude(m^3/s)	Annual flow	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩
	High flow	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩
	Low flow	🟥	🟥	🟩	🟥	🟥	🟩	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
Frequency(Days)	Number Floods	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩
Duration(Days)	Extreme low flows	🟩	🟩	🟩	🟩	🟩	🟥	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
	Low flow	🟥	🟥	🟥	🟥	🟥	🟥	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
	High pulse	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟥	🟥	⬜	⬜	⬜	⬜	⬜	⬜
	Small flood	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
	Large flood	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩
Timing(Days)	Start flood season	🟥	🟥	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟥	🟥	🟩	🟩	🟩	🟩
	Peak flood season	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	End flood season	🟥	🟥	🟥	🟩	🟩	🟥	🟥	🟥	🟥	🟩	🟩	🟥	🟥	🟥	🟥	🟩	🟩	🟥

🟩 Increase 🟥 Decrease 🟨 No change ⬜ Not relevant

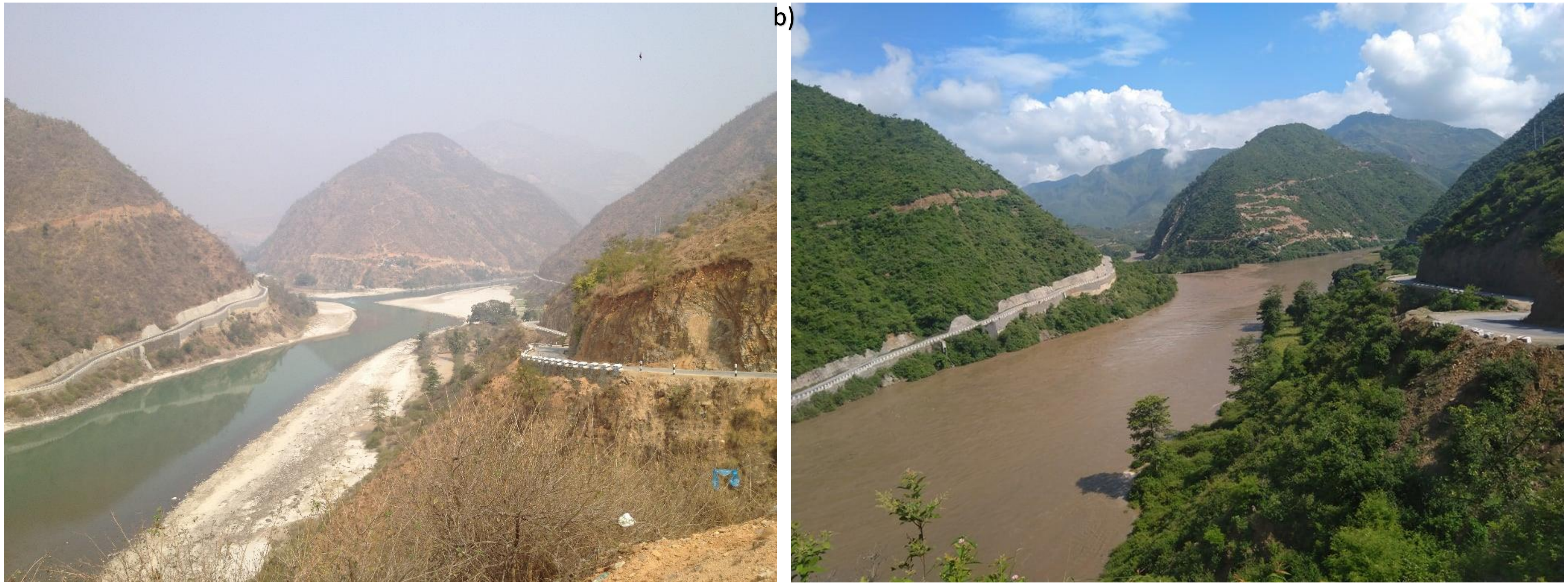


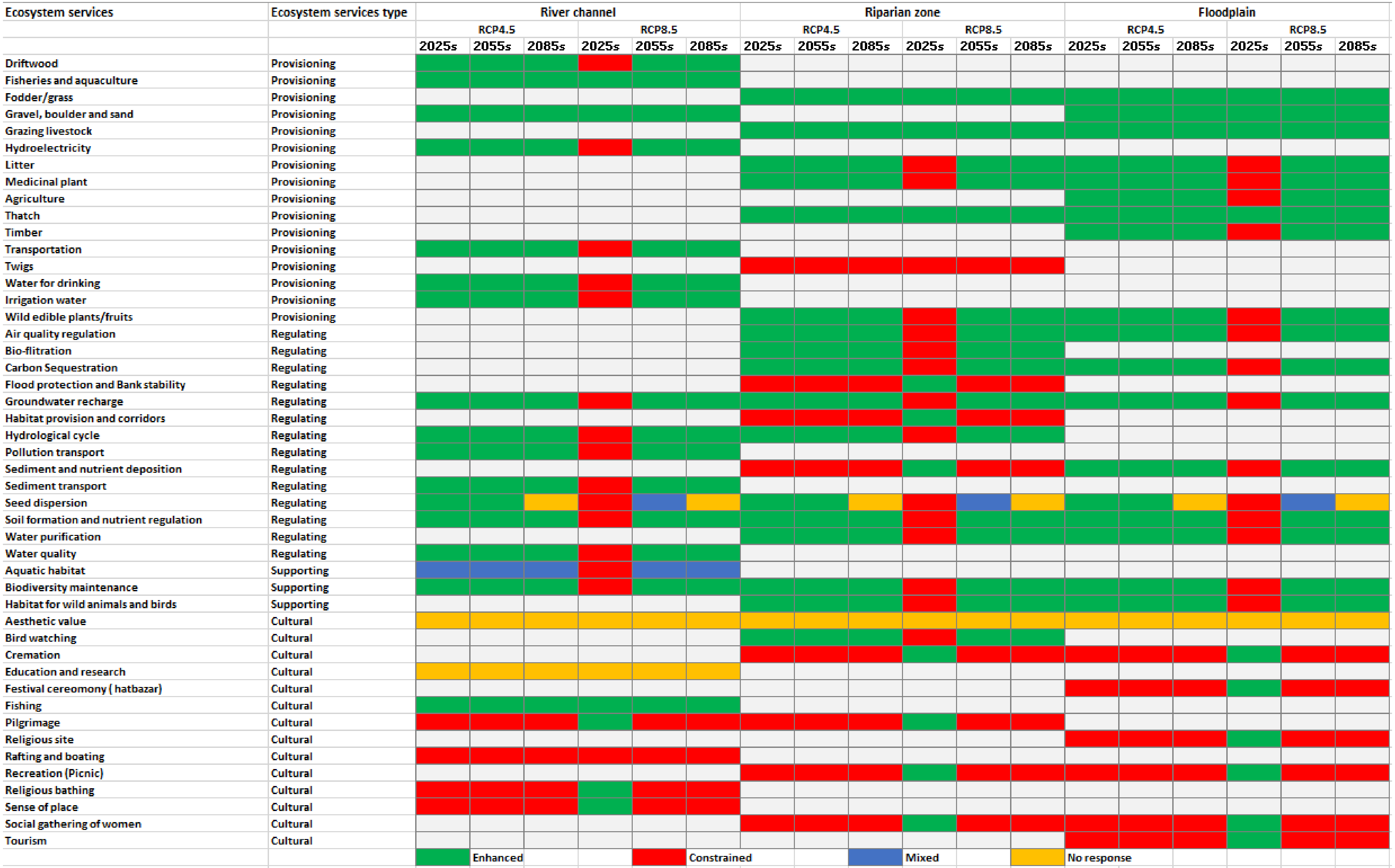
Figure 4. 5. a) Flow regime changes in the Sunkoshi River associated with different climate scenarios. This heat map displays the direction of change for 12 flow variables in two climate scenarios and three time periods; b) Flow during the winter/dry season in Sunkoshi (2019 February); Flow during the monsoon/wet season in Sunkoshi increase flood activity (2019 July flood).

4.5.4. Potential response of flow-dependent ecosystem services in the Sunkoshi Basin

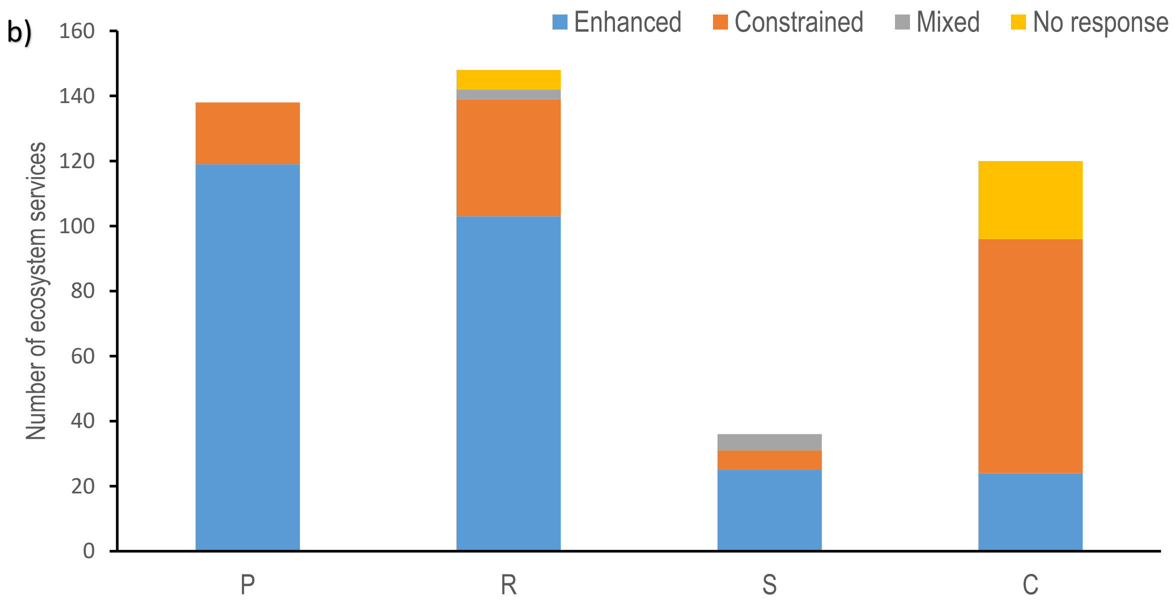
4.5.4.1. Influence of climate-induced flow regime changes on flow-dependent ecosystem services

The majority (45 of 47) of the flow-dependent ecosystem services observed across the riverine landscape are predicted to respond to potential flow regime changes. The two cultural services of aesthetic value, and education and research are predicted to not respond to the potential flow change (Figure 4.6a). The predicted response to flow regime change varies with flow-dependent ecosystem services type, their position across the riverine landscape, the climate change scenario, and, over time. Overall, most ecosystem service types are expected to be enhanced by the changes in flow regime due to climate change: i.e. 119 provisioning services, 103 regulating services, 25 supporting services, and 24 cultural services are predicted to be enhanced. By comparison, 19 provisioning, 36 regulating, 6 supporting and 72 cultural services are expected to be constrained by the projected flow regime changes. In addition, 3 regulating, and 5 supporting services will have a mixed response, being both enhanced and constrained (Figure 4.6b).

a)



Ecosystem services	Ecosystem services type	River channel						Riparian zone						Floodplain					
		RCP4.5			RCP8.5			RCP4.5			RCP8.5			RCP4.5			RCP8.5		
		2025s	2055s	2085s	2025s	2055s	2085s	2025s	2055s	2085s	2025s	2055s	2085s	2025s	2055s	2085s	2025s	2055s	2085s
Driftwood	Provisioning	🟩	🟩	🟩	🟥	🟩	🟩												
Fisheries and aquaculture	Provisioning	🟩	🟩	🟩	🟩	🟩	🟩												
Fodder/grass	Provisioning							🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Gravel, boulder and sand	Provisioning	🟩	🟩	🟩	🟩	🟩	🟩							🟩	🟩	🟩	🟩	🟩	🟩
Grazing livestock	Provisioning							🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Hydroelectricity	Provisioning	🟩	🟩	🟩	🟥	🟩	🟩												
Litter	Provisioning							🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩
Medicinal plant	Provisioning							🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩
Agriculture	Provisioning													🟩	🟩	🟩	🟥	🟩	🟩
Thatch	Provisioning							🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Timber	Provisioning													🟩	🟩	🟩	🟥	🟩	🟩
Transportation	Provisioning	🟩	🟩	🟩	🟥	🟩	🟩												
Twigs	Provisioning							🟥	🟥	🟥	🟥	🟥	🟥						
Water for drinking	Provisioning	🟩	🟩	🟩	🟥	🟩	🟩												
Irrigation water	Provisioning	🟩	🟩	🟩	🟥	🟩	🟩												
Wild edible plants/fruits	Provisioning							🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩
Air quality regulation	Regulating							🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩
Bio-flitration	Regulating							🟩	🟩	🟩	🟥	🟩	🟩						
Carbon Sequestration	Regulating							🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩
Flood protection and Bank stability	Regulating							🟥	🟥	🟥	🟩	🟥	🟥						
Groundwater recharge	Regulating	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩
Habitat provision and corridors	Regulating							🟥	🟥	🟥	🟩	🟥	🟥						
Hydrological cycle	Regulating	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩						
Pollution transport	Regulating	🟩	🟩	🟩	🟥	🟩	🟩												
Sediment and nutrient deposition	Regulating							🟥	🟥	🟥	🟩	🟥	🟥	🟩	🟩	🟩	🟥	🟩	🟩
Sediment transport	Regulating	🟩	🟩	🟩	🟥	🟩	🟩												
Seed dispersion	Regulating	🟩	🟩	🟨	🟥	🟦	🟨	🟩	🟩	🟨	🟥	🟦	🟨	🟩	🟩	🟨	🟥	🟦	🟨
Soil formation and nutrient regulation	Regulating	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩
Water purification	Regulating							🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩
Water quality	Regulating	🟩	🟩	🟩	🟥	🟩	🟩												
Aquatic habitat	Supporting	🟦	🟦	🟦	🟥	🟦	🟦												
Biodiversity maintenance	Supporting	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩
Habitat for wild animals and birds	Supporting							🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟩	🟩	🟥	🟩	🟩
Aesthetic value	Cultural	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Bird watching	Cultural							🟩	🟩	🟩	🟥	🟩	🟩						
Cremation	Cultural							🟥	🟥	🟥	🟩	🟥	🟥	🟥	🟥	🟥	🟩	🟥	🟥
Education and research	Cultural	🟨	🟨	🟨	🟨	🟨	🟨												
Festival cereomony (hatbazar)	Cultural													🟥	🟥	🟥	🟩	🟥	🟥
Fishing	Cultural	🟩	🟩	🟩	🟩	🟩	🟩												
Pilgrimage	Cultural	🟥	🟥	🟥	🟩	🟥	🟥	🟥	🟥	🟥	🟩	🟥	🟥						
Religious site	Cultural													🟥	🟥	🟥	🟩	🟥	🟥
Rafting and boating	Cultural	🟥	🟥	🟥	🟥	🟥	🟥												
Recreation (Picnic)	Cultural							🟥	🟥	🟥	🟩	🟥	🟥	🟥	🟥	🟥	🟩	🟥	🟥
Religious bathing	Cultural	🟥	🟥	🟥	🟩	🟥	🟥												
Sense of place	Cultural	🟥	🟥	🟥	🟩	🟥	🟥												
Social gathering of women	Cultural							🟥	🟥	🟥	🟩	🟥	🟥	🟥	🟥	🟥	🟩	🟥	🟥
Tourism	Cultural													🟥	🟥	🟥	🟩	🟥	🟥
		🟩	Enhanced			🟥	Constrained			🟦	Mixed			🟨	No response				



4.5.4.2. Potential flow-dependent ecosystem services response across the riverine landscape

Potential flow-dependent ecosystem services response to flow changes will vary across the riverine landscape. A significant difference in the distribution of potential flow-dependent ecosystem services responses to flow regime changes was recorded between the three lateral zones of the riverine landscape (Kolmogorov Smirnov test: $p<0.01$). There is greater potential for flow-dependent ecosystem services to change in the riparian zone compared to the floodplain and the river channel in the three time periods under both climate change scenarios (Figure 4.6c). The direction of response also varies with flow-dependent ecosystem services and lateral position. Enhanced responses of flow-dependent ecosystem services are predicted to be more numerous in the floodplain compared to riparian zones and river channels. Similarly, the potential constraint of flow-dependent ecosystem services responses will be greater in the riparian zone followed by the floodplain and the river channel (Figure 4.6c). In relation to the categories of flow-dependent ecosystem services, the most common responses are enhanced responses in provisioning and regulating services in all three zones. One cultural service (aesthetic value) has no response across all three zones. In the case of supporting services, the most common response is an enhanced response in the riparian zone and floodplain but these services are predicted to have a mixed response pattern in the river channel (Figure 4.6d).

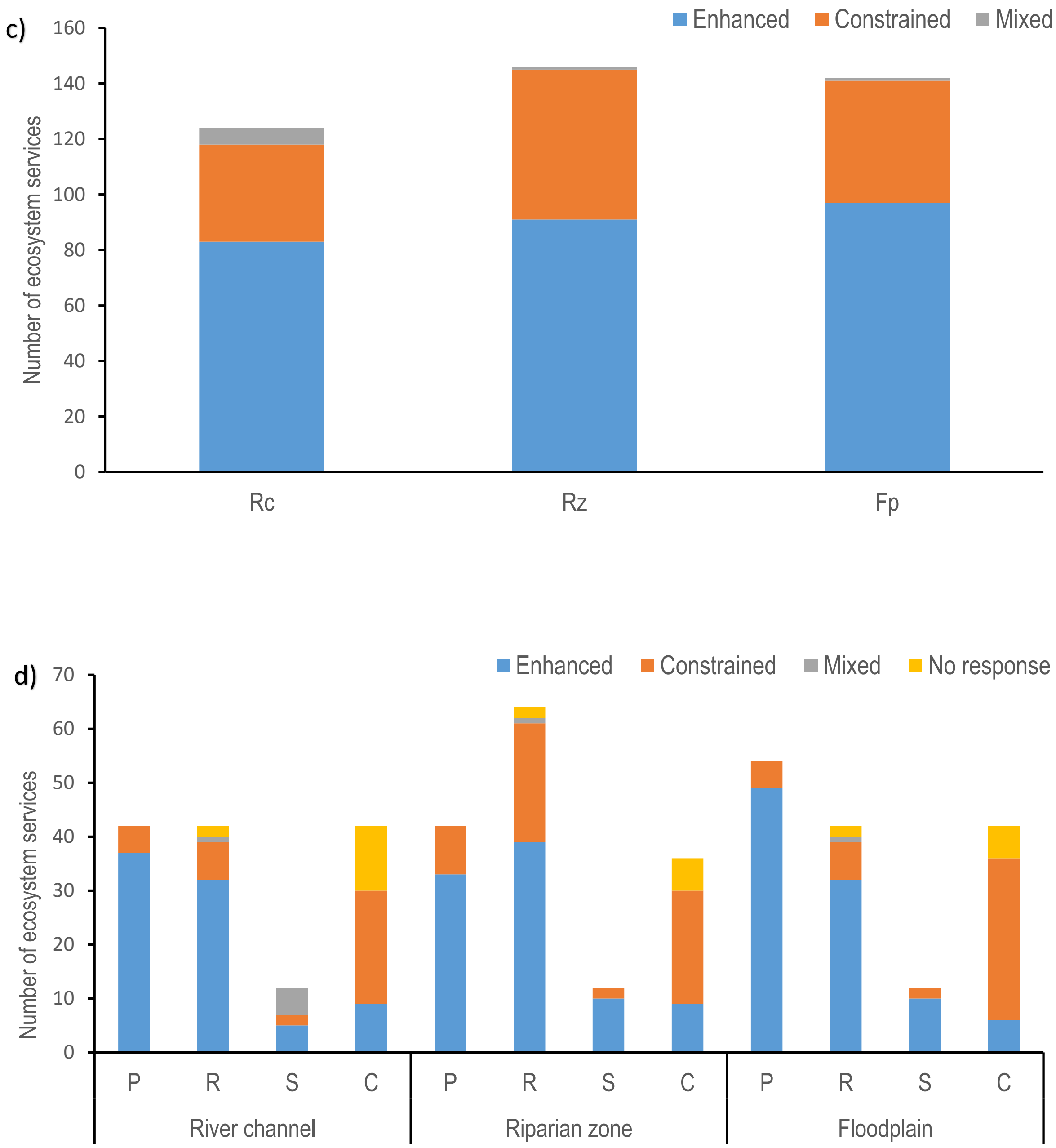


Figure 4. 6. a) Heat map on the response of ecosystem services to flow change based on climate scenario; b) Direction of change in ecosystem service types; c) Direction of change according to RL types; d) Overall response of ES in Sunkoshi Basin riverine landscape to flow change induced by climate, where P= Provisioning, R= Regulating, S= Supporting, C= Cultural, Rc= River channel, Rz= Riparian zone, Fp=Floodplain.

Overall, the response of flow-dependent ecosystem services to climate change was predominantly enhanced in the Sunkoshi Basin (61% of the flow-dependent ecosystem services were enhanced, 30% constrained, 7% no response, and 2% mixed) (Figure 4.6b). Similarly, the response of flow-dependent ecosystem services to climate change was predominantly enhanced in the floodplain (21.9 % of analysis was enhanced, 10% constrained, 1.8% no response and 0.2% mixed), enhanced in the riparian zone (20.6% of analysis were enhanced, 12.2% constrained, 1.8% no response and 0.2% mixed), and enhanced in the river channel (18.8% of analysis were enhanced, 7.9% constrained, 3.2% no response and 1.4% mixed) (Figure 4.6c).

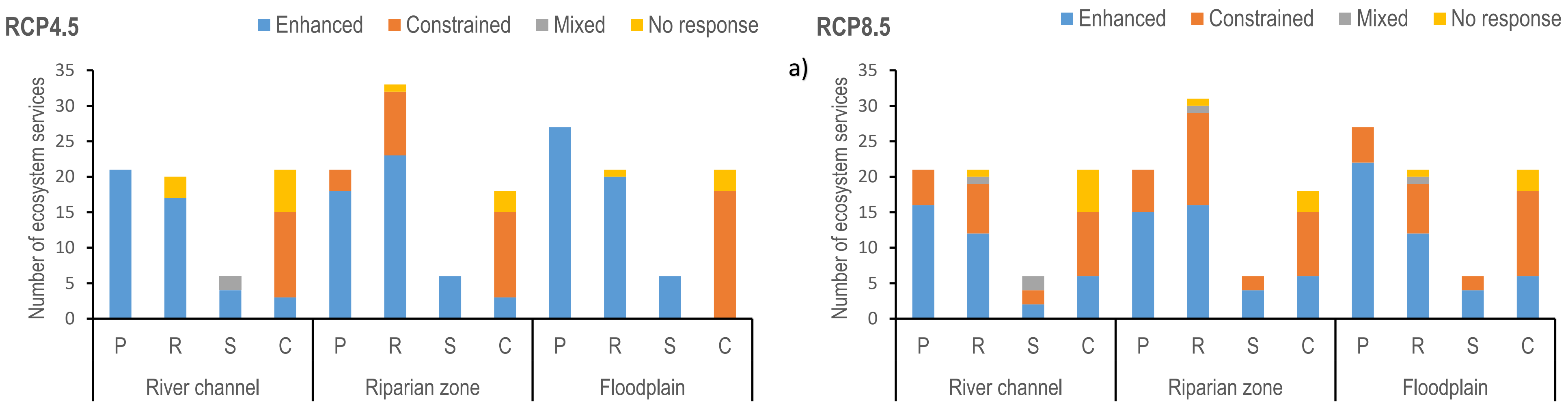
4.5.4.3. Response of flow-dependent ecosystem systems to different climate change scenarios

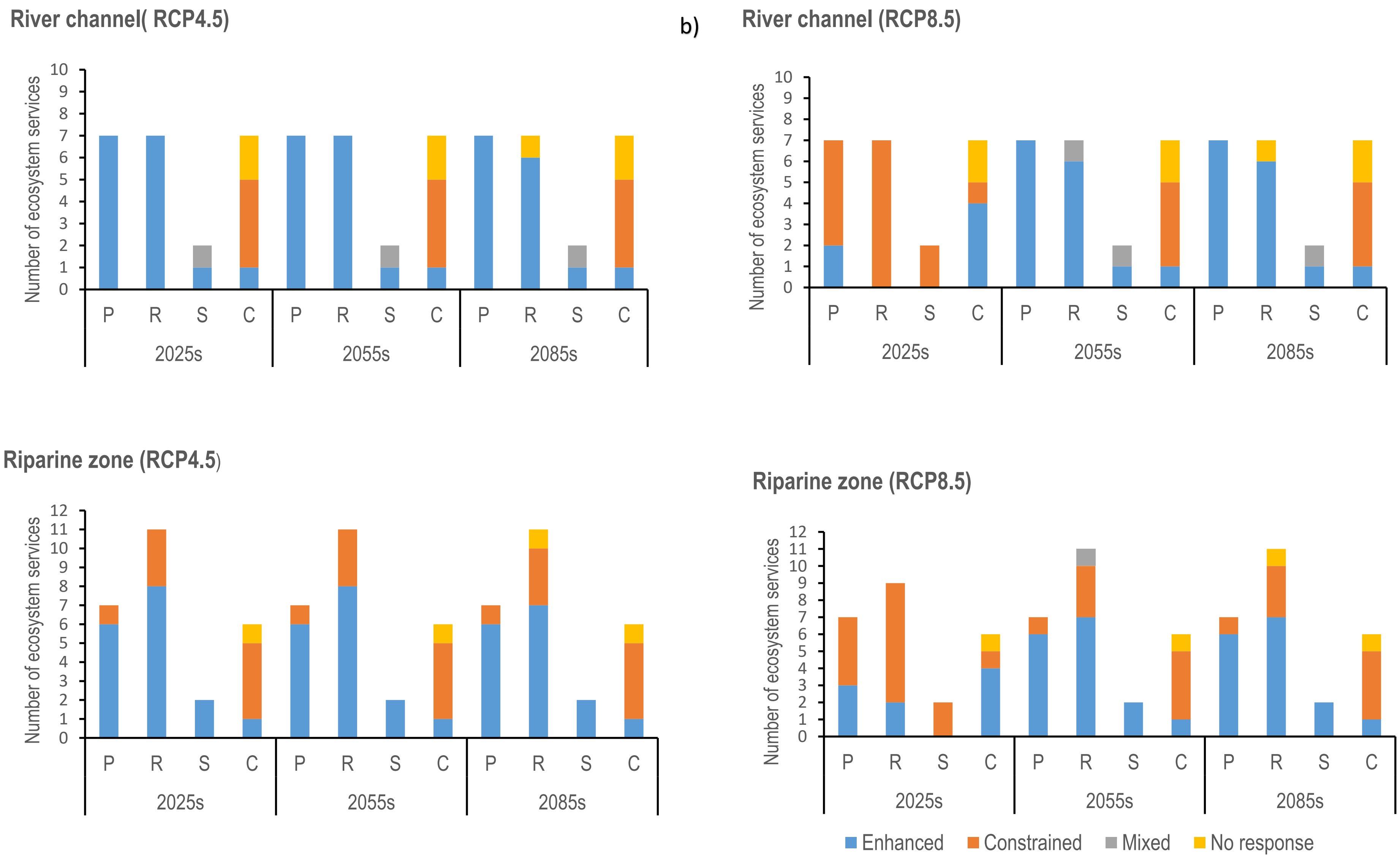
The response of flow-dependent ecosystem services in the Sunkoshi Basin is likely to differ under the two climate change scenarios. Most flow-dependent ecosystem service types are expected to be enhanced, but this will be greater under the RCP4.5 scenario. The total number of flow-dependent ecosystem services enhanced under the RCP4.5 scenario is 148, with 45 of these ESs in the river channel, 50 in the riparian zone, and 53 on the floodplain. This compares to a total number of flow-dependent ecosystem services enhanced under the RCP8.5 scenario of 121, with 36 of these flow-dependent ecosystem services in the river channel, 41 in the riparian zone, and 44 in the floodplain. Overall, 66 provisioning services 60 regulating services, 16 supporting services, and 6 cultural services will be enhanced throughout the riverine landscape under RCP4.5. For RCP8.5, 53 provisioning services, 40 regulating services, 18 cultural and 10 supporting services will be enhanced throughout the riverine landscape.

The response pattern is different within each lateral zone. Constrained responses under RCP4.5 are largely limited to cultural services with a handful of constrained responses also evident in the riparian zone for provisioning and regulating services. In contrast, constrained responses are more widespread under RCP8.5, occurring for all service types in all zones, though being most prevalent for cultural services in all zones and for regulating services in the riparian zone (Figure 4.7a).

4.5.4.4. Response of flow-dependent ecosystem services over time under the two climate scenarios

The potential response of flow-dependent ecosystem services over time, under the two climate change scenarios, was also predicted to differ. Overall, response patterns will be more consistent under RCP4.5 compared to RCP8.5 (Figure 4.7b). In the river channel, the majority of provisioning, regulating, and supporting services were expected to be enhanced over the three time periods, whereas these three flow-dependent ecosystem services are predicted to be initially constrained under the RCP8.5 scenario before being enhanced. This variance over time in a potential response is also shown in the riparian and floodplain zones. However, two cultural services revealed no response over time under both climate scenarios in the riverine landscape.


RCP4.5
Enhanced
Constrained
Mixed
No response
Number of ecosystem services
0
5
10
15
20
25
30
35
P
R
S
C
River channel
Riparian zone
Floodplain
a)
RCP8.5
Enhanced
Constrained
Mixed
No response
Number of ecosystem services
P
R
S
C
River channel
Riparian zone
Floodplain


River channel(RCP4.5)
b)
River channel (RCP8.5)
Riparine zone (RCP4.5)
Riparine zone (RCP8.5)
Number of ecosystem services
0
1
2
3
4
5
6
7
8
9
10
11
12
P
R
S
C
2025s
2055s
2085s
■ Enhanced
■ Constrained
■ Mixed
■ No response

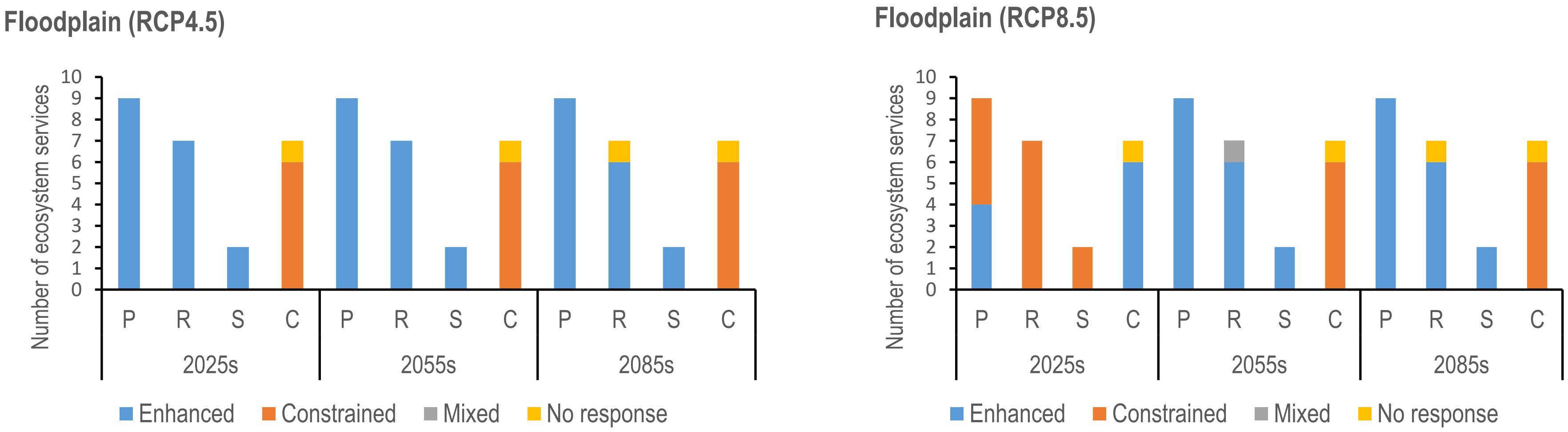


Figure 4. 7. a) Changes of Ecosystem services on the riverine landscape during the end of the century under RCP4.5 and RCP8.5 due to changes in flow regime, compared to the simulated historical (1995s) period; b) Changes of Ecosystem services on the riverine landscape during 2025s, 2055s and 2085s under RCP 4.5 and RCP 8.5 due to change in flow regime, compared to the reference period (1995s), where P= Provisioning, R= Regulating, S= Supporting, C= Cultural.

4.6. Discussion

4.6.1. Lateral dimension of flow-dependent ecosystem services varies in three zones of the riverine landscape

The lateral distribution of ecosystem service type varies in the riparian landscape because riverine landscapes display significant lateral complexity in biophysical character and ecosystem service capacity, from the river channel, through the riparian zone and across the floodplain (Thorp et al., 2006). This complexity is compounded by variations in hydrological connections across the riverine landscape. Reflecting this complexity, each lateral zone of the riverine landscape of the Sunkoshi Basin has a distinct composition of ecosystem services. For instance, there are 26 flow-dependent ecosystem services in the riparian zone, 25 in the floodplain, and 23 in the river channel in the Sunkoshi Basin (Figure 4.3b). This finding is similar to that of Chaudhary et al. (2016), which showed that the capacity to supply ecosystem services varied between the river and floodplain in Koshi Tappu Wildlife Reserve, Nepal. This heterogeneity of flow-dependent ecosystem services is a result of spatial variation in the biophysical template. This is based on the foundation tenet that ecosystem services arise from biophysical processes in ecosystems which are never homogeneous in space or time (Thorp et al., 2006). Riverine landscapes display spatial variation in the biophysical template and there is a congruence in the ecosystem services and physical template in a river network (Bajracharya et al., 2023b). Thus, this study shows variations in the biophysical template can be linked to variations in flow-dependent ecosystem services at the scale of the riverine landscape, encompassing the river channel, riparian zone, and floodplain in the Sunkoshi Basin.

4.6.2. Potential change in natural flow regime according to climate change in Sunkoshi

Projected changes in temperature, along with precipitation patterns and intensity, are likely to change river flows. Our results reveal that the potential change in flow character due to climate varies in the riverine landscape in Sunkoshi. A range of changes is projected to the magnitude, frequency, duration, and timing of flow components relative to the reference period. This finding is consistent with the findings of Stagl and Hattermann (2016). Of particular importance are increases in both high and very low flows. There are projected increases in high flow magnitude, frequency, and duration and the number of floods and large floods. Moreover, the duration of extremely low flows is projected to increase and magnitude decrease, resulting in water shortage. The finding is in line with Bharati et al. (2019), who showed that high flow and extreme low flow duration were increasing.

The projected annual discharge in the basin is also expected to increase by the end of the century, but this change will vary seasonally. The discharge is projected to decrease during the winter/dry season but increase during pre-monsoon, monsoon/wet, and post-monsoon seasons under both climate scenarios (RCP4.5 and RCP8.5). This finding is consistent with the results of Bajracharya et al. (2023a) for the Koshi River Basin; Bajracharya et al. (2018) for the Kaligandaki River; Bharati et al. (2014) and Khadka et al. (2014 and 2015) for the Koshi River; Immerzeel et al. (2013) for the Langtang River, all in Nepal. This projected increase in flow has the potential to help maintain ecosystem function, regulating numerous ecological processes and ecosystem services. For instance, the connectivity among riverine landscape units and periodic inundation by floodwaters support high levels of biodiversity and primary productivity (Opperman et al., 2010) and this will enhance ecosystem processes and their associated ecosystem services which in turn directly benefits the people.

4.6.3. Response of flow-dependent ecosystem services differ according to the riverine landscape

The response of ecosystem services to flow change depends on the lateral position in the riverine landscape. In the river channel, provisioning and regulating services were mostly enhanced by climate change-induced flow changes, while supporting services were more likely to exhibit a mixed response and cultural services mostly showed a constrained response (Figure 4.6d). High flows increase longitudinal hydrological connectivity and increase the productivity of riverine ecosystems (Leigh et al., 2015). These changes can be expected to lead to a higher capacity to increase and meet the development needs of hydropower generation, provide migration and spawning cues for aquatic animals, provide new feeding opportunities for fish and birds (waterfowl), and maintain diversity in the river channel, which helps to explain the general pattern of enhancement of provisioning flow-dependent ecosystem service in the channel. In contrast, these same changes are likely to limit access to rafting, boating, recreational fishing, etc, thus explaining the pattern of constraining cultural flow-dependent ecosystem services. An increase in river discharge can impact these activities by reducing people's safety with high flows and decreased water quality (Talbot et al., 2018). In addition, supporting services show mixed response patterns in the river channel. Supporting services are the fundamental process of the ecosystem that supports or aids in the production of all other ecosystem services for instance soil formation. Change in flow will change the rate of sediment erosional and deposition processes occurring within river channels which may have both positive and negative impacts on soil formation depending on where erosion and deposition occur and the volume of sediment transported (c.f. Talbot et al., 2018).

In the riparian zone, regulating services were mostly enhanced and constrained, provisioning and supporting services were mostly enhanced and less constrained whereas cultural services were mostly constrained (Figure 4.6 d). Riparian zones are where the interaction between terrestrial and aquatic ecosystems occurs. These areas are characterised by high levels of environmental heterogeneity, ecological processes and diverse plant communities (Gregory et al., 1991). Riparian plant communities exhibit a high degree of structural and compositional diversity compared to floodplains and river channels (Gregory et al., 1991). Plant diversity plays a crucial role in providing regulating services (Chaudhary et al., 2016). Our results show that most of the regulating services were supplied by the riparian zone. These plant communities would be expected to lead a higher capacity to increase regulating services in the riparian zone as a result of higher flows and stronger connections to the channel and floodplain. For instance, bio-filtration, carbon sequestration, flood protection, and bank stability will increase regulating services in the riparian zone. In terms of provisioning services, higher flows leading to moisture subsidy and higher connectivity will likely support higher productivity and thus increase grazing, litter decomposition, medicinal plants, thatch, and timber for building and fuel.

In the floodplain, like the channel, provisioning services were mostly enhanced, and cultural services were mostly constrained (Figure 4.6 d). This pattern likely reflects the key role that inundation during high flows plays in driving productivity on the floodplain, thus supporting food crops as well as other resources such as structural and fuel timber (Opperman et al., 2010; Schindler et al., 2014). Floodplains are known hotspots that generate a wide range of ecosystem services (Tomscha et al., 2017) and provide more than 25 percent of terrestrial ecosystem services (Tockner and Stanford 2002). In parallel, inundation limits people's access to the floodplain which is necessary for social activities and ecotourism. Walters et al. (2015) highlighted that flooding may impact tourism by reducing people's safety, damaging infrastructure, damaging sites of interest, and changing tourist perceptions of an area. There is also the potential risk for cultural heritage sites associated with increased flooding (Sesana et al., 2021).

4.6.4. Response of flow-dependent ecosystem services differ within the Sunkoshi Basin

Although there are clear contrasts in the response of flow-dependent ecosystem services with respect to the lateral position in the riverine landscape, there are also some generalisations that can be made in relation to the responses of the different service types across the entire landscape. The response of ecosystem services differs because of the change in ecosystem functioning as the result of the change in flow due to climate change. The result shows that the provisioning, regulating, and supporting services were enhanced whereas cultural services were constrained (Figure 4.6b). The degree of enhancement varied among service types. In particular, provisioning services tended to be enhanced more compared to other service types (Figure 4.6b) because it is easy to quantify compared to other services. This finding is in line with the finding of Egan and Price (2017) in the book Mountain Ecosystem Services and Climate Change. Most of the provisioning services were provided by the floodplain and the floodplain dominates the riverine landscape area compared to other riverine landscape units. Floodplains are likely to experience more frequent hydrological connections to the river channel and an increased duration of inundation. This will stimulate primary production, thus enhancing the productivity of the riverine ecosystem overall (Opperman et al., 2010) and positively impacting provisioning services.

In contrast, cultural services were more likely to be constrained by climate change. Given the nature of cultural services, the capacity to benefit from cultural services is directly related to the people’s accessibility to the riverine landscape for instance religious bathing, swimming, picnics, social gatherings, etc. The literature review by Talbot et al. (2018) mentioned that recreational activities are negatively impacted by flooding and people were less likely to visit a recreational site after a flood. Chang and Bonnette (2016) mentioned in their study, information on the effects of flood and drought on the cultural system is limited despite these being the most critical social and economic sectors. Kandel et al. (2018) highlighted that even though the importance of cultural services was recognized, it was difficult to link with climate change-induced flow alteration for changes in cultural benefits. However, clear links are evident for services such as rafting and fishing. The extremely low and high water levels can have dramatic effects on boating, rafting, swimming, and fishing because these are directly related to river functions. Flooding may impact these activities due to damaging infrastructure and reducing people's safety (Talbot et al., 2018). The constraints of cultural services included tourists deciding to avoid visiting flooded places which impact revenue losses (Kala, 2014).

4.6.5. The response of flow-dependent ecosystem service types varies with flow regime component

Projected flow regime changes could have various impacts on flow-dependent ecosystem services. The riverine landscape in the Sunkoshi Basin is likely to experience flow regime change over time under future climate scenarios. Our findings show that the magnitude, frequency and duration of high flow will increase in the future. High flows increase hydrological connectivity and trigger booms in the productivity of riverine ecosystems (Leigh et al., 2015). Positive impacts of higher flows might include greater feeding opportunities for fish and birds, recharging of floodplain water tables, and recruitment opportunities for plants and animals. High flows will also increase in wetter perimeters facilitating lateral exchange between the riparian zone and the stream, increasing soil moisture content, and prolonging access to soil moisture. As a result, there could be greater plant diversity and productivity, increasing the habitat for grassland birds (for instance Swamp Francolin, Bengal Florican, Indian courser). Shifts in the timing of peak flows will also likely impact specific services.

For example, such a shift will disrupt the recruitment of riparian species, disrupt the dispersal of seeds onto the floodplain, and impact the survival of certain fish species whose larval emergence is timed to avoid high flows and freshwater fish production (Gibson et al., 2005).

On the other hand, the projected decreases in the magnitude of low flows and increases in the duration of extremely low flow during the dry season could have adverse impacts on river ecosystems and their associated services. For instance, lower flows can lead to increased water temperature and reduced dissolved oxygen, which can negatively affect aquatic organisms. Lower flows will also tend to reduce the wetted perimeter, decreasing soil moisture content and thus the productivity of floodplain and riparian vegetation, including that of agricultural systems (Gibson et al., 2005). During the low flow, there will also be hydrological disconnection among riverine landscape zones, in other words, the floodplain and riparian zone will be isolated from the river channel. Even in the river channel, there will be potential for fragmentation of aquatic habitats and organisms during extreme low flow periods. Thus, reduced flows during the dry season may have a negative impact on the ecosystem and the associated ecosystem services in the riverine landscape with services in the riparian zone and floodplains likely to be more impacted.

4.6.6. Potential responses of flow-dependent ecosystem services to climate change on the riverine landscape under two climate scenarios

The potential response of flow-dependent ecosystem services differs across the riverine landscape under two climate scenarios. The results suggest a consistent response pattern within each lateral zone for RCP4.5 but a more complex response under the RCP8.5 scenario across the riverine landscape (Figure 4.7a). While the response of ecosystem services differs among river channel, riparian zone, and floodplain under two climate scenarios, the pattern of change whereby the majority of services, other than cultural services, are enhanced is maintained over time (Figure 4.7b). This means that there might be no loss of flow-dependent ecosystem services in the riverine landscape in the Sunkoshi Basin. Overall, the projected increases in flow in the near future due to climate change can improve the function of the riverine ecosystem and its associated services in the Sunkoshi Basin.

4.7. Conclusion

The distribution of the flow-dependent ecosystem services varies laterally across the riverine landscape. There was a significant difference in the distribution of flow-dependent ecosystem services between the river channel, riparian zone, and floodplain zones. Thus, lateral characteristics of the riverine landscape establish the response of flow-dependent ecosystem services to flow change driven by climate change. Flow regime characteristics will all potentially change, but these changes will differ among riverine landscape units, as well as over time under two climate scenarios. The response of flow-dependent ecosystem services in the Sunkoshi riverine landscape is likely to differ under the two climate scenarios. Most ecosystem service types are expected to be enhanced, but this will be greater under the RCP4.5 scenario. Overall, provisioning services will be enhanced throughout the riverine landscape. Most of the ecosystem services were enhanced under RCP4.5 and RCP8.5 over time except for 2025s under RCP8.5. The exception to this pattern is cultural ecosystem services, which are typically projected to be constrained under both scenarios over time. Therefore, the response of ecosystem services to the changing climate on the riverine landscape was very complex. However, given the complexity of ecosystem services of the riverine landscape, our results collectively show that provisioning, regulating, and supporting services were enhanced in the riparian zone followed by floodplain and river channel by 2100 under RCP4.5 and 8.5.

Sunkoshi ecological system provides abundant flow-dependent ecosystem services to the communities that live there. More than 80 % of people in the basin are dependent on the ecosystem services provided by the basin for their sustainable livelihood. The remoteness of mountain communities in the basin, often means that they have limited communication and transportation as a result, these communities are marginalised. In addition, these communities have limited access to other resources and a relatively low capacity to adapt to changes (cf. Bhatta et al., 2015). Given this, there has been understandable concern about the impact that climate change might have on the flow-dependent ecosystem services in the Sunkoshi Basin. This study has shown that overall, climate change is likely to enhance these ecosystem services through the end of the 21st century. This should not be cause for complacency given the uncertainty of projections in relation to the responses of flow-dependent ecosystem services to climate change and the less positive suite of changes projected under high emissions scenarios.

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Chapter 5: The role of geomorphological organization in the response of flow-dependant ecosystem services to climate change in river networks

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Sunkoshi River at Khurkot hydrological station during the dry (winter) season.

MANUSCRIPT INFORMATION PAGE

The role of geomorphological organisation in the response of flow-dependant ecosystem services to climate change in a river network.

Sagar R. Bajracharya, Michael Reid and Bradley Evans
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We, the Research PhD candidate and the candidate's Principal Supervisor, certify the following text, tables and figures are the candidate's original work.

Type of work	Page number(s)
Text	255-295
Tables 5.1 – 5.5	265, 277, 289, 282, 284
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5.1.**Abstract**

Hierarchy theory provides a sound conceptual framework for dissecting spatial and temporal domains of influence in river ecosystems. It is well recognised that riverine landscapes are hierarchical systems, and that components of the riverine landscape can be distinguished by different rates of pattern and processes according to the level of organization. Multiple processes operating at varying scales in the riverine landscape construct a range of different templates and influence the riverine landscape at different scales. Climate change will influence the river function and this will influence the association between physical drivers and ecological responses at different scales. In this study, we examine the response of flow-dependent ecosystem services to climate change on three levels of geomorphological organization within the river network in the Koshi River Basin, Nepal, using the ArcGIS suites, Soil and Water Assessment Tool (SWAT) and Indicators of Hydrological Alteration (IHA) based on RCP8.5. Results show there is congruence between the distribution and composition of response in flow-dependent ecosystem services to climate change and the geomorphological organization of a river network. The response of flow-dependent ecosystem services to climate change varies among the three levels of geomorphological organizations, the variation is high in functional process zones and riverine landscape units but low in sub-basins. The physical template is important in determining the flow-ecosystem service's response to climate change and the importance of the management, conservation, and rehabilitation of flow-dependent ecosystem services.

5.2.**Introduction**

Hierarchy theory was developed to deal with complex and multiscale systems and provides a sound conceptual framework for dissecting spatial and temporal domains of influence in river ecosystems (Parsons and Thoms, 2007). It also helps to provide a common understanding of the nature of the research problem and to identify the scales of relevant subsystem components, the underlying processes or phenomena and the important variables involved (Dollar et al., 2007). A hierarchical system can be viewed as a series of graded organizational levels that are constrained within a nested vertical structure (O’Neill et al., 1989). When applied to river systems, these organizational levels range from large basin systems down to small mesohabitats. These geomorphological components sit within a hierarchy of influence, where larger-scale features establish the conditions within which small-scale features form and lower levels influence the structure and functioning of features at higher levels.

It is recognized that riverine landscapes are hierarchical systems and according to hierarchy theory, the riverine landscape can be distinguished by different rates of processing and morphological character according to the level of organization. Multiple processes operate at different scales in the riverine landscape to construct a whole range of different physical templates (Thoms et al., 2008). Processes operating at different scales imply that there is a need to observe the influence or association between physical drivers and ecological response at an appropriate scale. Hierarchy framework helps to identify the right scale driver influencing an ecological response and determine the influences of physical drivers on ecological responses in a riverine landscape. Hierarchy theory has been applied as a framework to explore the association between the riverine landscape and ecology at multiple scales in several studies (Boyero and Bailey, 2001; Parsons et al., 2004; Delong and Thoms, 2016; Thoms et al., 2016; Elgueta et al., 2021).

The physical template of riverine landscapes is important because flow-dependent ecosystem services are generated by the biophysical processes of the physical template. The emerging evidence suggests heterogeneity of the underlying biophysical template should be a key consideration in understanding ecosystem services across riverine landscapes because different services will be supplied by different features of the biophysical template (Bajracharya et al., 2023). The heterogeneity of the physical template shapes riverine ecosystem structure and function and determines the types, abundance, and arrangement of ecosystem services in a river network (Bajracharya et al., 2023). Thus, the arrangement of ecosystem services across a river network is congruent with the type and distribution of physical templates in the river network (Bajracharya et al., 2023). For example, Bajracharya et al. (2023) found that the supply of ecosystem services varied in the river network of the Koshi basin, with ecosystem services highest in the low-elevation floodplain followed by the braided and meandering functional process zones (FPZs). Thorp et al. (2010) showed that the relationship between ecosystem structure and hydrogeomorphic features differs greatly in different stretches of the riverine landscape. Thorp et al. (2010) argue that a general pattern exists whereby anastomosing and anabranching reaches provide high ecosystem services, meandering reaches provide high to medium ecosystem services and constricted and straight reaches provide low ecosystem services. Similarly, Large and Gilvear, (2015) demonstrated that ecosystem services are high in mid-reaches and low in gorge sections and that ecosystem services varied considerably with longitudinal position and reach type for the Lana River in Siberia. Finally, Tomscha et al. (2017) showed that the highest diversity of ecosystem services was concentrated in the floodplain.

The strong relationship between the physical template of rivers and the services they provide means that when the physical template experiences a change in character, ecosystem services can be expected to change in response. Climate change will alter the physical templates of rivers globally, principally through its impact on flow regimes. Projected changes in the temperature along with precipitation patterns and intensity are likely to change river flow regimes resulting in flow variability and uncertainty in water availability (Dixit et al., 2009). The visible impact of climate change is even more palpable in the upstream part of the Himalayan region (Immerzeel et al., 2020; Viviroli et al., 2007). However, the response of changing climate to river flow is likely to differ within the basins of the Himalayas due to the source of runoff and hydrological processes varying by location and season (Immerzeel et al., 2012). For instance, runoff is governed by snow and glacier melt in most of the upper part of the Himalayan basin whereas the runoff in the lower part of the basin is governed by rainfall and groundwater with minimal contribution of snow and glacier melt. A study by Stagl & Hattermann, (2016) showed that climate change might impact the long-term monthly, seasonal, and annual flow of rivers together with changes in the timing of peak flow and variability of high and low flows under two future scenarios by evaluating five GCM under three RCP (2.6, 4.5 and 8.5). Thus, changes in river flows have an important impact on water availability, irrigation, flood management, and overall water resources planning. Furthermore, changes in streamflow can affect the water-dependent ecosystem because streamflow is a master variable that shapes the structure and function of rivers (Poff and Ward 1989).

The flow regime is therefore a critical component of riverine landscapes that maintains the ecological integrity of the ecosystems (Bunn and Arthington, 2002). Changes in the flow regime can have dramatic effects on a range of key features of river ecosystem structure and function, including hydrological connectivity, productivity, nutrient diversity, habitat availability and energy flow within the riverine landscape (Gibson et al., 2005). For instance, the increase in the magnitude of high flow will increase the duration of connectivity between the main river channel and floodplain, which will promote the exchange of nutrients, materials, organisms, and energy among riverine landscape units and enhance the biodiversity and productivity of ecosystems in the riverine landscape (Opperman et al., 2010; Wiens, 2002).

The interplay between biotic and abiotic components generates distinct patterns within the riverine landscape (Thoms et al., 2017). Previous studies have demonstrated that the pattern of the response in ecological processes in the hierarchical system of the riverine landscape showed a clear response signal at a certain level of organization or a specific scale. These patterns have been shown for benthic macroinvertebrates (Boyero and Bailey, 2001; Parsons et al., 2003), fish (Elgueta et al., 2019), food webs (Maasri et al., 2019; Thoms et al., 2017), and ecosystem (Delong and Thoms, 2016) across scales ranging from individual riffles, through reach, functional process zones to entire basins. However, there is only a handful of studies that explicitly examine the distribution and composition of ecosystem services at multiple scales.

This paper examines the response of flow-dependent ecosystem services to climate change in a Himalayan River basin. Given the hierarchical manner in which river systems function, the study examines responses to processes and patterns across scales in the riverine landscape. Specifically, we investigate the response of flow-dependent ecosystem services to climate change if there is any association between physical drivers and the pattern and character of ecological response to climate change and if the response of ecosystem services varies according to the hierarchical geomorphological organization of a river network. In this study, we used three levels of geomorphological organization within the river network (Sub-basin, FPZ and Riverine landscape units) to examine the relationships between flow-dependent ecosystem services and climate change. To understand the response of ecosystem services, we formulated four research questions: i) Do flow-dependent ecosystem services respond differently according to scale due to climate change? ii) At which scales do responses vary most? iii) What are mechanisms that drive variation in response? iv) Do response types vary among ecosystem service types (i.e. provisioning, regulating, supporting and cultural services)?

5.3. **Study area**

The Koshi River Basin is one of the most important river systems in Nepal. The basin is situated in the central Himalayas and eastern sub-catchment of the Ganges River Basin and one of the most sensitive areas to climate change in the Himalayas (Yao et al., 2019). The Koshi is a transboundary and perennial river that drains 55,929 km^2 in China and Nepal (Figure 5.1). The elevation range within the basin is extreme, extending from the highest point in the world, 8,848 m.a.s.l at the summit of Mount Everest, to just over 30 m.a.s.l in the plains. This variation in elevation results in highly contrasting climatic zones within the basin, from humid tropical in the south, through subtropical and temperate, to cold and arid in the north (Dixit et al., 2009). The climate in the southern part of the basin is strongly influenced by the South Asian monsoon, whereas to the north the Tibetan plateau lies in a rain shadow area. Precipitation patterns in the basin are directly associated with the summer monsoon, with about 80 percent of the annual precipitation falling between June and September. Precipitation is highly heterogeneous in the Koshi River Basin due to varying climates and topography. Annual precipitation ranges from 207 mm in the trans-Himalaya to more than 3,000 mm in the eastern mountains and mid-mountains of Nepal (Neupane et al., 2013). The upper part of the basin contains a substantial reserve of fresh water in the form of snow and glaciers and plays a key role in the irrigation of downstream areas. The region also has a large potential for hydropower development and provides services to ecosystem functioning. The long-term average annual discharge of the basin is 1,545 m^3/s at Chatara hydrological station (Sinha et al., 2019). The basin covers five physiographic zones and encompasses a great diversity in topography, climate, vegetation, demography and culture and has a high ecological significance, serving as a vertical linkage for fauna and flora.

The Koshi River Basin is home to more than 40 million people (Uddin et al., 2015), many of whom are dependent on the flow-dependent ecosystem services of the Koshi River landscape. The basin is also home to sensitive and crucial ecosystems, with protected areas that support a high level of biodiversity – it is a hot spot of ecosystem services and functions as a vital corridor for various fauna (ICIMOD and MoFSC, 2014). The flow of services (e.g., supporting, provisioning, regulating, and cultural) provided by the riverine ecosystem contributes to the well-being of the populations residing in the basin as well as the downstream areas, and the global community. The majority (83 percent) of people in the Koshi River Basin in Nepal depend on agriculture as a source of income, and almost half (49 percent) of them depend on agriculture as a primary source (Dixit et al., 2009).

The Koshi River is one of the most dynamic rivers in the world. It shows evidence of deep gorge and later channel shifting exceeding about 115 km westward due to sedimentation and tectonic activities during the past 200 years (Kafle et al., 2015). The dynamic nature of the Koshi is revealed by its erosive nature, and high capacity to carry sediment from the highlands to the lower reaches, having built a megafan of some 15,000 km^2 in area in the low altitude plains (Danish et al., 2013). In its meandering sections, the Koshi has rendered about 1,295 km^2 of land in Nepal and about 7,770 km^2 of land in Bihar, India, which was renowned for its rice field and orchards, useless as a result of channel movements and sand deposition, (Mahato and Shulka, 2013). The Koshi River Basin suffers from frequent floods and has experienced 10 major floods within the last 60 years. A flood on 18th August 2008, deposited 1-2 m of sediment on the southern plain of the basin (Chen et al., 2013).

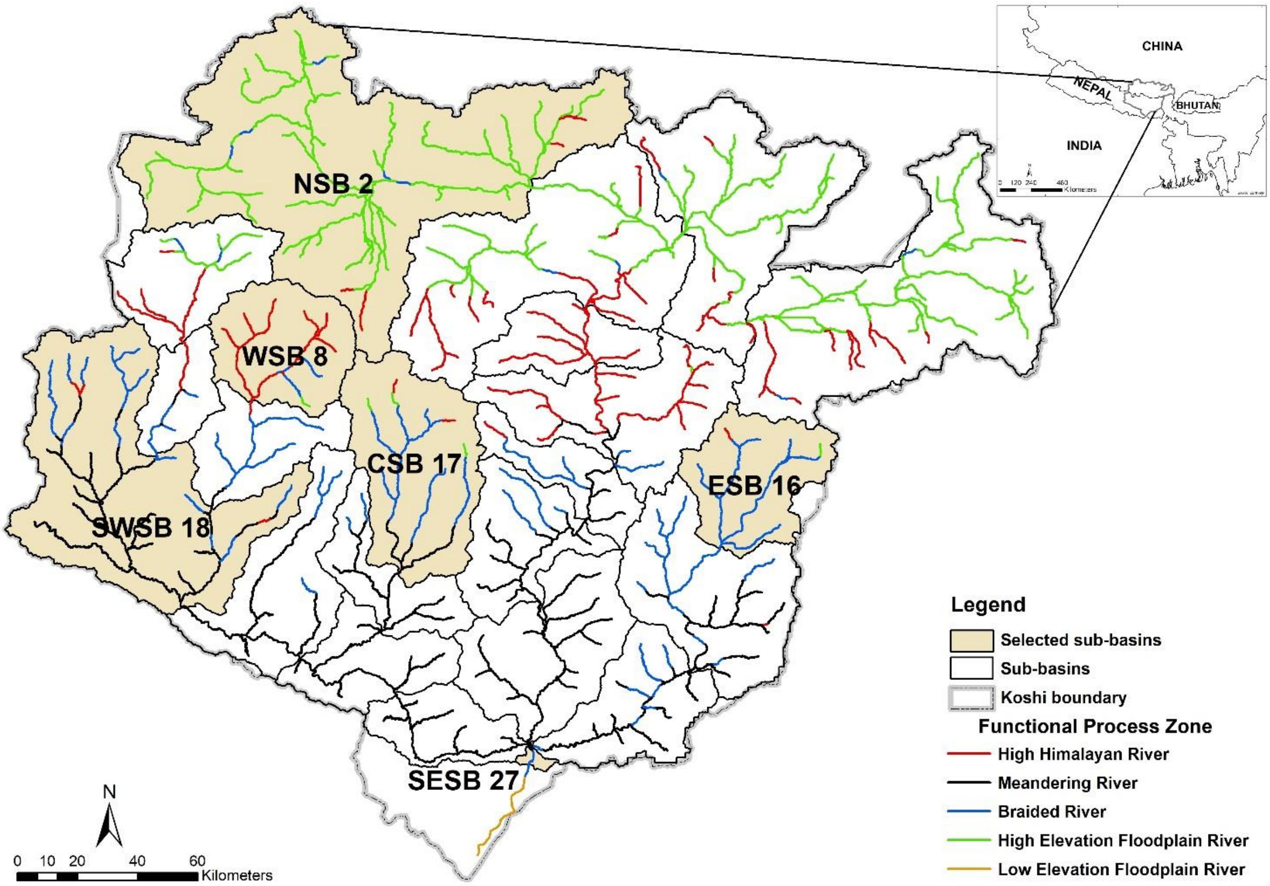


Figure 5. 1. The location map of the study area. NSB 2 = Northern sub-basin 2, WSB 8 = Western sub-basin 8, ESB 16 = Eastern sub-basin 16, CSB 17 = Central sub-basin 7, SWSD 18 = Southwestern sub-basin 18, SESB 27 = Southeastern sub-basin 27.

5.4.**Methods and data**

Five analytical steps were used to determine the response of flow-dependent ecosystem services to climate change in the entire river network in the Koshi River Basin. These steps are illustrated in Figure 5.2 and explained in detail in subsequent sections. First, the Soil and Water Assessment Tool (SWAT) model was used to model future flows. These modelled flows were then used to derive Indicators of Hydrological Alteration (IHA) values based on a range of flow regime variables which were applied to the riverine landscape. Second, the response in key riverine ecosystem functions to changes in flow regime at each level was determined. Third, the river network was determined in three levels (sub-basin, FPZs and riverine landscape units), simultaneously the ecosystem services of the riverine landscape were collated via a search of relevant studies in Nepalese rivers, field observation, surveying residents and Nepal census data. These services were then allocated to the sub-basins, FPZs and riverine landscape units of the Koshi River Basin. Fourth, the direction of the functional response of ecosystem services to flow regime change in the riverine landscape was determined. Fifth, a matrix of the projected response of ecosystem services in the Koshi River network was determined for each component within each level of the spatial hierarchy of the river network.

5.4.1. ***Step1: Determine flow regime change for different climate scenarios***

The SWAT model built for this study used long-term daily data from 21 precipitation stations, 11 temperature stations, and 1 hydrological station (Chatara) from 1981 to 2010. The 2010 land use (30 m resolution) data was obtained from ICIMOD (Uddin et al., 2015). The soil data was obtained from the Soil and Terrain Database Programme (SOTER) (Dijkshoorn and Huting, 2009). SRTM DEM of 90m×90m resolution was used to delineate the watershed in the model

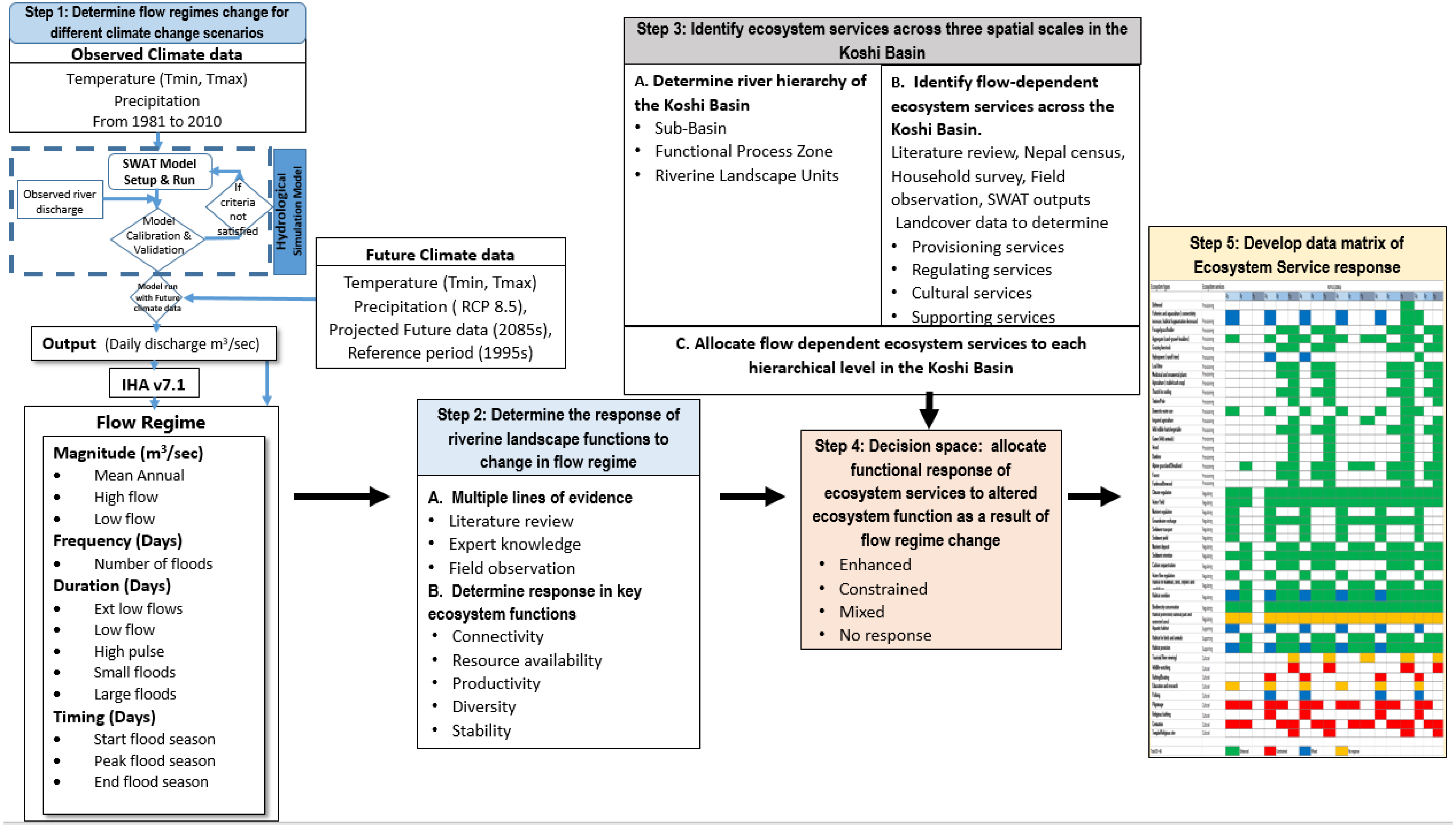


Figure 5. 2. Determining the response of flow-dependent ecosystem services to potential climate change across three spatial scales in the Koshi River Basin. For each climate scenario, 100 years of daily data were generated, and from 2071 to 2100 (2085s), 30 years of average data were in this study. The Household survey data was obtained from the ICIMOD Poverty and Vulnerability Assessment (PVA) data. The Nepal Census data was from the Nepal National Census of 2011. SWAT - Soil and Water Assessment Tool.

5.4.1.1. Climate scenarios

In this study, the future climate dataset for the entire Koshi River Basin was based on selected Coupled Model Intercomparison Project 5(CMIP5) General Circulation Models (GCM) and downscaled to a 10x10 km spatial resolution and daily time steps as recommended by Lutz et al., (2016). In the dataset, the GCMs were selected for the region using the ‘Envelope’ approach and downscaled using quantile mapping. In the envelope approach, suitable GCMs were chosen from the universal sets of GCMs available covering a range of temperature and precipitation projections as outlined in Table 5.1. I used an ensemble average of the four selected GCMs for RCP8.5 for this study. The GCM climate dataset 1995 (average annual mean from 1981 - 2010) was used as the reference data and the average annual mean from 2071 to 2100 as the 2085 projection. Under RCP8.5 in 2085s the recent flow regime might be highly altered, posing a serious threat to riverine landscape and riverine ecosystem services. Therefore, RCP8.5 is considered the extreme case for risk management. This climate scenario data can be downloaded from the ICIMOD webpage (http://rds.icimod.org/clim).

Table 5. 1. Selected climate models and scenarios used in this study.

RCP Projection	RCP 8.5
Warm, dry	CMCC_CMS_r1i1p1
Warm, wet	CanESM2_r3i1p1
Cold, wet	bcc-csm1-1_r1i1p1
Cold, dry	inmcm4_r1i1p1

5.4.1.2. SWAT model set up and run in Koshi River Basin

I used the Soil and Water Assessment Tool (SWAT) hydrological model to assess the hydrological character of the Koshi River Basin under the RCP8.5 climate scenario. The SWAT model has been successfully tested and applied in many Himalayan river basins in Nepal (Bharati et al., 2014, 2016, 2019; Devkota and Gyawali, 2015; Kaini et al., 2021). The tool runs with spatial and temporal data. Spatial data include soil type, land cover/land use and elevation while temporal data include climate data. Outlets are generated automatically at the intersection of the stream by the SWAT model, based on the threshold area defined. However, in my case, manual outlets were added at the discharge stations for calibration and validation and to simulate natural hydrological processes like routing, groundwater storage, and infiltration. To delineate the watershed, the final outlet was defined at the Chatara station. This resulted in the creation of 27 sub-basins. Among the 27 sub-basins, we selected six sub-basins for the analyses. These sub-basins were spatially distributed in the Koshi River Basin from east to west and north to south (Figure 5.1). The selected sub-basins are situated in the north (NSB 2), the west (WSB 8), the southeast (ESB 16), the centre (CSB 17), the southwest (SWSB 18) and the southeast (SESB 27) (Figure 5.1). These six sub-basins were selected to capture the east-to-west and north-to-south precipitation gradients created by the monsoon and the north to south temperature gradient created by altitude. These sub-basins also represent the trans-Himalayan, high Himalayas, middle mountain and southern plain physiographic regions of the basin.

5.4.1.3. Model calibration and validation

Observed daily discharge data were used to calibrate and validate the SWAT model. Model calibration was done via SWAT- Calibration and Uncertainty Programs, once the SWAT model was calibrated and validated and able to simulate the discharge at the outlet of the catchment realistically and with reasonably high accuracy, then the model was run for a reference period and a future climate change scenario based on RCP8.5. For this exercise, we used 30 years (1981 - 2010) average annual mean climate variable (Temperature and Precipitation) as a reference period. The discharge obtained from the simulated SWAT model then was treated as baseline data for the reference period of 1981 to 2010. These reference period simulated discharges were compared with future simulated discharges for an ensemble of 4 selected GCMs under the RCP 8.5 scenario. For robustness of the hydrological model, the Nash-Sutcliffe Simulation Efficiency (NSE), Coefficient of Determination (R^2), and Percent Bias (PBIAS) were calculated to verify the SWAT results, as recommended by Nash and Sutcliffe (1970) and Moriasi et al. (2007).

5.4.1.4. Flow regime in Koshi River Basin

The simulated daily discharges from SWAT were used to generate four components of the flow regime: i) magnitude, ii) frequency, iii) duration, and iv) timing. In this analysis, we did not include the rate of change. Using the Indicators of Hydrological Alteration (IHA) version 7.1, the flow regime was generated for reference and future periods. Subsequently, the future change in the flow regime was calculated relative to the reference period. The IHA calculates fundamental characteristics of the flow regime, which greatly influence the ecological processes in river ecosystems. Finally, these variables were grouped into their relevant flow regime component. Accordingly, annual flow, high flow and low flow were grouped into magnitude; the number of floods in frequency; extreme low flow, low flows, high flow pulses, small floods and large floods in duration, and start, peak and end flood season in timing (Figure 5.2).

5.4.2. ***Step 2: Determine the response of riverine landscape functions to changes in flow***

The primary driver of the river ecosystem functioning is the flow regime. Therefore, it is very important to consider which flow characteristics will change in the future due to climate change. This change determines which key ecosystem functions are influenced because different flow variables have different ecological functions (Chapter 4). Multiple lines of evidence approach were taken to determine the response of riverine landscape functions to changes in the flow regime. Potential changes in five ecosystem functions of connectivity, resource availability, productivity, diversity and stability (cf. Thorp et al., 2008) were derived for the Koshi River Basin. The scientific literature (Bharati et al, 2019; Mathews and Richter, 2007; The Nature Conservancy, 2009; Rai et al., 2019; Datry et al., 2017; Poff and Zimmerman., 2010; Poff et al, 1997) was used to determine the link between flow regime changes and ecosystem function changes.

For instance, changes to the frequency variable of the number of floods will increase the frequency of connection among three riverine landscape units and increase productivity, resource availability, and diversity within a floodplain and riparian zone. Changes to the magnitude variables of the mean annual, high flow and low flow all have the potential to influence the key ecosystem functions. High flow provides adequate habitat for aquatic organisms and provides new feeding opportunities for aquatic and terrestrial organisms. Low flow concentrates prey into limited areas to benefit predictors and maintain suitable water temperatures, dissolved oxygen and water chemistry. Changes to annual flow (a magnitude variable), may also have a general effect of increasing connectivity. Changes to the timing variables of the timing of start, end and peak of the flood season may not influence the overall amount of connectivity among units, but may have important implications in relation to synchronisation with ecological responses to flooding. This understanding of the relationships between flow regime variables and river ecosystem function was used to infer the response of these functions to flow change in the Koshi River Basin. Finally, based on these relationships, the matrix table (Figure 5.3) was prepared to set out the response of riverine landscape functions to changes in flow regime.

*5.4.3. **Step 3: Determine ecosystem Services associated with Sub-basins, FPZs and riverine landscape units of the Koshi River Basin***

5.4.3.1 Determine the river hierarchy (sub-basins, FPZ, riverine landscape units) of the Koshi River Basin

In this study, the response of ecosystem services to climate change is determined for three hierarchical levels of the river network (Figure 5.3). i) Sub-basin: this is the largest spatial scale of the riverine landscape in this study. Sub-basins are defined by topography, geology and climate; ii) Functional process zone (FPZ): FPZs sit within sub-basins and are defined as lengths of the river system that have similar flow regime, sediment regime and geological history; iii) Riverine landscape unit (RLU): RLUs sit within FPZs and are defined by their lateral position in relation to the main channel. These units are, the river channel itself, the riparian zone and the floodplain. Following is the process of how three levels (sub-basins, FPZs and riverine landscape units) were determined.

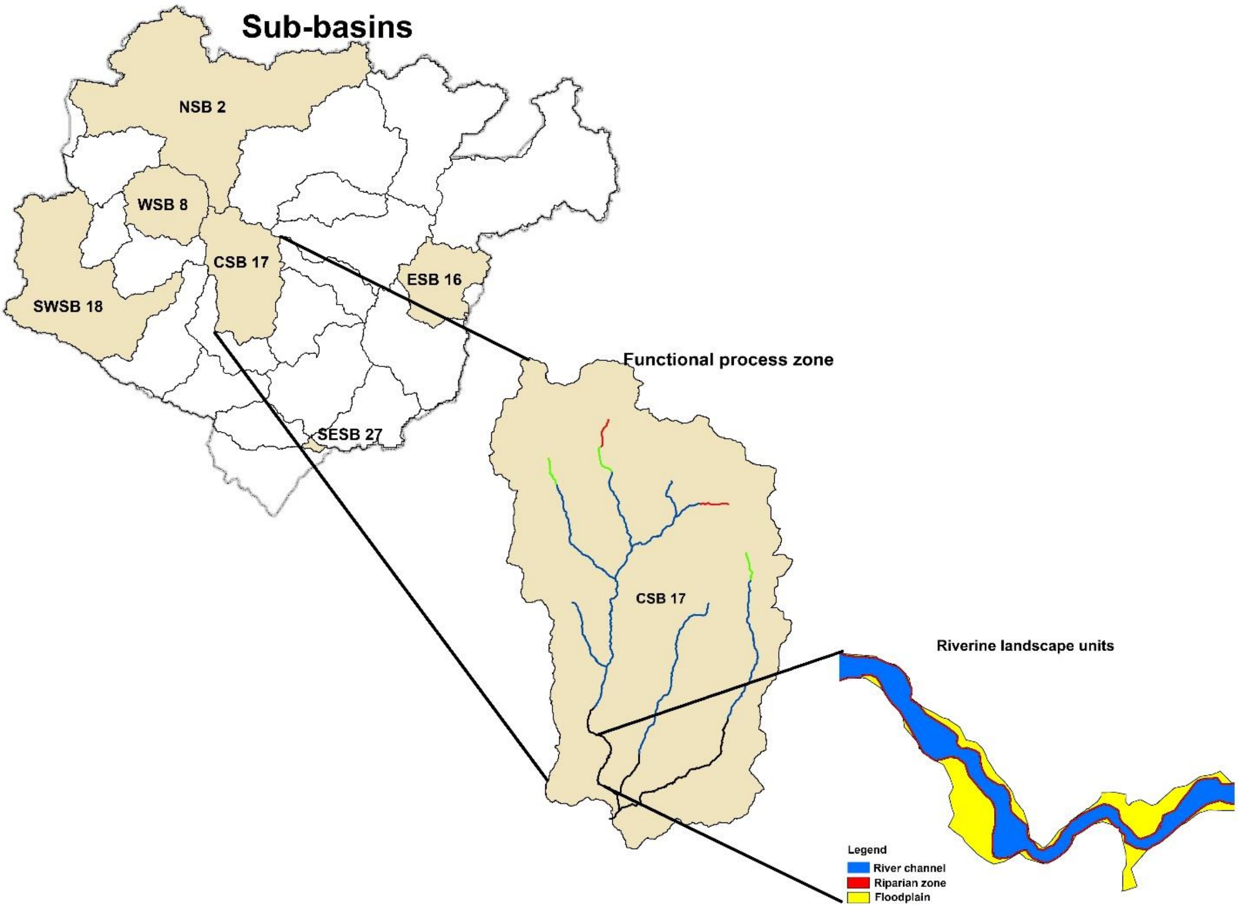


Figure 5. 3. A conceptual diagram of three levels of geomorphological organization within the river network in the Koshi River Basin.

As described in step 1, the hydrological model SWAT was used to generate sub-basins in the Koshi River Basin. The sub-basin was the default product of the hydrological model run.

The FPZs within sub-basins were delineated by a dataset of hydrogeomorphic variables (1,272 sites by 15 variables) generated by ArcGIS tools that were analysed using multivariate statistical techniques to identify groups of sites with similar physical characteristics. Sites were classified using the flexible unweighted pair-group method with arithmetic averages (UPGMA) fusion strategy, as recommended by Belbin and McDonald (1993), based on the 15 variables (Bajracharya et al., 2023). Groups of sites with similar physical character were selected from the dendrogram representation of the cluster analysis, whereby the least number of groups with maximum similarity was chosen. This step required the identification of an inflexion point in the relationship between the number of groups in the classification and their corresponding similarity value (Thoms et al. 2018). This analysis was also used to construct an FPZ nomenclature for the Koshi River Basin. Once identified, the sites were overlaid on the drainage network with their corresponding group nomenclature from the cluster analysis. Groups equate to FPZs. Sequences of the same group delineate FPZ segments in the river network - lengths of the river with similar valley-floodplain settings and river morphologies, inferred to be influenced by similar geomorphic processes (Thoms et al. 2018). Finally, Analysis of Similarity (ANOSIM) and SIMilarity PERcentage analysis (SIMPER) were used to determine differences in hydrogeomorphic variables and which hydrogeomorphic variables contribute to group similarity of each FPZ. For more details, potential readers of the paper refer to the manuscript by Bajracharya et al., (2023). Five FPZs emerged from the classification of the 1,272 sites in the Koshi River network. These 5 FPZs were i) High Himalayan River (FPZ1) was associated with narrow gorges and high down valley slopes, and in-channel velocities; ii) Meandering River (FPZ2) was associated with relatively open valleys and well-developed floodplain surfaces (Figure 5.1) and occur in the lower slopes of the southern Himalayan region; iii) Braided River (FPZ3) was associated with moderate down valley slope; iv) High Elevation Floodplain River (FPZ4) and v) Low Elevation Floodplain River associated with the floodplain (FPZ5).

The river networks (river channel) were prepared from a 90 m SRTM Digital Elevation Model from the Arc Hydro tool in ArcGIS. These outputs were inputs for running the Floodplain Model (FLDPLN, Kastens 2008) to determine floodplain extent as a function of floodwater depth. This output was input to the Valley Floor Mapper to delineate the valley floor area. The valley floor area was used as a surrogate for potential floodplain areas. The river networks were used to generate the riparian zone assuming the width of the riparian zone is 30 meters from the river channel. Then it was buffered 30 meters from the river channel via ArcGIS.

5.4.3.2 Identify ecosystem services across three spatial scales in the Koshi River Basin

In this study, we used four sources of information to map the distribution of ecosystem services on the riverine landscape. First, literature focusing on ecosystem services on the riverine landscape in the context of Nepal was reviewed. Second, spatial data sets obtained from the International Centre for Integrated Mountain Development (ICIMOD) provided land cover information for 2010 at a resolution of 30m for the entire Koshi River Basin. These data sets were used as a proxy for ecosystem services. In addition, the SWAT model, developed for the Koshi River Basin and used in step 1, also gave data on ecosystem services across the basin. In addition to hydrological modelling, SWAT can simulate water-dependent provisioning and regulating ecosystem services as well as proxy variables to estimate associated supporting and cultural services through river networks (cf. Crossman et al., 2013; Francesconi et al., 2016). Third, household surveys were undertaken as part of The Poverty and Vulnerability Assessment (PVA) for 2011-2012 and the Nepal Census data (CBS, 2011) (Ministry of Health and Population, 2011) provided household-level data on the use of ecosystem services for each Village Development Committee district (VDC) in the Nepal section of the Basin. Fourth, additional data obtained from various Nepalese government departments (eg. Nepalese Tourism Board, Nepal Electricity) provided information on a variety of ecosystem services, including the location of dams, cultural, tourism and recreational sites and activities. With the available information and data, a list of ecosystem goods and services was prepared. Then the list was categorized into provisioning, regulating, cultural and supporting services following the MEA framework (MEA, 2005). Finally, the provisioning, regulating, cultural and supporting ecosystem services associated with the riverine landscape of the Koshi were partitioned according to sub-basin, FPZs and riverine landscape units (river channel, riparian zone and floodplain). Here and through the remainder of the chapter, the ecosystem services denote flow-dependent ecosystem services.

5.4.4. Step 4: Allocate functional response of ecosystem services to a change in ecosystem function as a result of flow regime change

The combination of steps 2 and step 3 gives knowledge that enables the functional response of ecosystem services to a change in riverine ecosystem function as a result of flow regime change. We focused on high-flow and low-flow events because the ecological functions associated with these characteristics of a flow regime (high and low flow) often serve as ecological bottlenecks that present critical stresses and opportunities for a wide array of riverine species (cf Poff et al., 1997). To determine the direction of response (enhanced, constrained, mixed, or no response) within the three hierarchical levels of riverine landscapes, multiple lines of evidence approach were used based on the literature (Rai et al; 2019; Datry et al., 2017; Carolli et al., 2017; Cui et al., 2017; Grizzetti et al., 2016; Vaughn et al., 2015; Shrestha and Aryal., 2010; Palmer et al., 2009; Gibson et al., 2005; Talbot et al., 2018), expert opinion and knowledge and field observation. The field observation photo and literature used to determine the direction of response are listed in Annex I and II. A similar approach was used by Schneider et al. (2013); and Hornung et al. (2019) to link the impact of measures and human activities to ecosystem services.

5.4.5. Step 5: Assess the response of ecosystem services to climate change

To determine the response of 46 ecosystem services to climate change, a data matrix table was prepared that links the ecosystem services with change in riverine ecosystem functions as the result of the change in flow regime change with respect to the 2085s time period under RCP8.5 climate scenarios and three hierarchy/zones of riverine landscapes (sub-basin, FPZ and RLU). Finally, the output responses of ecosystem services to climate change were counted to observe the total impact of climate on riverine landscape according to sub-basins, FPZs and riverine landscape units where the ecosystem services were enhanced, constrained, mixed and no response. A similar matrix approach was used by Burkhard et al. (2009); Burkhard et al. (2012); Schneider et al. (2013); Burkhard et al. (2014); Sohel et al. (2015); Jacobs et al. (2015) to assess the capacities of different land cover classes to supply of ecosystem services.

5.4.6. ***Statistical analyses***

Comparisons of responses in ecosystem services among sub-basins, FPZs and RLUs were carried out using Analysis of Similarity (AnoSim) using resemblance matrices of Euclidian distances between sampling units in Primer 7 version7.0.22 (Primer-e 2022).The AnoSim statistic compares the mean of ranked dissimilarities between groups to the mean of ranked dissimilarities within groups. An R-value close to "1.0" suggests dissimilarity between groups while an R-value close to "0" suggests an even distribution of high and low ranks within and between groups.

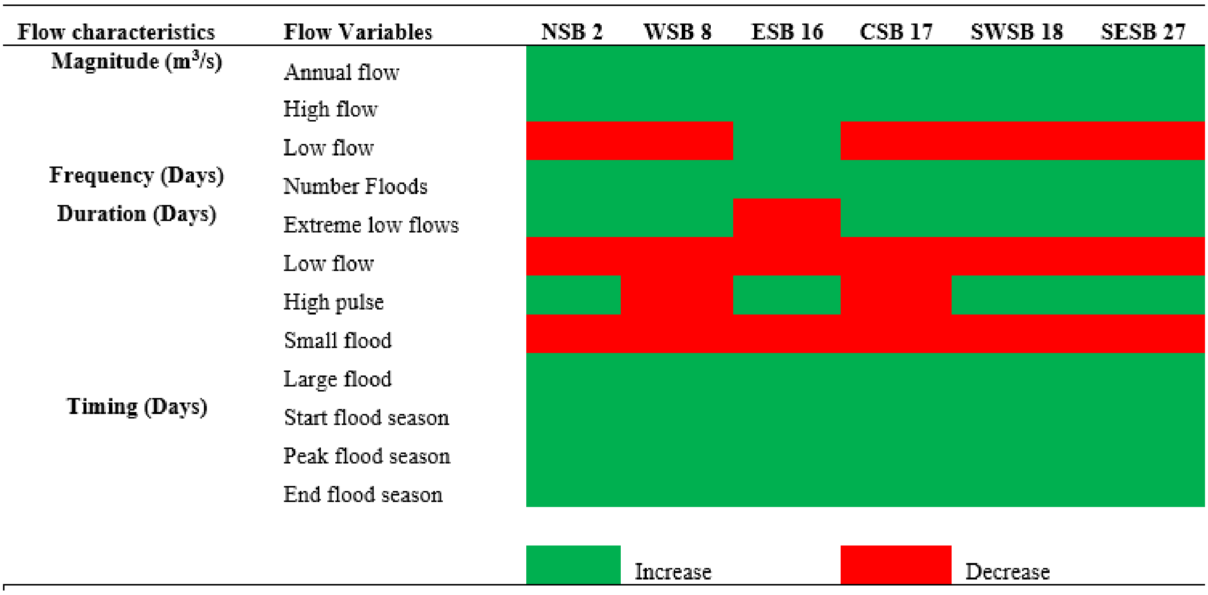
5.4.7. ***Limitations of the study***

The major limitations of the present study lie in the limited household and ecosystem services data availability and accurate information in the high Himalayan areas of Tibet and Nepal (The northern part of our study area). These areas are very remote and have less accessibility. Due to the unavailability of ecosystem services data, we used landcover and SWAT outputs as proxy ecosystem services to fulfill those gaps. Furthermore, there is no information, data and literature related to water abstraction in the basin.

5.5. **Results**

5.5.1. ***Hydrological responses to climate change will vary according to sub-basins.***

Climate change is projected to influence the four components of magnitude, frequency, duration and timing of the flow regime in each sub-basin (Figure. 5.4). Variables characterising the frequency and timing components of the flow regime are projected to increase in all sub-basins. The patterns for magnitude and duration variables are more mixed. Among the magnitude variables, annual flows and high flow magnitudes increased for all sub-basins, while low flow magnitudes decreased for all but one sub-basin (ESB 16). Among the duration variables, the number of large flood days is projected to increase for all sub-basins, while the number of small flood days and low flow days are projected to decrease for all sub-basins. A less consistent pattern across sub-basins is evident for extreme low flow days and high pulse days, with the former increasing in all sub-basins except one (ESB 16) and the latter increasing in all but two sub-basins (WSB 8 and CSB 17). In addition, the pattern of change differs among sub-basins. NSB 2, SWSB 18 and SESB 27 show the same response pattern, whereas WSB 8 and CSB 17 show a different, though matched pattern and ESB 16 shows a unique response pattern compared to all sub-basins (Figure 5.3).



Flow characteristics	Flow Variables	NSB 2	WSB 8	ESB 16	CSB 17	SWSB 18	SESB 27
Magnitude (m^3/s)	Annual flow	🟩	🟩	🟩	🟩	🟩	🟩
	High flow	🟩	🟩	🟩	🟩	🟩	🟩
	Low flow	🟥	🟥	🟩	🟥	🟥	🟥
Frequency (Days)	Number Floods	🟩	🟩	🟩	🟩	🟩	🟩
Duration (Days)	Extreme low flows	🟩	🟩	🟥	🟩	🟩	🟩
	Low flow	🟥	🟥	🟥	🟥	🟥	🟥
	High pulse	🟩	🟥	🟩	🟥	🟩	🟩
	Small flood	🟥	🟥	🟥	🟥	🟥	🟥
	Large flood	🟩	🟩	🟩	🟩	🟩	🟩
Timing (Days)	Start flood season	🟩	🟩	🟩	🟩	🟩	🟩
	Peak flood season	🟩	🟩	🟩	🟩	🟩	🟩
	End flood season	🟩	🟩	🟩	🟩	🟩	🟩

🟩 Increase 🟥 Decrease

Figure 5. 4. Heat map of the changes in the flow regime of the study area. NSB 2 = Northern sub-basin 2, WSB 8 = Western sub-basin 8, ESB 16 = Eastern sub-basin 16, CSB 17 = Central sub-basin 7, SWSD 18 = Southwestern sub-basin 18, SESB 27 = Southeastern sub-basin.

Importantly, the degree of projected change to the flow regime with respect to the reference period (1995s), is particularly high in relation to hydrological extremes (floods and droughts). High flow magnitudes are projected to increase in all sub-basins with the relative change in magnitude ranging from 0.83 in SWSB 18 to 8.1 in WSB 8 (Table 5.2). Similarly, large flood days are projected to increase substantially, with increases ranging from 1.31 in SESB 18 to 4.94 in WSB 8. At the other end of the scale, there is also substantial change, with decreases in low flow magnitudes in most sub-basins and increases in extreme low flow days in most basins (Table 5.2). Overall, the projected hydrological changes will result in more extreme hydrological conditions.

Table 5. 2. The relative change of the flow regime.

Flow characteristics	**Flow Variables**	**RCP 8.5 (2085s)**					
		NSB 2	WSB 8	ESB 16	CSB 17	SWSB 18	SESB 27
Magnitude	Annual flow	0.43	1.71	1.26	0.69	0.46	0.51
	High flow	1.44	8.10	1.48	1.20	0.83	0.87
	Low flow	-0.43	-0.09	0.01	-0.03	-0.06	-0.01
Frequency	Number Floods	1.36	4.94	2.83	2.36	1.49	1.31
Duration	Extreme low flows	0.76	0.84	-1.00	0.03	0.29	0.43
	Low flow	-0.61	-0.50	-0.15	-0.27	-0.43	-0.52
	High pulse	0.59	-0.92	0.33	-0.23	0.69	0.52
	Small flood	-0.56	-0.96	-0.60	-0.35	-0.57	-0.53
	Large flood	1.36	4.94	2.83	2.36	1.49	1.31
Timing	Start flood season	0.11	0.06	0.21	0.14	0.10	0.06
	Peak flood season	0.04	0.03	0.28	0.03	0.08	0.06
	End flood season	0.09	0.13	0.14	0.10	0.03	0.05
	Duration of wet days	0.45	0.44	0.71	0.53	0.29	0.3

NSB 2 = Northern sub-basin 2, WSB 8 = Western sub-basin 8, ESB 16 = Eastern sub-basin 16, CSB 17 = Central sub-basin 7, SWSD 18 = Southwestern sub-basin 18, SESB 27 = Southeastern sub-basin 27.

As noted above the impact of climate change on flow regimes varies according to sub-basins. With regard to the detail of these spatial patterns, WSB 8 is projected to experience the greatest increase in flows, with the highest relative change of all sub-basins for annual flows, high flow magnitudes, and the number of flood days. Interestingly, WSB 8 also experiences the greatest increase in extreme low flows suggesting that this sub-basin will be impacted most strongly by the increase in hydrological extremes. In contrast, ESB 16 is projected to experience more water availability generally, with substantial increases in annual flows, and high and low flow magnitudes. This sub-basin is also projected to experience a decline in the number of extreme low flow days and is projected to experience the greatest number of wet days and the greatest increase in the duration of the peak flood season (Table 5.2).

*5.5.2. **Response of flow-dependent ecosystem service in the Koshi River Basin***

Flow-dependent ecosystem services are likely to change due to climate-induced flow modification. Overall, regulating services were the most numerous (234), followed by provisioning (192), cultural (103) and supporting (51) services (Figure 5.). Most of the 46 ecosystem services changed in response to flow modifications; however, the pattern of response varied significantly among ecosystem service categories (KS test p<0.01). Of these, cultural services are mostly constrained, with no services enhanced by climate change (Figure 5.5). The remaining service categories do not include any that are constrained, with regulating and provisioning services overwhelmingly enhanced and supporting service responses split fairly evenly between mixed and enhanced responses.

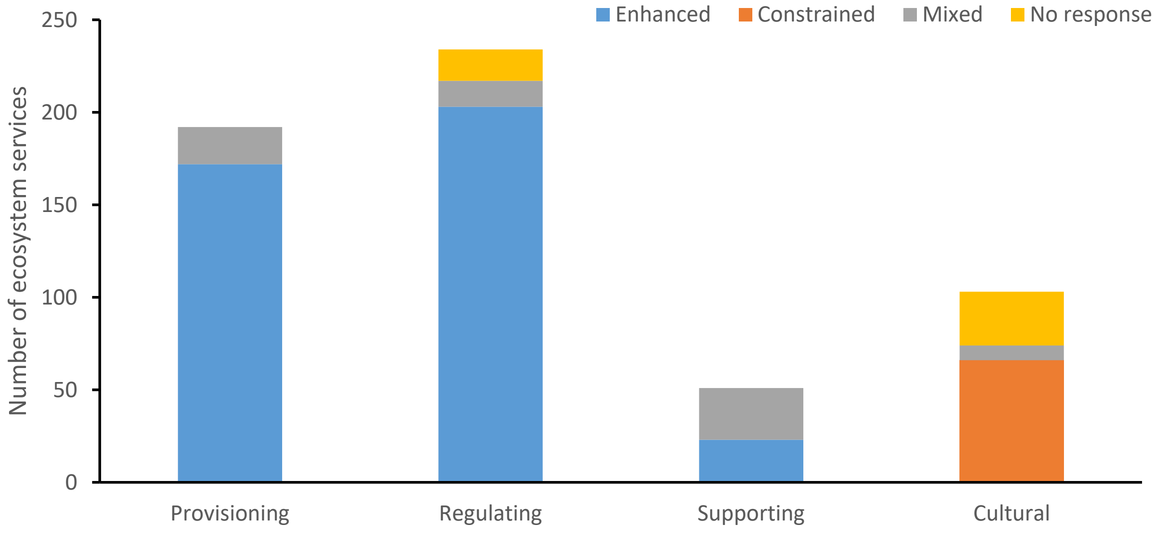


Figure 5. 5. The response patterns of ecosystem services to climate change in the Koshi River Basin.

5.5.3. ***Response of the flow-dependent ecosystem services among sub-basins in the Koshi River Basin***

The pattern of responses in ecosystem services was fairly consistent across sub-basins (ANOSIM Global R = -0.06, p = 0.95), with this pattern confirmed by pairwise analysis of similarity (Table 5.3) which showed no differences between individual sub-basin pairings. Thus, the overall pattern of ecosystem services predominantly being enhanced, with much lower numbers being constrained, experiencing a mixed response or no response, holds across sub-basins (Figure 5.6).

Table 5. 3. ANOSIM R statistics (bottom) and probabilities (top) for pairwise comparison of ecosystem service responses in sub-basins. R values below 0.25 indicate groups are not separable (Clarke and Gorley 2001).

	NSB 2	WSB 8	ESB 16	CSB 17	SWSB 18	SESB 27
NSB 2		1	0.98	1	0.8	0.19
WSB 8	-0.105		0.99	1	0.78	0.19
ESB 16	-0.095	-0.095		0.99	0.72	0.16
CSB 17	-0.089	-0.089	-0.087		0.82	0.33
SWSB 18	-0.059	-0.059	-0.052	-0.061		0.56
SESB 27	0.13	0.13	0.174	0.055	-0.063	

NOTE: NSB 2 = Northern sub-basin 2, WSB 8 = Western sub-basin 8, ESB 16 = Eastern sub-basin 16, CSB 17 = Central sub-basin 7, SWSD 18 = Southwestern sub-basin 18, SESB 27 = Southeastern sub-basin 27.

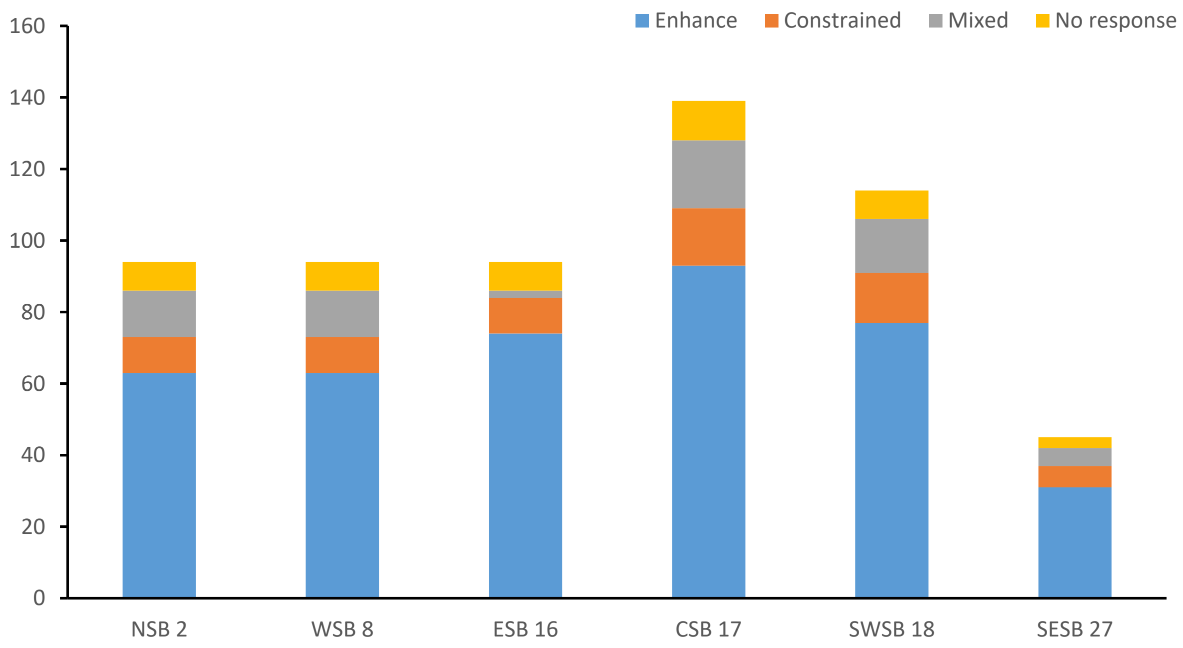


Figure 5. 6. The response patterns for ecosystem services to climate change according to the sub-basins, NSB 2 = Northern sub-basin 2, WSB 8 = Western sub-basin 8, ESB 16 = Eastern sub-basin 16, CSB 17 = Central sub-basin 7, SWSD 18 = Southwestern sub-basin 18, SES 27 = Southern sub-basin 27.

The pattern in the response of ecosystem services to climate change, by category, was also consistent among all sub-basins. For instance, most provisioning and regulating services were enhanced across all sub-basins. In contrast, supporting services are mostly projected to have a mixed response, with the remainder being enhanced, except in ESB 16, where all supporting services are enhanced. Cultural services also show a similar pattern across sub-basins, though in this case, most services are constrained by climate change, with a minority of services having no response or a mixed response. No cultural services are enhanced by climate change in any basin. Overall, the response of ecosystem services to climate change was consistent among sub-basins whereas the character of response varied between ecosystem service categories (Figure 5.7).

Figure 5. 7. The response patterns for ecosystem service types to climate change among the sub-basins, NSB 2 = Northern sub-basin 2, WSB 8 = Western sub-basin 8, ESB 16 = Eastern sub-basin 16, CSB 17 = Central sub-basin 7, SWSD 18 = Southwestern sub-basin 18, SESB 27 = Southeastern sub-basin 27.

5.5.4. ***Response of flow-dependent ecosystem services between and among FPZs in the Koshi River Basin.***

The number of ecosystem services generated varies among FPZs, with Meandering River FPZ and Braided River FPZ, and Low Elevation Floodplain River FPZ generating more services than High Elevation Himalayan River FPZ and High Elevation Floodplain River FPZ. This pattern is consistent among the sub-basins in which the respective FPZs occur. While the most common response in ecosystem services in all sub-basins and FPZs is projected to be enhanced, the pattern of response in ecosystem services is projected to vary among FPZs (ANOSIM Global R = 0.307, p = 0.001). Pairwise comparisons show that most FPZ pairings are significantly different, with little variation across sub-basins. Only the pairings among Meandering River FPZ and Braided River FPZ, and Low Elevation Floodplain River FPZ not being separable (Table 5.4).

Table 5. 4. ANOSIM R statistics (bottom) and probabilities (top) for pairwise comparison of ecosystem service responses in FPZs. R values below 0.25 indicate groups are not separable (Clarke and Gorley 2001).

	FPZ1	FPZ2	FPZ3	FPZ4	FPZ5
FPZ1		0.002	0.001	0.046	0.02
FPZ2	0.48		0.28	0.001	0.67
FPZ3	0.425	0.03		0.001	0.28
FPZ4	0.103	0.693	0.348		0.002
FPZ5	0.504	-0.093	0.086	0.778	

NOTE: FPZ1 = High Himalayan River, FPZ2 = Meandering River, FPZ3 = Braided River, FPZ4 = High Elevation Floodplain River FPZ5 = Low Elevation Floodplain River

Most of the FPZs responded the same irrespective of which sub-basin it was in except FPZs in ESB 16 (Figure 5.8). For instance, the response of ecosystem services in High Himalayan River FPZ, Meandering River FPZ, Braided River FPZ and High Elevation Floodplain River FPZ is a combination of enhanced, constrained, mixed and no response in NSB 2, WSB 8, CSB 17 and SWSB 18, whereas the response of ecosystem services in High Himalayan River FPZ, Braided River FPZ and High Elevation Floodplain River FPZ differed in the ESB 16 (Figure 5.8).

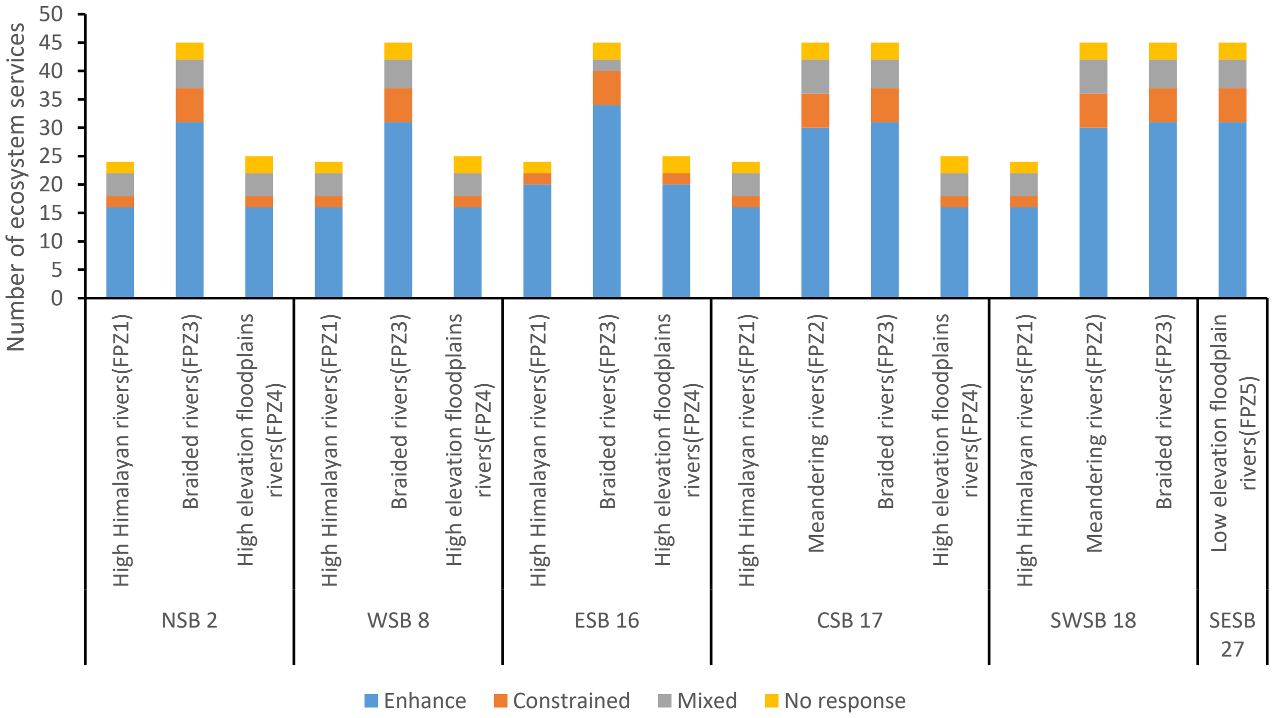


Figure 5. 8. The response patterns of ecosystem services vary according to FPZs within sub-basin, NSB 2 = Northern sub-basin 2, WSB 8 = Western sub-basin 8, ESB 16 = Eastern sub-basin 16, CSB 17 = Central sub-basin 7, SWSD 18 = Southwestern sub-basin 18, SESB 27 = Southeastern sub-basin 27.

The response patterns for ecosystem service categories for FPZs within the sub-basin are illustrated in Figure 5.9. Consistent with the patterns exhibited for ecosystem services as a whole variation in response patterns within ecosystem service types are mostly in relation to FPZ, although patterns within ESB 16 are somewhat contrasting. For example, most provisioning services are projected to be enhanced or experience a mixed response; however, ESB 16, enhanced dominates the response of ecosystem services in all FPZs. Similarly, most regulating services are projected to be enhanced, constrained and mixed, while in ESB 16, enhanced dominates the response of ecosystem services in all FPZs. Finally, most supporting services experienced a mixed or enhanced response, except in ESB 16, where all supporting services were enhanced.

5.5.5. ***Response of flow-dependent ecosystem services between and among the river channel, riparian zone and floodplain in the Koshi River Basin.***

The response patterns for riverine landscape units within FPZs are illustrated in Figure 5.10. The response of ecosystem services differs among the river channel (Rc), riparian zone (Rz) and floodplain (Fp) (ANOSIM Global R = 0.465, p = 0.001). This difference held for all pairwise comparisons (Table 5.5).

Table 5. 5. ANOSIM R statistics (bottom) and probabilities (top) for pairwise comparison of ecosystem service responses in Riverine Landscape Units. R values below 0.25 indicate groups are not separable (Clarke and Gorley 2001).

	Rc	Rz	Fp
Rc		0.001	0.001
Rz	0.664		0.001
Fp	0.472	0.324	

NOTE: Rc = River channel, Rz = Riparian zone, Fp = Floodplain

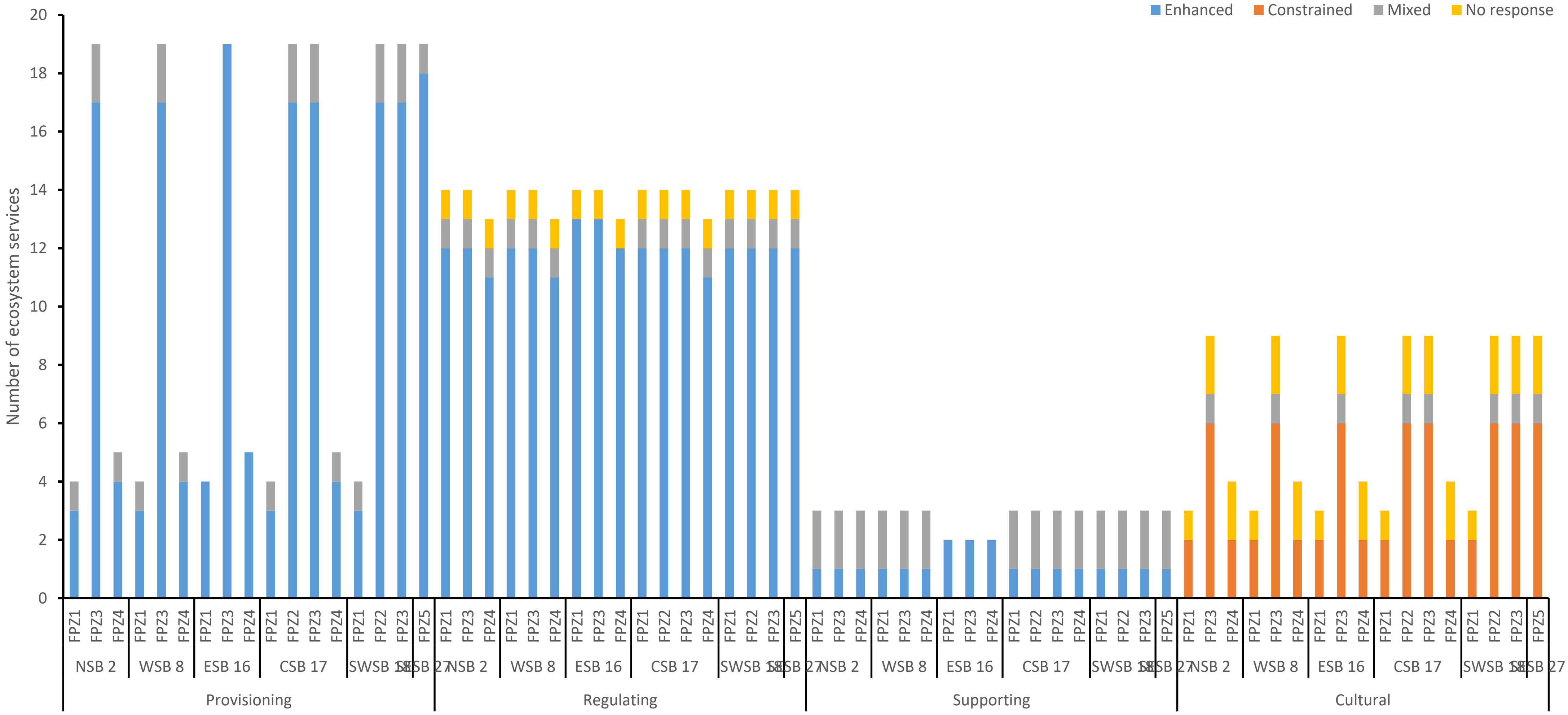


Figure 5. 9. The difference in the response patterns of ecosystem service types among FPZs within sub-basins. FPZ1 = High Himalayan River, FPZ2 = Meandering River, FPZ3 = Braided River, FPZ4 = High Elevation Floodplain River FPZ5 = Low Elevation Floodplain River, NSB 2 = Northern sub-basin 2, WSB 8 = Western sub-basin 8, ESB 16 = Eastern sub-basin 16, CSB 17 = Central sub-basin 7, SWED 18 = Southwestern sub-basin 18, SESB 24 = Southeastern sub-basin 27.

These contrasts reflect a pattern whereby the services of Rc units are projected to experience the full range of response types, albeit predominantly enhanced, while the services of the Rz and Rp units, also dominated by an enhanced response, are not subject to a mixed response (Figure 5.10). The responses in ecosystem services of Rz and Fp units are distinguished by the greater dominance of enhanced responses for Fp units (Figure 5.10). Response patterns in riverine landscape units vary slightly among FPZs. For Rc units, the full range of responses, dominated by enhanced responses, are projected in all FPZs, but constrained responses are relatively more common in Braided River and Meandering River. Similarly, for Fp units, enhanced responses dominate for all FPZs, but constrained responses are the next most common response in Meandering River, Braided River and Low Elevation Floodplain River, while no response is the next most common in High Elevation Floodplain River. For Rz units, the response pattern is consistent across all FPZs.

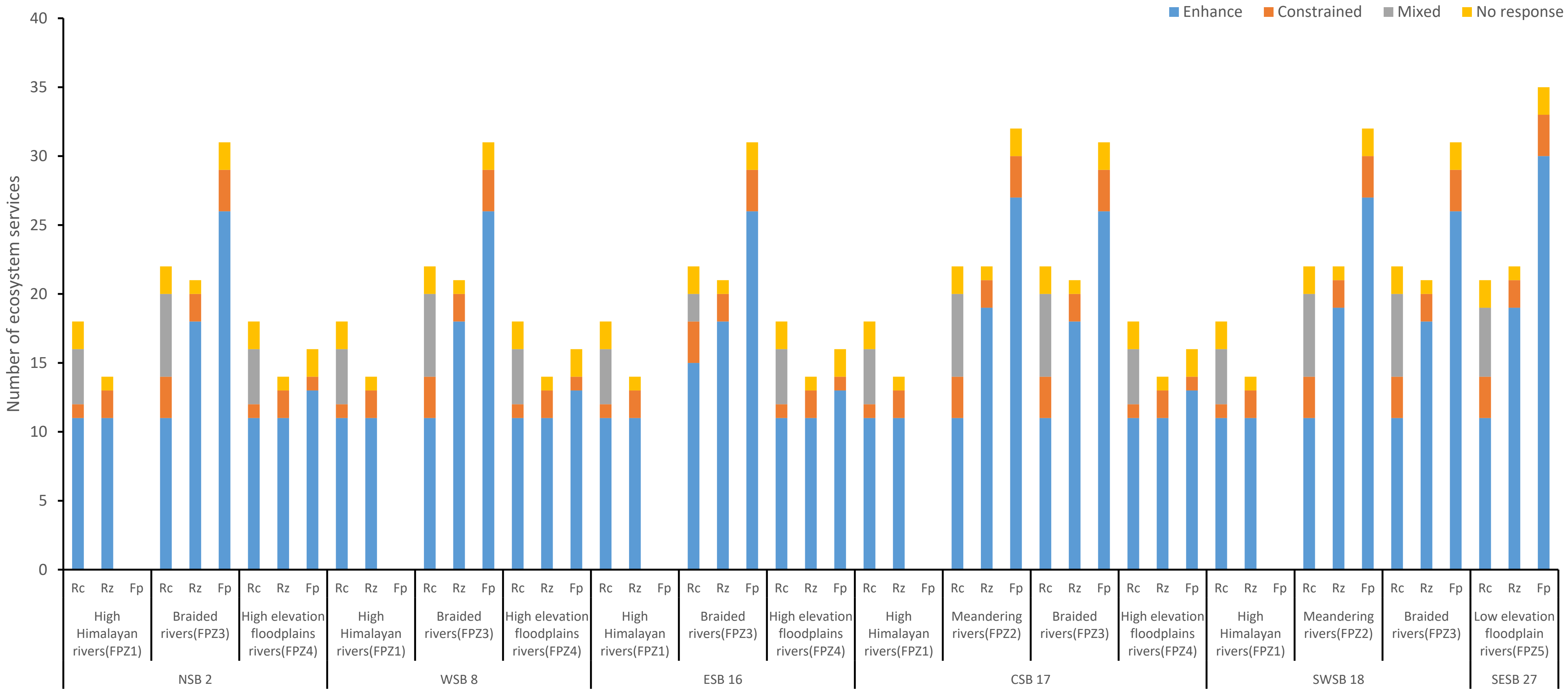


Figure 5. 10. The response patterns of ecosystem services to climate change vary depending on the lateral position within FPZs and sub-basins NSB 2 = Northern sub-basin 2, WSB 8 = Western sub-basin 8, ESB 16 = Eastern sub-basin 16, CSB 17 = Central sub-basin 7, SWSD 18 =southwestern sub-basin 18, SESB 27 = Southeastern sub-basin 27.

The pattern of ecosystem service response among riverine landscape units differs among the four ecosystem service groups. Provisioning and supporting services in the riverine landscape are all projected to be enhanced in Rz and Fp units while in the Rc both enhanced and mixed responses are projected. Regulating services are mostly projected to be enhanced, with some services projected to experience no response in all units and a mixed response projected for some services in the Rc unit. Cultural services were mostly constrained in all units, with constrained being the only response projected in the Rz. No response is projected for some services in the Fp and Rc, and some Rc services are projected to experience a mixed response (Figure 5.11).

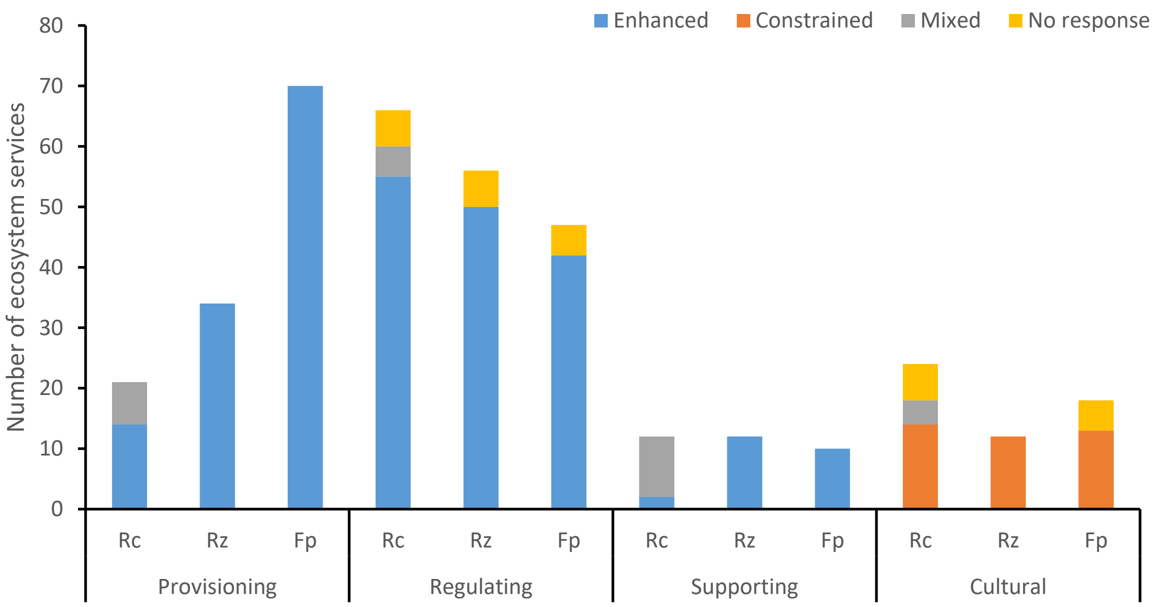


Figure 5. 11. The response patterns of ecosystem service types to climate change vary depending on the lateral position, Rc = River channel, Rz = Riparian zone, Fp = Floodplain.

5.5.6. *The response of flow-dependent ecosystem services among the three riverine landscape units was complex.*

The analysis of similar results shows that there are essentially two groups of flow-dependent ecosystem service responses in relation to riverine landscape units among FPZs: i) the response of ecosystem services in the High Himalayan River FPZ is broadly the same among units (Rc, Rz, Fp) with the analysis of similarities values less than 0.25; ii) Ecosystem services in the riverine landscapes of the two floodplains (High Elevation Floodplain River FPZ and Low Elevation Floodplain River FPZ) are projected to response differently among riverine landscapes (Rc, Rz, Fp), with analysis of similarities values greater than 0.5. The response of ecosystem services to the riverine landscape varies according to its position in the riverine landscape. However, irrespective of the three riverine landscape units (Rc, Rz and Fp) where it is in sub-basins the response of ecosystem services to climate change is almost the same.

5.6.**Discussion**

5.6.1. The response of flow-dependent ecosystem services to climate change is not the same according to the level of hierarchy organization in the river network

There was congruence between the distribution and composition of response in flow-dependent ecosystem services to climate change (Chapter 4). The study design (3 levels of the organization) demonstrated that the response of flow-dependent ecosystem services to climate change varies according to the level of organization in the hierarchy. The response of ecosystem services to climate change is the same on the sub-basin scale. This is likely because the sub-basins have broadly similar physical templates that will be altered in a similar way by hydrological changes stemming from future climate change (Bajracharya et al., 2023). The relatively uniform nature of the sub-basins is illustrated by the similar composition of FPZs with respect to FPZs (Bajracharya et al., 2023; Thorp et al., 2010).

The response of flow-dependent ecosystems does vary for both Function Process Zones (FPZs) and Riverine Landscape Units (RLUs) because of the contrasting physical templates of the different FPZs and RLUs, and the contrasting way in which hydrological changes will affect these templates at both scales and thus drive changes to the ecosystem services at each scale. This result is consistent with hierarchy theory (hierarchy of influence), where higher-level factors control processes and patterns at lower levels, while lower levels influence the structure and functioning of those at the higher level (Thorp et al., 2008; Delong and Thoms 2016; Harris et al., 2008). The FPZs are heterogeneous physical templates with high biocomplexity, different stream hydraulics, and critical factors shaping biotic communities and delimiting ecosystem processes (Thorp et al., 2008). Similarly, the various RLUs are also contrasting physically and with respect to the manner in which hydrological changes will affect them (Chapter 4). For example, any changes to within-channel flows will have no impact on the floodplain, while changes to the frequency and magnitude of flooding will have a more dramatic impact on processes on the floodplain than those in the channel. The biotic communities of channels, riparian zones and floodplains are obviously highly contrasting, but this matching of ecological patterns with physical patterns at specific scales has also been demonstrated in relation to macroinvertebrate communities and FPZs (Elgueta et al., 2021, Parsons et al., 2003). This study further reinforces the importance of looking at the hierarchical organization of river networks and acknowledging the importance of FPZs and RLUs in terms of the response of ecosystem services to climate change.

Overall, the response of flow-dependent ecosystem services to climate change varies according to or depending on where it is in the level of organization in the hierarchy of the riverine landscape. The FPZs and RLUs are the levels in the river system hierarchy that exert the greatest control on the response of flow-dependent ecosystem services to climate change in the river network.

5.6.2. The nature of the physical template governs the response of flow-dependent ecosystem services.

The response of flow-dependent ecosystem services is strongly influenced by the physical characteristics of the riverine landscape (Chapter 4). FPZs and RLUs have emerged as an appropriate scale to view the physical template and its relationship with ecosystem structure and function in river networks. The abundance, richness and evenness of FPZ types as well as spatial variation of biophysical template across the riverine landscape can inform about physical habitat diversity which is important for ecological structure and function in river networks (Thoms et al., 2007). Climate change modifies the physical template through the change in flow regime and morphology. Change in flow is the key driver for physical template heterogeneity (Bajracharya et al., 2023). The heterogeneity of the physical template shapes riverine ecosystem structure and function and determines the types, abundance, and arrangement of ecosystem services (Bajracharya et al., 2023; Thorp et al., 2008). Ecosystem services are congruent with the type and distribution of FPZs in a river network and the presence of contrasting features of channel, riparian zone and floodplain at the landscape scale (Bajracharya et al., 2023; Chapter 4). Thus, the heterogeneity of the physical template is the main cause of the heterogeneous response of flow-dependent ecosystem services. This is the reason there is often a deterministic relationship between the response of flow-dependent ecosystem services and physical templates.

5.6.3. The response of flow-dependent ecosystem services varies according to climate change.

Flow-dependent ecosystem services are projected to experience a range of responses to the projected changes in the flow regime (Chapter 4). These responses vary in relation to spatial scale and levels of the organisation, there are distinct patterns in ecosystem service type (Figure 5.5). In particular, while most provisioning and regulating services service types are projected to be enhanced, supporting services are equally likely to experience a mixed response, while cultural services are most likely to be constrained by the projected flow changes. The general pattern for non-cultural flow-dependent ecosystem services in the Koshi River network likely to be enhanced is because of high spatial connectivity and high levels of environmental heterogeneity (Poff, 2002). Capon et al. (2013) suggest that riverine ecosystems have evolved under conditions of high environmental variability and hydrologic extremes, thus the increases in connectivity and extremes can be argued to benefit these systems.

Provisioning services were enhanced more in the Meandering River FPZ, Braided River FPZ and Low Elevation Floodplain River FPZ (Figure 5.9). This might be due to the lower slope and the presence of floodplains in these functional process zones. The lower slope ranges from 0 to 7 degrees in the FPZs. Floodplain ecosystems support high levels of biodiversity and levels of productivity that generally exceed production (Opperman et al., 2010). Floodplains are known hotspots that generate a wide range of ecosystem services (Tockner and Standford 2002). Meandering River FPZ and Braided River FPZ floodplains have also been shown to have a greater capacity to supply provisioning services (Bajracharya et al., 2023). The pattern of enhanced regulating services is the same in all FPZs except High Elevation Floodplain River FPZ. This result may be because the High Elevation Floodplain River lies in the Tibetan plateau, which supports less riparian and floodplain vegetation due to harsh environmental factors like high elevation, low temperatures, and low precipitation. Vegetation is critical to the regulating services generated by channel, riparian and floodplain units in the riverine landscape.

The contrasting pattern of dominance of constrained responses in cultural services is likely a reflection of how the projected hydrological changes may reduce the accessibility of riverine systems to people (Milcu et al., 2013). The literature review by Talbot et al. (2018) noted that recreational activity is negatively impacted by flooding and people were less likely to visit a recreational site after a flood. Walters et al. (2015) highlighted that flooding may impact tourism by reducing people's safety, damaging infrastructure, damaging site of interest, and changing tourist perceptions of an area.

In addition, supporting services were dominated by mixed responses. Supporting services are the fundamental process of the ecosystem that supports or aids in the production of all other ecosystem services for instance soil formation. Change in flow will change the rate of sediment erosional and deposition processes occurring within the river network which will influence the positive and negative impacts on soil formation depending on where erosion and deposition occur and the volume of sediment transported (c.f. Talbot et al., 2018).

5.6.4. Function process zone and riverine landscape unit are the right scales to manage a flow-dependent ecosystem in the riverine network.

In order to manage riverine ecosystems effectively and efficiently, the basic processes governing ecosystem structure and functioning must be understood at appropriate scales. This study shows the close association between the physical character of FPZs, RLUs and ecosystem services. This in turn suggests that FPZs and RLUs represent appropriate assessment targets for the conservation, rehabilitation, and management of ecosystem services in the entire river network, similar to the finding of Elgueta et al. (2019). The differences in abundance and diversity of the FPZs and the existence of strong connections between RLUs and the link from these spatial units with particular ecosystem services should be central to the design of monitoring programmes that account for the hydro-geomorphological and biological diversity of the entire river network (cf. Elgueta et al., 2019). Therefore, the management of flow-dependent ecosystem services should be focused on the FPZ and RLU levels, not basin and sub-basin levels.

5.7.**Conclusion**

The response of ecosystem services to climate change differs among FPZs and riverine landscape units and most of the spatial variation in the response of ecosystem services comes at these levels of organisation. In contrast, the nature of the response of ecosystem services to climate change was consistent among all sub-basins. It highlights that the response of ecosystem services is governed by variation in the physical template of the FPZ and riverine landscape, not variation in the physical template at the scale of the sub-basins. Climate change will influence flow-dependent ecosystem services. This modified template will affect the interaction between physical driver and biological components within the riverine landscape resulting in the modification of ecosystem structure and function and complex response in ecosystem services. In other words, physical templates are important in determining the response of flow-dependent ecosystem services to climate change. Therefore, the response of flow-dependent ecosystem services to climate change varies between FPZ.

This study further highlights the importance of looking at the hierarchical organization of river networks. While strong variation in response was evident among FPZs and riverine landscape units, it is important to note that the variation among units was influenced by what FPZ the units were in; in other words, the units’ position about the next level of spatial organization in the river network hierarchy, demonstrating the concept of top-down constraint. Similarly, the variation among FPZs was influenced by the riverine landscape unit being assessed, demonstrating a bottom-up influence. Thus, in addition to demonstrating which levels of the spatial organisation are important when seeking to understand the impacts of climate change on flow-dependent ecosystem services, this study has also highlighted the importance of the hierarchical structure of river networks.

5.8.**References**

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Chapter 6: Synthesis and conclusion

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Dense settlement on the floodplain of the Sunkoshi River Basin

6.1. Introduction to this chapter

People have interacted with and shaped riverine landscapes for social and economic benefits for millennia (Diamond, 2011). Humans have optimized the capture of ecosystem services and increased the opportunity to use the many ecosystem services provided by riverine landscapes by increasing social-ecological linkages. Understanding the coupling between humans and riverine landscapes is important for many ecological, social, economic and management reasons (Huang et al., 2022; Thoms and Sheldon, 2019; Chen and Liu, 2014). However, many riverine landscape models do not fully capture important human–environment couplings. Humans and society are viewed commonly as external drivers to river systems and not as connected social-ecological systems. In addition, prevailing models such as the River Continuum Concept (RCC, Vannote et al., 1980) view rivers as simple, linear systems with a continuous gradient of biophysical conditions from headwaters to mouth.

An emerging trend in river science is the acknowledgment of the importance of riverine landscapes as a social-ecological system (Gilvear et al., 2016). People utilise resources provided by riverine landscapes and in turn, the biophysical character of these landscapes can influence the manner in which people use and interact with rivers (Parsons and Thoms, 2018). Therefore, this thesis challenges the view that riverine landscapes are only a biophysical component. Riverine landscapes are social-ecological systems because of complex interactions and feedback between the environment and humans, where humans influence the use, value, production and demand of ecosystem services. Thus, humans are part of riverine landscapes and are not external drivers. Moreover, a biophysical focus on ecosystem services of riverine landscapes only provides information about the ecological state of the river ecosystem and not the social part of the riverine ecosystem. With such perspectives of the riverine landscape, we cannot understand the natural process and direct influence of humans at relevant scales in the environment and cannot fully determine the use and social value of ecosystem services. A biophysical understanding cannot fully incorporate community perceptions, priorities, values, attitudes and benefits, knowledge of which may generate more meaningful insights into the contribution of ecosystem services to human well-being than purely biophysical assessments.

As noted above, prevailing models such as the RCC view riverine landscapes as simple, continuous biophysical gradients. However, this thesis has shown that riverine landscapes are not simple gradient models, rather, the physical templates of rivers are made up of distinct spatial units or patches (e.g. FPZs) that exist within larger units (e.g. sub-basins) and are themselves made up of smaller units (e.g. RLUs). Moreover, the spatial arrangement of the physical river template is not necessarily clinal and units can repeat themselves along the river network (Thorp et al., 2006).

The flow-dependent ecosystem services arise from the interaction between ecological function and the physical template, thus the physical template should dictate the occurrence of ecosystem services. This thesis has confirmed a congruent association between the physical template and ecosystem services, and variations in the supply, use and value of ecosystem services within the entire river network can be expected. In particular, the thesis has shown that patterns in ecosystem services in river systems relate to the physical template composed of a hierarchical set of defined patches as described above.

Climate change modifies the physical template through a change in the flow regime. This change will change the interaction between flow regime and geomorphology which can influence the provision of ecosystem services within a river network. Climate change affects riverine landscapes principally through its effect on the flow regime (Poff, 2002). This thesis has demonstrated changes to the flow regime due to climate change over the remainder of this century. Moreover, these changes can be expected to affect flow-dependent ecosystem services, with these changes likely to vary over time, in relation to emissions scenarios and according to lateral position within the riverine landscape and functional process zone.

This thesis contributes to the emerging trend in river science that riverine landscapes are social-ecological systems. These social-ecological systems can be understood and researched via an ecosystem service and a complex adaptive system approach. A complex adaptive system approach looks at the interactions between physical character, drivers, controllers, and responders (Figure 6.2) and ecosystem services are a means to investigate these complex interactions between riverine landscapes and humans (Hanna et al., 2018). Humans obtain benefits from these interactions through the ecosystem services that riverine landscapes provide. The ecosystem services reflect a series of dynamic interactions and feedback between the social and ecological components of riverine landscapes. As such, humans must be viewed and modelled as part of the riverine landscape rather than seen as external drivers of social-ecological systems (Parsons, 2019; Hand et al., 2018; Chen and Liu, 2014). In this regard, this thesis modifies and strengthens earlier frameworks of Pickett et al. (2003), and Thoms et al. (2022) used to model social-ecological interactions in riverine landscapes. The modified framework acknowledges the role of the physical template and how it directly influences ecosystem services as well as its ability to incorporate climate change. The modified framework also incorporates the role of society and geography as controllers in the system because society is part of the environment (the riverine landscape in this instance). Therefore, the thesis evaluated not only the biophysical state of a riverine landscape but also the state of social influences in the riverine landscape for the use/benefit of natural resources at a larger scale in a systematic way. This thesis also sheds light on the river character (physical template), riverine ecosystem services and its response to climate change in the large Himalayan Koshi basin in the central Himalayan region where studies are scarce.

This chapter provides a synthesis of the research presented in this thesis and is organised into four sections. Section 6.2 summarizes the main findings related to the objectives of the thesis and highlights the original research contributions from Chapters 2-5. Section 6.3 outlines the scientific contributions of the thesis and the importance of altered templates and controllers in riverine landscapes. Section 6.4 provides suggestions for future research areas and Section 6.5 provides concluding remarks on the thesis.

6.2. Summary of thesis chapters and their research contributions.

This thesis aims to understand the relationship between the physical template and flow-dependent ecosystem services, how the physical template determines the distribution, and abundance of ecosystem services within riverine landscapes and the influence of climate change on this relationship within a large Himalayan river basin. To achieve these aims, two thesis objectives were proposed and these were addressed within four research manuscripts which were presented as Chapters 2-5. These objectives in relation to the four chapters are set out in Table 6.1. Each manuscript has contributed to the body of knowledge in the context of the main theme which is summarized in the following section. Overall, this thesis, addressed a knowledge gap on the interaction between biophysical and social components – viewing the importance of the riverine landscape as a social-ecological system from an ecosystem services perspective through a complex adaptative systems framework.

Table 6. 1. Summary of manuscript objectives and key findings from each manuscript.

Manuscript	Manuscript objective	Key findings	Original contributions
1. The heterogeneity of ecosystem services across the riverine landscape of the Koshi River Basin, Nepal This manuscript addresses thesis objective 1: To examine the congruency between the physical template of a large Himalayan river basin and the supply of flow-dependent ecosystem services.	To investigate the congruency between the physical template and ecosystem services, and also spatial distribution, use and value of flow-dependent ecosystem services in relation to the spatial arrangement of the physical template across a river network.	The physical template of the Koshi River Basin was heterogeneous being composed of five river zones (FPZs) that repeat themselves downstream. The High elevation floodplain FPZ was the dominant FPZ whereas the Low elevation floodplain FPZ was less abundant. The floodplains are distributed intermittently in the Koshi River Basin and irregularly distributed among FPZs. A larger portion of the floodplain area is located upstream (73%), and the lowest to the lower part (11%) is in the Koshi River Basin. There was a high degree of congruency between the physical template and the abundance and use of ecosystem services - while the distribution of potential value did not correspond to the physical template. The distribution of ecosystem services was significantly different among the five FPZs. Provisioning services were more abundant than	• The geomorphology of the Koshi River Basin is a heterogeneous landscape that does not conform to traditional clinal river models. • The heterogeneous nature of the physical template provides the unique structure and function of the ecosystem. • The physical template is important for providing flow-dependent ecosystem services and dictates ecosystem services whereas the use and value of ecosystem services are controlled by geography and society. • The riverine landscapes in the Koshi River Basin are heterogeneous in terms of physical template and flow-dependent ecosystem services.

		Regulating services, Cultural and Supporting services. The total abundance of ecosystem services was highest in the Low elevation floodplain FPZ and lowest in the High elevation floodplain FPZs. The relative use and value of ecosystem services differed significantly among FPZs, but the spatial distribution of relative use and value differed in the abundance of ecosystem services, location and population between FPZs.	
2. Future climate and its potential impact on the spatial and temporal hydrological regime in the Koshi Basin, Nepal. The manuscript addresses thesis objective 2: To examine the effects of climate change on the response of flow-dependent ecosystem services	To examine changes in the future climate and its impact on the hydrology in the Koshi River Basin at a sub-basin scale over time.	Annual average temperature, precipitation and discharge are predicted to increase across the six sub-basins of the Koshi over time. This increase will be greater under the RCP8.5 than the RCP4.5. But there is an interannual (seasonal) influence on the increase of these variables across the basins. The potential change in the flow components was projected to increase in all sub-basins. Flow regimes were varied among 6 sub-basins and the change in flow regime varies across the sub-basins in space and time.	• The effect of potential climate change in the Koshi River Basin is complex. • The potential change in flow regime response is complex in the Koshi River Basin

within a larger Himalayan River Basin. .		The frequency of occurrence of high and extremely low flow events demonstrates the increase in hydrological extremes problem. The impacts strongly accelerated and altered the flow regime up to 2100 with the largest projected increases for RCP8.5 scenarios.	
3. The response of ecosystem services to climate change within the lateral position of the riverine landscape in the Sunkoshi Basin, Nepal. This manuscript addresses thesis objective 1: To examine the congruency between the physical template of a large Himalayan river basin and the supply of flow-dependent	1) To examine the distribution of ecosystem services that vary across the lateral position of the riverine landscape. 2) Determine the flow character of the Sunkoshi under different climate scenarios over time. 3) Investigate the potential response of flow-dependent ecosystem services to hydrological alterations brought by climate change differs according to the lateral position of the riverine landscape.	The distribution of flow-dependent ecosystem services varies laterally across the riverine landscape. The abundance of ecosystem services was greater in the riparian zone followed by floodplains and river channels. Provisioning services were the most abundant ecosystem services followed by regulating, cultural, and supporting services in the Sunkoshi riverine landscape. The flow regime will potentially change but these changes will differ among lateral positions as well as between the two climate scenarios and over time. The magnitude, frequency and duration of flood events will increase as well as the duration of extremely low flows, whereas the flood season under the RCP4.5 scenario will	• The riverine landscape influences the ecosystem services depending on where that is located across the lateral dimension. • There was a different response to the flow change depending on the lateral position. • The lateral position dictates and influences ecosystem services as well as response to flow change • The response of flow-dependent ecosystem services to climate change (flow regime) is not uniform. It varies depending on the lateral position.

ecosystem services and objective 2: To examine the effects of climate change on the response of flow-dependent ecosystem services within a large Himalayan River Basin.		be shorter compared to that under the RCP8.5 scenario. The potential response of the ecosystem services to climate change significantly varies according to the lateral position. There is greater potential for ecosystem services to change in the riparian zone compared to the floodplain and the river channel across the three time periods of both climate change scenarios Most of the ecosystem services observed across the Sunkoshi riverine landscape will potentially respond to flow regime changes while two cultural services have no change. The potential response varies with ecosystem services type, their position across the riverine landscape, climate change scenario and over time.	
4. The role of the geomorphological organisation in the response of flow dependant ecosystem services to climate	Determine the hierarchical response of flow-dependent ecosystem services to climate change in a larger Himalayan River basin	There was congruence between the distribution and composition of response in flow-dependent ecosystem services to climate change and the geomorphological organization of a river network.	• The response of flow-dependent ecosystem services to climate change varies between FPZs. And the physical template is important in determining the ecosystem

change in a river network. This manuscript addresses thesis objective 1: To examine the congruency between the physical template of a large Himalayan river basin and the supply of flow-dependent ecosystem services and objective 2: To examine the effects of climate change on the response of flow-dependent ecosystem services within a large Himalayan River Basin.	The pattern of the response of ecosystem services to climate change was consistent among all sub-basins - dominated by enhanced response. Most of the ecosystem services were enhanced by flow change whereas regulating services show a higher number of enhanced responses followed by provisioning, culture and supporting. A significant difference in the response of ecosystem services was observed among FPZs. Each FPZ displays a different response of ecosystem services to climate change. The response of ecosystem services also differs depending on lateral position. However, irrespective of a riverine landscape where it is in sub-basins and FPZs the response of ecosystem services to climate change is almost the same. The response of the ecosystem services to climate change to two floodplains (High Elevation Floodplain and Low Elevation Floodplain) was different.	service’s response to climate change. • The scale or hierarchy is important to look at the flow-dependent ecosystem response to climate change in the riverine landscape. • Function process zone and riverine landscape unit are the right scales or levels of organization to examine the response of ecosystem services to climate change in the riverine landscape. As well as the right scales to manage the ecosystem services.

6.2.1. Research question 1

Does the abundance, distribution, use and value of flow-dependent ecosystem services vary according to the spatial character of the physical template of the riverine landscape?

This research question was examined in Chapter 2 and by answering this research question I addressed thesis objective 1. The aim of Chapter 2 (Manuscript 1) is to understand the relationship between abundance and distribution of ecosystem services and the physical template in the entire river network. One objective was proposed to address this aim: investigate the spatial distribution of flow-dependent ecosystem services in relation to the spatial arrangement of the physical template across a river network. This manuscript addresses a knowledge gap with regard to understanding how ecosystem services vary and respond according to the characteristics of functional process zones (FPZ). It also addresses the lack of systematic comparison of ecosystem services among many types and arrangements of FPZs at the river network scale and links the use and social value of ecosystem services to FPZs within a large Himalayan river basin. This study, for the first time in the Himalayas, has brought the physical template, ecosystem services, geographic location and population density together to look at both the provision of ecosystem services and the social component of the riverine landscape. This is presented in a manuscript *"The heterogeneity of ecosystem services across the riverine landscape of the Koshi River Basin, Nepal", and* has been published in *The Annals of the American Association of Geographers.*

Bajracharya, S.R., Thoms, M.C., Parsons, M. (2023). The heterogeneity of ecosystem services across the riverine landscape of the Koshi River Basin, Nepal. *Annals of the American Association of Geographers,* 1-23.

Understanding the character of the physical template of the Koshi River Basin is important to comprehend the distribution and composition of ecosystem services in the river network of this large Himalayan River basin. This study reveals the distribution and composition of ecosystem services vary according to the character and spatial organization of FPZs in the Koshi basin because physical templates were heterogeneous. Thus, heterogeneity of the physical template is a primary factor governing the distribution, abundance, use and value of ecosystem services in river networks. The unique characteristic of each FPZ limits the range and distribution of potential ecosystem services. For instance, hydropower, and white water rafting are limited to a few physical templates. Each FPZ had a distinct occurrence of ecosystem services and the distribution of FPZs highlights that ecosystem structure, function and services can vary significantly in the river network. This result concurs with the argument of Thorp et al (2010) that ecosystem services in the river network are outcomes of the physical template dynamics of the river network and not necessarily of its longitudinal position within the river network (Thorp et al., 2008). In addition, the distinct nature of FPZs contrasts with the traditional view that the rivers function as a continuous network of ecological processes from headwater to mouth. It confirms that the Koshi River Basin does not fit the traditional clinal river model.

River characterization is a way to identify physical templates within a river network. The analysis of river characterization showed that the Koshi River Basin was characterized by five functional process zones that significantly differ from each other in terms of their physical character. The study also computed the spatial distribution of floodplains within the river network and results showed that floodplains were distributed intermittently in the Koshi basin and irregularly distributed among the FPZs, which contrasts traditional perspectives of rivers. The result showed that 73% of the floodplain is located upstream, 16% in the middle part of the basin and the remaining 11% in the lower part of the basin.

Chapter 2 showed that the Koshi River is spatially heterogeneous and there is a high degree of congruency between the physical template and ecosystem services as well as the relative use of the ecosystem services, while the distribution of the potential value of ecosystem services did not correspond to the physical template. The similarity between FPZs and the potential value was low within the Koshi river network because the physical template determined the intrinsic value of ecosystem services in the riverine landscape, whereas the human dimension was the main component determining the potential value in the riverine landscape of the Koshi. Physical templates were the link between ecosystem services and use by people.

Overall, the Koshi River Basin is spatially heterogeneous and there is a high degree of congruency between the physical river template and ecosystem services. Ecosystem services are also heterogeneous within a river network. The observed patterns demonstrate that ecosystem services are outcomes of the physical template of the riverine landscape and the physical template of the riverine landscape dictates the occurrence of ecosystem services. However, the capacities of the ecosystem and the physical template of the riverine landscape do not fully control the relative use of ecosystem services. Instead, the potential value of ecosystem services is not controlled by physical templates but is heavily influenced by place and demographic characteristics.

6.2.2. Research question 2

Does the flow regime vary in space and time within the riverine landscape as a result of potential climate change?

This research question was examined in Chapter 3 and by answering this research question I addressed thesis objective 2. Chapter 3 projected future climate change and its impact on the flow regime in the Koshi River Basin and demonstrated there was a difference in flow changes across the basin in space and time. This study assessed changes in the future climate and their impact on hydrology in six sub-basins in the Koshi River Basin and helped to reveal the complexity of hydrology response to climate change in the Koshi River Basin. The results showed the sub-basins of the Koshi River Basin were likely to be markedly affected by changing temperature, precipitation, and discharge in the three time periods under both climate scenarios. There was a spatial variation in the changes in these variables. For instance, the increase in temperature will be greater in the sub-basin located in the northern region. Precipitation increase will be greater in the south-eastern sub-basin and discharge will be greater in the eastern sub-basin. The impacts strongly accelerate over time, with increasing rates of increase in annual mean temperature, precipitation and altered flow regime up to 2100 and the largest projected increases for RCP8.5 scenarios. The manuscript "*Future climate and its potential impact on the spatial and temporal hydrological regime in the Koshi Basin, Nepal*." demonstrates the complex response of the flow regime due to climate change within the Koshi Basin. The pattern of change varies across the sub-basin in space and time. This manuscript has been published in the Journal of Hydrology: Regional Studies.

Bajracharya, S.R., Pradhananga, S., Shrestha, A.B., Thapa, R. (2023). Future climate and its potential impact on the spatial and temporal hydrological regime in the Koshi Basin, Nepal, has been published by the *Journal of Hydrology: Regional Studies*

https://doi.org/10.1016/j.ejrh.2023.101316

Climate change is projected to influence components of the flow regime in each sub-basin. Changes in flow regime vary among the sub-basins over time and the degree of change will be greater in RCP8.5 compared to RCP4.5. The magnitude and frequency of peak discharge in all sub-basins are projected to increase under both RCPs over all time periods (2025s, 2055s, and 2085s). Furthermore, the timing of the peak discharge period will also change. Moreover, the impact on flow alteration varies according to sub-basins and seasons for the different time periods under both RCPs. The flow alteration results showed that the frequency and duration of low flow, as well as high flow, are likely to increase under both RCPs for all time periods. In other words, hydrological extremes (high flow and low flow) are projected to occur more frequently in all sub-basins in the Koshi River Basin. The increase in the duration of the high flow is greater than for the low flow.

Overall, there is a difference in flow regime change across the basin in space and time. The flow regime in the Koshi Basin is projected to be significantly impacted by climate change. The frequency in occurrence of high and extremely low flow events demonstrates the “too much or too little water” problem. It shows that the basin is vulnerable to both floods and drought, resulting in a very risk-prone livelihood for inhabitants (c.f. Bharati et al., 2019). There is a complex response of flow regime change due to climate change within the Koshi River Basin.

6.2.3. Research question 3

Does the capacity of the physical template to supply flow-dependent ecosystem services differ laterally across the riverscape and the floodscape areas of the riverine landscape? Does the response of ecosystem services to climate change differ laterally across the riverine landscape?

This research question was examined in Chapter 4 and by answering this research question, I addressed the thesis objectives 1 and 2. The results of Chapters 2 and 3 complement each other and provide the foundation for Chapter 4. This study aims to understand the distribution of ecosystem services according to lateral position in the riverine landscape and the potential response of flow-dependent ecosystem services to climate change in the riverine landscape based on hydrological alteration in relation to lateral position in the riverine landscape. Three objectives were proposed to address this aim: i) To examine how the distribution of ecosystem services varies according to lateral position in the riverine landscape ii) Determine the flow character of the Sun Koshi under different climate scenarios. iii) Investigate the potential response of flow-dependent ecosystem services to hydrological alterations brought by climate change differs in relation to lateral position in the riverine landscape. This chapter fills a knowledge gap in understanding the variety of ecosystem services in relation to lateral position in the riverine landscape and how responses of ecosystem services to climate change might vary according to lateral position. The results highlight that the distribution of the flow-dependent ecosystem services does vary laterally across the riverine landscape and this lateral position in the riverine landscape influences the response of these services to flow change driven by climate change. There was a significant difference in the distribution of ecosystem services between the river channel, riparian zone, and floodplain zones. These findings are presented in a manuscript "*The response of ecosystem services to climate change within the lateral position of riverine landscape in the Sunkoshi Basin, Nepal.*". This manuscript will be submitted to the Ecohydrology journal.

Bajracharya, S.R., Reid, M., Evans, B. J. 2023 (In preparation). The response of flow-dependent ecosystem services to climate change within the lateral position of the riverine landscape in the Sunkoshi Basin, Nepal. *Ecohydrology*

Chapter 4 demonstrated that the magnitude, frequency, duration, and timing of flows will all change under the different climate scenarios, but these changes will differ among the three riverine landscape zones, the climate scenarios, and over time. Increases in floods and drought as well as in the timing of the flood season are projected and can be expected to change ecosystem processes. As a result, climate change will influence the provisioning of flow-dependent ecosystem services. These responses will vary over time and depending on which of the riverine landscape units those services originated. Most of the ecosystem services observed across the riverine landscape are projected to respond to potential flow regime changes. However, two cultural services (aesthetic value and education) are projected to show no response. Overall, most ecosystem service types are expected to be enhanced due to the projected changes in the flow regime over time.

There is greater potential for ecosystem services to change in the riparian zone, than in the floodplain and the river channel in the three time periods under both climate change scenarios. The direction of response also varied with ecosystem services and lateral position. Overall, enhanced responses in provisioning and regulating services are projected to dominate in all three zones.

The response of ecosystem services in the Sunkoshi riverine landscape is likely to differ under the two climate change scenarios. Most ecosystem service types are expected to be enhanced but this will be greater under the RCP4.5 scenario. Overall, provisioning services will be enhanced throughout the riverine landscape. The response pattern is consistent within each lateral zone for RCP4.5 while overall it is complex under the RCP8.5 scenario across the riverine. The findings of this study highlight that the distribution and response of flow-dependent ecosystem services to climate change are not uniform in relation to lateral position in the riverine landscape.

6.2.4. Research question 4

Does the potential response of flow-dependent ecosystem services to climate change vary according to the hierarchical organization of the river system?

This research question was examined in Chapter 5 and by answering this research question I addressed thesis objectives 1 and 2. The results of Chapters 2 and 3 provide a foundation for Chapter 5. This study aims to understand the characteristics and pattern of the response of flow-dependent ecosystem services to climate change in relation to the hierarchical organization of the river network. This study examines whether there is any congruence between the distribution and composition of responses in flow-dependent ecosystem services to climate change and the geomorphological organization of a river at the sub-basin, functional process zone and riverine landscape unit scales. Moreover, the study seeks to establish at which scale the response of flow-dependent ecosystem services to climate change varies most. The material presented in Chapter 5 is presented as the manuscript *"The response of flow-dependent ecosystem services to climate change varies according to the geomorphological organization of a river network*." The study informs on the pattern of response in flow-dependent ecosystem services to climate change in relation to the hierarchical organization of a river network – and demonstrates that scale needs to be considered when investigating these responses. The study shows that the response of ecosystem services to climate change is not uniform and varies according to the river network. This manuscript will be submitted to the River Research and Applications journal.

Bajracharya, S.R., Reid, M., Evans, B. J. 2023 (In preparation). The role of geomorphological organization in the response of flow-dependent ecosystem services to climate change in a river network. *River Research and Applications*

While the nature of the response of ecosystem services to climate change was consistent among all sub-basins, there was substantial variation in response among FPZs and the three landscape units irrespective of sub-basins. This pattern suggests that the strong response signal among FPZs and riverine landscape units exists because flow-dependent ecosystem services are generated by the river's physical template. In other words, physical templates are important in determining the response of flow-dependent ecosystem services to climate change, not a sub-basin. The hierarchical organization of the riverine landscape is important in relation to the response of flow-dependent ecosystem services to climate change. Explicit focus at a range of scales will help us to understand the relation to, or influence of, physical drivers on ecological responses at the right scale in the riverine landscape and also allow identification of the correct physical driver and ecological response.

6.3. Main scientific contribution of the thesis

6.3.1. The importance of a conceptual framework for the representation of ecosystem services across the riverine landscape

Riverine landscapes are diverse landscapes sustained by the interplay of physical, biological, and chemical processes that can support high biodiversity and provide ecosystem services for people (Yarnell et al., 2015; Gilvear et al., 2016). Identifying and understanding the various biophysical and social drivers, components, processes, and interrelated states of river systems is challenging; however, conceptual frameworks can aid in understanding these complex environments. Frameworks are used in many disciplines as a means to organize ideas, aid in the understanding of complex systems, link cause and effect, and guide decisions about system management (Thoms et al., 2022). They also help different disciplines work together in an integrated way (Dollar et al., 2007). Flow chain models demonstrate interactions between various components at multiple scales within complex adaptive systems. Flow-chain models have been used to demonstrate the effect of change in physical heterogeneity on food webs in river ecosystems (Thoms et al., 2017) and the ecological concept of disturbance in urban river systems (Grimm et al., 2017). The model of Dollar et al. (2007) is adopted by many researchers to provide a conceptual framework to represent how ecosystem services are arrayed across riverine landscapes and to understand direct and indirect influences upon these ecosystem services. For instance, Delong and Thoms, (2016) used the model to focus on interactions between physical, chemical and biological structure and function within riverine landscapes.

6.3.2. Components of flow chain model for the character of ecosystem services across the riverine landscape

Flow-chain models have four basic components representing the dynamic interplay of abiotic and biotic characteristics in riverine landscapes (Figure 6.1). Drivers are the main agents of change; functions are a series of controllers or processes that are governed by the agents of change; templates are those surfaces (both abiotic and biotic) upon which drivers and functions act; and finally, there are a series of responders (Dollar et al., 2007). Responders can be sets of processes, organisms, or parts of the biophysical environment present across the riverine landscape. From this flow chain model, it is conceptualised that ecosystem services within a riverine landscape are the product of multiple abiotic and biotic interactions. The flow chain diagram (Figure 6.1) showed the directional influence of the driver on the physical template. The product of this interaction influences the ecosystem response. Controllers thus control the feedback and interactions of the ecosystem processes. The flow model is a way to understand multiple interacting components across riverine landscapes. I used Pickett et al.'s (2003) flow chain model to illustrate ecosystem services in riverine landscapes (Figure 6.1).

[redacted]

Figure 6. 1. The ecosystem theoretical framework of the flow chain model, (Pickett et al., 2003).

Note: The opposite black arrow represents the feedback and interactions of the ecosystem processes.

6.3.3. Conceptual framework of the thesis

In this study, I modify and strengthen the earlier flow chain models of Pickett et al. (2003), and Thoms et al. (2022) by adding the importance of an altered physical template for ecosystem response and the importance of controllers for the use and social value of ecosystem service in the riverine landscape. In this framework, flow is the primary driver or agent of change that acts upon the physical template of the riverine landscape, resulting in an altered physical template where interaction between biotic and abiotic events happens and influences the ecosystem response. Geography and society are two key controllers influencing the potential use and social value of ecosystem services within riverine landscapes (Figure 6.2). Communities (people) are responders to this dynamic ecosystem in this flow chain model. Therefore, this study has brought both the provision of ecosystem services and the social system together by assessing the physical template of the riverine landscape with society and location.

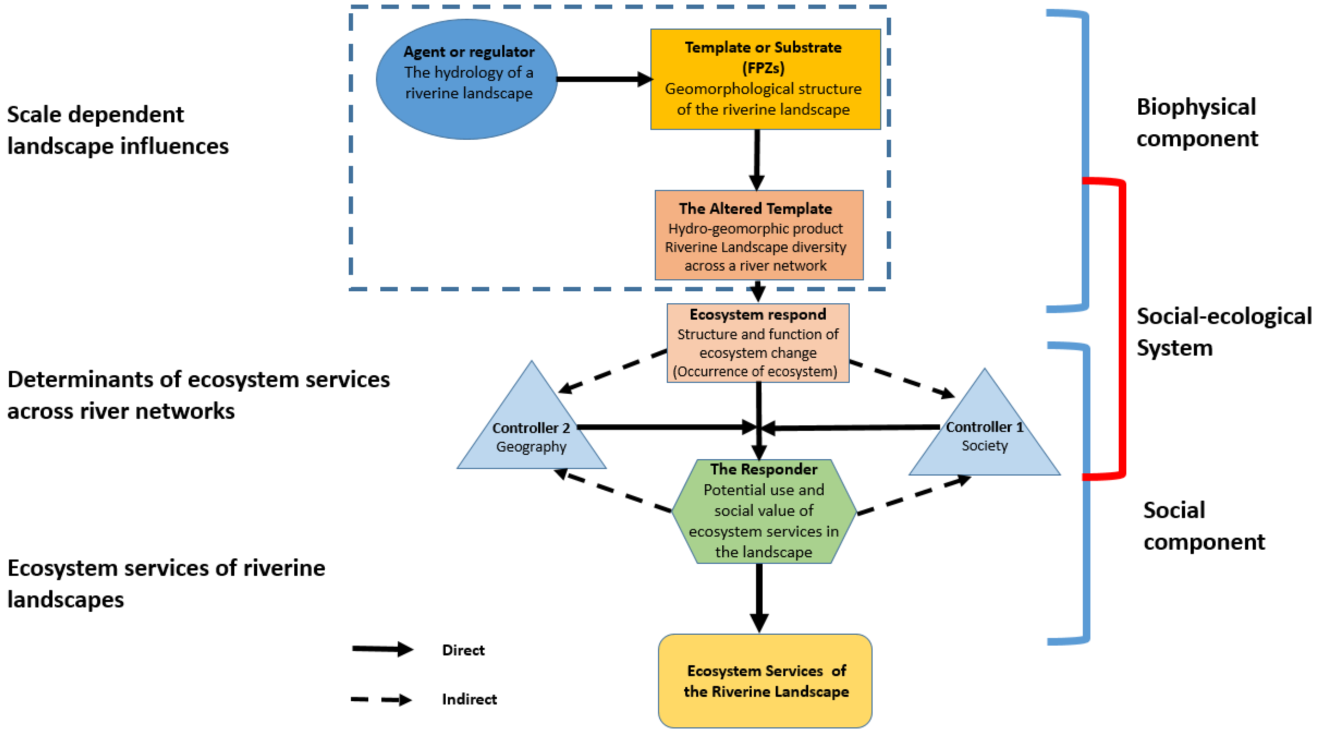

Figure 6. 2. Framework to determine the riverine landscape as a social-ecological system.

6.3.4. The role of physical template for the provision of ecosystem services and observation of climate change in a flow chain model

The physical template is key for ecosystem services within the riverine landscape because it directly influences ecosystem functions and services by changing the spatial and temporal components of the biophysical habitats within riverine landscapes. Climate change modifies the physical template through the change in flow regime and interaction between the flow regime and geomorphology. This is the key driver of physical template heterogeneity. The heterogeneity of the physical template shapes riverine ecosystem structure and function and determines the types, abundance, and arrangement of ecosystem services in a river network (Bajracharya et al., 2023). In addition, ecosystem services respond according to changes in the physical template because of the dynamic interaction of physical, biological and chemical components. Therefore, the spatial distribution of ecosystem services depends on the spatial arrangement of the physical template. This relationship underpins the congruence between ecosystem services and the type and distribution of FPZs and riverine landscape units, which are an expression of the interaction of physical processes. The distribution of FPZs highlights that ecosystem structure, function and services can vary significantly in the river network. This part of the conceptual model (Figure 6.2, blue dash line) is the first explicit articulation of the importance of the physical template to ecosystem services, not only with respect to ecological function but also benefits to people. It also elucidates that the physical template changes according to climate change and helps to observe the response of ecosystem services to climate change in the river network.

6.3.5. The role of controllers to the responder (human) in the flow chain model

The controllers, such as society and geographic location, are key influences on the use and social value of ecosystem services within riverine landscapes. The social preferences for ecosystem services depend on who is involved, where they live, how they interact with their resources and their access to resources (Kandel et al., 2018). These controllers interact through a series of direct and indirect feedbacks between ecosystem response and responder in the riverine landscape. The controllers can modify the behaviour of the responders (Pickett et al., 2003). In particular, controllers influence the consumption of ecosystem services and determine the potential use and social value of ecosystem services and also help to know the spatial variance of use and social value of ecosystem services within the riverine landscape.

This refined model (Figure 6.2) is the first to include the role of controllers (society and geography) as part of the social system in the flow chain model that influences the use and social value of ecosystem services in the riverine landscapes (Figure 6.2).

Most widely used river models view society as an external driver of the environment rather than as a part of the environment and do not incorporate the social state of a riverine ecosystem (Parsons et al., 2016). This means the traditional river models only view the riverine landscape from a biophysical viewpoint. As a result, models of riverine landscapes cannot incorporate natural processes and direct influences of humans at relevant scales in the environment. There is thus a knowledge gap in relation to viewing the riverine landscape as a social-ecological system that considers society as an internal component of an ecosystem, not an external driver of ecosystem structure and function. The incorporation of the concepts of controllers and responders in the framework (Figure 6.2) provides the complete picture of the riverine landscape as a social-ecological system and can help bridge the knowledge gap on humans as a part of the environment. Thus, this modified framework helps us to understand the complex interplay of biophysical and social components within the riverine landscape as well as the role of controllers for the provision of ecosystem services, their use and social value in the riverine landscape.

Overall, this framework illustrates the riverine landscape is a complex adaptive system – adding the benefits to the flow chain model expands the consideration of the riverine landscape as a social-ecological system, not just a biophysical landscape. It also helps us to understand:

i) The structure of the riverine landscape directly influences the distribution and abundance of ecosystem services and its ability to observe climate change.

ii) The role of the controller society and geography for ecosystem services within riverine landscapes.

6.3.6. The physical character of the Himalayan River is not a continuum

This thesis implemented the Riverine Ecosystem Synthesis (RES) concept and Functional Process Zone (FPZ) approach to a Himalayan River system. This approach showed that the Koshi River Basin includes five functional process zones which differ significantly from each other in terms of their physical character, demonstrating that the river systems of the Koshi Basin are dynamic downstream arrays of hydrogeomorphic patches formed by catchment, valley and channel geomorphology, hydrological regime and climate. Moreover, the study has shown that the spatial arrangement of the five FPZs is not clinal and repeats in some instances along the river network. This distinct nature of patches contrasts with the traditional view that rivers exhibit continuous gradients in ecological and physical processes from headwater to mouth (Vannote et al., 1980). In addition to showing that the riverine landscapes of the Koshi Basin are composed of patches at multiple spatial and temporal scales, the study also showed that these patches influence the distribution of ecosystem services.

6.3.7. Contribution to the mountain riverine ecosystem services

Himalayan riverine landscapes are important and provide water resources to over half of the world’s biodiversity hotspots, fresh drinking water, hydropower and irrigation for 1.3 billion people or approximately 20 percent of the world’s population (Schild, 2008). Furthermore, about 10 percent of the world’s population depend directly on these mountain resources for their livelihoods and well-being, while an estimated 40 percent depend indirectly on these resources for goods such as food, timber, hydroelectricity and medicine and a wide range of services such as fresh air and water, climate regulation, carbon storage, and the maintenance of aesthetic, cultural, and spiritual values (Schild, 2008; Kandel et al., 2018). However, these mountain regions have been referred to as a global '*White Spot*' (Schild, 2008) in terms of environmental knowledge.

This study creates a knowledge base on the distribution of physical templates as well as focuses on the variation of the ecosystem services within the entire river network. This knowledge base will help us to understand ecosystem function, services and goods that can contribute to maintaining, protecting, rehabilitating, conserving, supply and demand and trade-offs between different riverine ecosystem services in the Himalayan Rivers in the face of climate change. In addition, this study addresses the potential value concept, which is a promising tool for eliciting people's preferences in ecosystem services assessment and analysis of trade-offs. This approach incorporates community perceptions, priorities, values, attitudes, and benefits which may generate more meaningful insights into the contribution of ecosystem services to human well-being. The outcomes of such studies help communities, decision makers to understand how ecosystem services have contributed to human well-being and acknowledge the importance of physical templates in terms of the management of ecosystem services. The knowledge derived from this thesis will assist the systematic study of the complex rivers of the Himalayan region in the future. To the best of my knowledge, this thesis is the first study that examines the distribution of physical template and flow-dependent ecosystem services, viewing the riverine landscape as a social-ecological system in Himalayan rivers as well as the response of ecosystem services to climate change according to the hierarchical organization of riverine landscape. Overall, the Himalayan basin is complex in terms of the physical template, ecosystem services and climate change response.

6.3.8. Contribution of the thesis

This thesis contributes to understanding of the interaction between drivers, physical character, controllers and responders within the context of complex adaptive systems and implements this knowledge to understand the riverine landscape as a social-ecological system. The thesis also improves knowledge of the interaction among physical templates, ecosystem services and people at a large scale in a systematic way. Finally, it also provides vital information on how flow-dependent ecosystem services may respond to climate change in the Himalayan basin.

This study has highlighted the importance of the riverine landscape as a social-ecological system incorporating ecosystem services as a bridge between nature and society. The ecosystem services in the river network are outcomes of the dynamic interactions between the physical template and the ecosystems it supports within the river network. As a result, there is congruency between the physical template and ecosystem services with the abundance and distribution of ecosystem services governed by the physical template. However, the relative use and potential value of the ecosystem do not show congruency with the physical template because it is controlled by geography and society.

Climate change is a disturbance to flow-dependent ecosystem services. The effect of climate change in the Koshi River Basin is complex and the impact on hydrological regimes varies according to space and time. The response of flow-dependent ecosystem services to climate change varies according to time and lateral and longitudinal dimensions of the riverine landscape. Furthermore, the response of flow-dependent ecosystem services to climate change varies according to the hierarchical organization of the riverine landscape. The response was very clear at the FPZ and RLU scale. This study further demonstrates the importance of observing the hierarchical organization of river networks and acknowledging the importance of physical templates in terms of the management of ecosystem services.

Overall, this thesis contributes to our understanding of the riverine landscape as a complex adaptive system. The complex adaptive system is the mechanism to understand riverine landscapes as social-ecological systems, whereas ecosystem services are an indicator to look at an interaction between the environment and humans in a social-ecological system through a complex adaptive system approach. Recognising the importance of the riverine landscape as a social-ecological system can help to bridge the knowledge gap with regard to humans being a part of the environment not an external driver of the system. Furthermore, this thesis also improves knowledge of the interaction among physical templates, ecosystem services and people at a large scale in a systematic way, and demonstrates how the riverine ecosystem services may respond to climate change.

6.4. Suggestion for further research

This research has highlighted several gaps in our knowledge of riverine landscapes and ecosystem services.

6.4.1. Scale influences in rivers

Hierarchy and scale are central tenets of river science (Gilvear et al., 2016). Parsons et al. (2004) suggested that using a scale of measurement derived from a parallel hierarchy is a sound approach to multiscale investigations of the ecosystem in the river system. Therefore, scale is very important to decipher the response of ecosystem services to physical processes because these may be operating at different spatial and temporal scales. Most of the studies on the relationship between the character of the biophysical template and ecosystem services are restricted to smaller scales (site-specific and < 1km reach scale) (cf. Gilvear et al., 2016). Riverine ecosystems are challenging to study. Understanding based on small-scale and location-specific studies cannot be scaled up easily because we do not know how processes interact at larger scales. Larger river ecosystems are more complex than smaller river ecosystems because of a positive relationship between scale and complexity in the study of natural ecosystems (Thoms and Sheldon, 2019). Larger rivers are also more complex systems due to the interaction of many biophysical and social components at multiple scales.

6.4.2. Scale has an influence on river management

Most studies of riverine ecosystem services do not consider the hierarchy of river system organization for instance Large and Gilvear (2015); Tomscha et al. (2017). The response of flow-dependent ecosystem services to climate change varies according to the level of organization in the hierarchy. For instance, responses vary little among sub-basins, but more substantially among RLUs and FPZs due to the heterogeneous nature of the physical template at the RLU and FPZ scales. Therefore, for effective management, conservation, restoration, utilization and asset trading of riverine ecosystem services should focus on FPZs and RLUs instead of other levels of organizations in the riverine hierarchy. Earlier most of the ecosystem services management strategies were focused on sub-basin or catchment levels. Hence, there should be robust research needed for effective and efficient management, conservation, restoration, utilization and asset trading of riverine ecosystem services at the FPZ and RLUs.

6.4.3. Role of water temperature for flow-dependent ecosystem services

The principal environmental change arising from greenhouse gas emissions is temperature increase. Temperature increases, in turn, have a range of impacts on climate that effect the flow regime. In this study, I only considered changes in flow regime (magnitude, frequency, rate of change, duration, and timing), not temperature. Water temperature should be considered in future studies of ecosystem services in the riverine landscape because the thermal regimes of riverine ecosystems, directly and indirectly, influence ecological processes (Pletterbauer et al., 2018). Most aquatic fauna are ectotherm, so they are directly and indirectly dependent on the surrounding temperatures (Pletterbauer et al., 2018). In addition, many biological processes, including the metabolism of organisms, are tightly controlled by temperature (Palmer et al., 2009; Arthington et al., 2010). Therefore, a change in the thermal regime could directly influence physiological processes such as growth, phenology and behaviours such as habitat preference in riverine landscapes (Lucas and Lloréns, 2008). Consequently, for a complete understanding of the ecosystem services within the riverine landscape, there should be consideration of temperature in relation to riverine ecosystem services.

6.4.4. Flow-dependent ecosystem services in a changing climate

Assessment of climate change and its consequences for the physical template and the provision of flow-dependent ecosystem services is a very recent development. While this study has made a substantial contribution to our understanding of the impact of climate change on the physical template and flow-dependent ecosystem services in Himalayan river systems, there remains much uncertainty. In particular, there is limited knowledge of likely climate change in the Himalayan region and its effects on flow regimes, for instance uncertainties about the rate and magnitude of climate change and potential impacts, particularly in relation to water, ecological and socio-economic in the basin. It is, therefore, imperative that further research refine climate projections and understand the ecological consequences of climate change in Himalayan River basins. In addition, with respect to flow-dependent ecosystem services, there is a particular paucity of studies on the response of cultural services to climate change. Therefore, focused and comprehensive studies are needed to understand the uncertainty of the climate model and its consequences in the flow-dependent ecosystem services.

6.5. Concluding Remarks

This thesis advocates that the physical template of a river is important for the production of flow-dependent ecosystem services. The production of flow-dependent ecosystem services in riverine landscapes is congruent with the character and heterogeneity of the physical template. This congruency exists because flow-dependent ecosystem services are the product of interactions between the physical template of the riverine landscape and the ecosystem processes that the template supports. This means that the physical template of the riverine landscape dictates the occurrence of ecosystem services. The Koshi River Basin is spatially heterogeneous particularly at the FPZ and riverine landscape unit scales, which thus means that flow-dependent ecosystem services are also spatially heterogeneous at these scales.

The Koshi River Basin is likely to be markedly affected by climate change. There is a complex response to the flow regime due to climate change, which reflects the complex way in which flow regime changes play out across the important and distinct spatial units of the physical template. It is important to remember that, climate change will likely influence the flow regime and modify the physical template via a change in the interaction between flow and geomorphology, thus driving further responses in flow-dependent ecosystem services. A physical template as well as riverine landscape units help to observe climate change and the response of ecosystem services in the river network. The response of the flow-dependent ecosystem service to climate change is not uniform in the lateral position of the riverine landscape and the Koshi River network.

This study is the first to examine at the relationship between the physical template and flow-dependent ecosystem services in a large Himalayan River basin and to assess the influence of climate change on this relationship. This thesis is built on four components: i) riverine landscapes, ii) ecosystem services. iii) climate change and iv) social-ecological systems.

Ultimately, this thesis contributes a significant amount to the emerging trend to address a significant knowledge gap in interdisciplinary river science, by emphasizing that the riverine landscape is not just a biophysical ecosystem, but also a social-ecological system and a complex adaptive system.

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Annex

Annex I Field observed for mapping of ecosystem services and pictures used for the analysis of matrix table

Communities residing on the bank of the Tamakoshi River.

Encroachment of vegetation on river channel in Sunkoshi River

Social gatherings of women for houses hold stuff (washing clothes)

Sand, gravel quarry

Household direct use of water from the river channel

Restaurants on the bank of the river (Recreation or tourism)

Twigs brought from the river

Forest in floodplain

Fishing

Temple

Boating

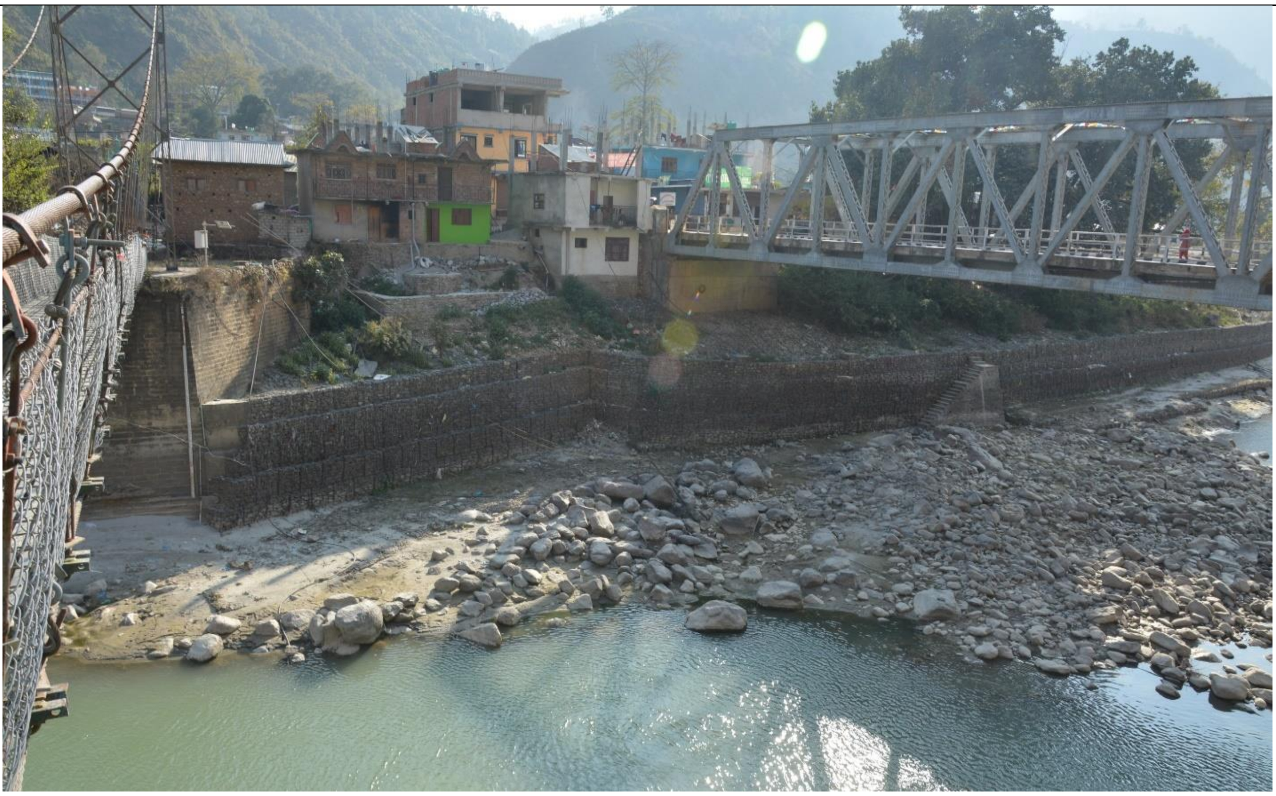
Making concrete brick

Education and research

Agricultural land

Sand and gravel quarry

Transport



Research and education (Stream gauge)

Religious bathing

Transporting bamboo from upstream to downstream

Household settlement and agriculture on the floodplain

Pasture and wetland in the Koshi River Basin floodplain area near Koshi Barrage

Cultivated land in the Koshi floodplain

The fish market near the Koshi River

Direct irrigated to cultivation land from the Koshi River

Aquaculture in the Koshi Basin

Drifwood on floodplain

Jet boat for recreation

Mango cultivation in the floodplain of Koshi River Basin

Pilgrimage, the temple at the confluence of Sunkoshi and Balefi river

The main outlet of our Sunkoshi study area (Chapter 4, calibration and validation point)

Annex II Supplementary literature table for the decision on the response of ecosystem services to altered flow regime change, NOTE Y =Yes

Citation	Title of paper	Alteration of flow	Extremely low flow	Low flow	High flow	Small flood	Large flood	Ecosystem function	Ecosystem response	Effect on Ecosystem Services	Remark	Primary flow component (Characteristics)
Carolli et al (2017)	Assessing the impacts of water abstractions on river ecosystem services: an eco-hydraulic modelling approach	Specified		Y				Habitat	Lower flow in the centre or river channel is good for adult marble trout	Enhance	Fish abundance and habitat suitability	Magnitude
		Specified				Y	Y	Productivity	An increase of higher stream flow is suitable for hydroelectricity production but damages the hydropower during large flood	Enhance and decrease (Means mixed)	Increase the hydropower production for distribution and decrease when damaged by large floods	Magnitude
Cui et al (2017)	Assessment of the impact of climate change on flow regime at multiple temporal scales and potential ecological implications in an alpine river.	Not specified							Changes in flow regime could have positive impacts on aquatic ecosystems in the near scenario but more negative effects in the far period scenario.	Enhance and decrease (Means mixed)		Not specified
		Specified				Y	Y	Habitat, resource availability	An increase in the magnitude and duration of extreme flow could have positive and negative impacts on aquatic ecosystems. For positive impact, there is a positive correlation between riparian plants and an increase in the flow regime	Enhance and decrease (Means mixed)	Increase riparian plants will help flood protection and erosion prevention, sediment retention, and enhance local climate regulation	Magnitude and duration
		Specified				Y	Y	Habitat	Increment of high flow will increase the connectivity between the floodplain and the main river channel. As a result, fish and other mobile organisms have more access to floodplains for food, breeding etc.	Enhance	Abundance of fishes	Magnitude
		Specified				Y	Y	Habitat	On the other hand, floods will damage new habitats, and increase the mortality rate of aquatic invertebrates and depth of bed scour.	Decrease	Habitat fragmentation, increased siltation and sedimentation, Decreased flood protection and erosion prevention	Magnitude

Datry et al (2017)	Flow intermittence and ecosystem services in rivers of the Anthropocene	Specified	Y		Diversity, habitat, productivity, resource availability	The dry phase of the river also promotes local and **regional diversity**, **providing habitat** and food for semi-aquatic and terrestrial biota, Dry channels and the riparian zones of the intermitted river are crucial migration corridors and habitats for numerous terrestrial vertebrate species maintaining and enhancing biodiversity at the river network, Wetting and drying also govern microbially and **activate nutrient cycling and organic matter and increase leaf litter formation and enhance the fertility capacity of soi**l for agriculture, Vegetation colonizing dry riverbeds likely reduce erosion, promotes genetic diversity locally and helps regulate local climates, it also helps to increase the grazing space for livestock.	Enhance	Enhance the soil fertility and enhance agriculture **productivity** and more food for people to eat and sell, more place for grazing livestock and enough grass/ fodders for the animal, healthy cattle will increase the milk and meat product for people to consume and sell, Reduce the erosion will stable the bank of river and risk of landslide and sedimentation is low, good for downstream people those are on flood risk area	Magnitude
Gibson et al (2005)	Flow regime alterations under changing climate in two river basins: Implications for freshwater ecosystems	Specified	Y		Habitat	Lower summer flows can lead to an increase in water temperature and reduced dissolved oxygen. Lower flows also indicate a reduced wetter perimeter, which would **decrease habitat availability** and impact lateral exchanges between the riparian zone and the stream.	Decrease	Decrease the essential environment components for organism and loss of organism. For instance, if there is less fish then it hampers the fisherman. Reduce wetter perimeter, will decrease the soil moisture content and decrease the agriculture productivity and riverine vegetation	Magnitude

		Specified	Y				Habitat, resource availability	During the low flow the encroachment of river channels by riverine vegetation	Enhance and decrease (Means mixed)	**Prevent erosion**, increase the grazing space for cattle, ease the terrestrial organisms for habitat provision and corridors	Magnitude
		Specified				Y	Productivity, habitat	A shift in the timing of peak flow can alter the retention time of **organic matter** and disrupt the recruitment of riparian species that rely on appropriately timed high flows to disperse seeds onto floodplains and impact the **survival of certain fish species** whose larval emergence is timed to avoid high spring flows.	Decrease	Impact on the food web, mortality rate of fish larval might be high	Timing
Grizzetti et al (2016)	Assessing water ecosystem services for water resource management.	Not specified					Habitat, resource availability	The high impacts of flow modification on ecosystem services. For instance, fisheries and aquaculture, water for drinking, water for non-drinking, water purification, air quality, erosion prevention etc.	Enhance and decrease (Means mixed)		Not specified
Hauer et al (2013)	The impact of discharge change on physical instream habitats and its response to river morphology	Specified	Y				Habitat	Extensive habitat fragmentation, habitat suitability depends on velocity/depth ratio	Enhance	During the low flow riffles and pools are suitable for grayling habitats	Magnitude
Ignacio Palomo (2017)	Climate change impacts on ecosystem services in High Mountain areas: A literature review	Not specified					Resource availability	Decrease stream flow affecting the availability to meet the water demands of tourists	Decrease	The decrease in tourism impacts the livelihood of people (hotels, restaurants, tourist guides etc) who depend on tourists and a decrease in tourism revenues	Not specified

Leigh et al (2015)	Ecological effects of extreme climate events on riverine ecosystems: insights from Australia	Specified	Y				Y	Habitat, resource, productivity	Extreme low flow alters **water quality** and reduces **habitat availability**, driving organisms to refugia. Extreme floods increase hydrological connectivity and trigger booms in **productivity** but can also alter channel morphology and cause disturbances such as hypoxic blackwater events.	Enhance and decrease (Means mixed)	Decrease in drinking water, loss of biodiversity due to habitat loss, the nutrient transformation from the floodplain, and increase in vegetation which enhances climate regulation	Duration
Lloyd et al(2003)	Does flow modification cause geomorphological and ecological responses in rivers? A literature review from an Australian perspective.	Specified				Y	Y	Habitat, resource availability	Floodplain trees can die if the inundated period is too long and macrophyte species richness may decrease	Decrease	Decrease in use and value of timber, local climate regulation	Duration
		Specified	Y			Y	Y	Habitat	Birds breeding and abundance are affected by flow modification. Wetlands that flood and dry naturally tend to have higher values for breeding records, species richness, and number of species breeding than do wetlands where the area and duration of inundation have been altered.	Enhance	Community perception on the importance of habitat provision, increase bird watching and tourism	Duration
Neube et al (2018)	A framework for assessing instream supporting ES based on hydro-ecological modelling	Specified		Y	Y				Future changes in the flow regime could lead to changes in magnitude, timing, duration and distribution of flow, which might impact the increase or decrease of supporting ecosystem services.	Enhance and decrease (Means mixed)	Enhance and decrease of supporting services impact the entire ecosystem of services	Magnitude, duratio timing and frequenc

Palmer et al (2009)	Climate change and river ecosystems: Protection and adaptation options.	Specified			Y	Y	Habitat, productivity	Native cottonwood trees along the riverbanks become established during annual peak flow that overtop the banks and creates favourable establishment conditions during the annual snowmelt runoff event.	Enhance	Increase the use and value of timber **production** and local climate regulation	Magnitude
		Specified		Y			Diversity	A highly stable flow regime supports a great **diversity** of plant species and community types.	Enhance	Increase the soil moisture content, more vegetation, more grazing for livestock and wild edible plants and fruits	Magnitude and duration
		Specified	Y				Habitat	For fish, amphibians and water-dispersed plants, **habitat** fragmentation is due to prolonged of low extreme flow.	Decrease	Constrain the movement of organisms, less food to eat, decreased body mass and a mortality rate high	Magnitude
		Not specified					Habitat	Early snowmelt impacts the spawning times of fishes.	Decrease	The mortality rate high, and the low fish population, hamper the livelihood of the people dependent on fishes	Timing
		Specified				Y	Habitat, diversity	For the rivers where large flood is frequent compared to the historical period, species may be lost unless they are capable of moving to less affected areas.	Decrease	Species loss, less **biodiversity** and hamper entire ecosystem services	Magnitude
		Specified			Y	Y	Habitat, diversity, resource availability	Particle size and hydraulic forces are major determinants of stream **biodiversity** and excessive bottom erosion is well known to decrease abundances and lead to dominance by a few taxa.	Decrease	Decrease the abundances of taxa, hamper entire ecosystem service, loss in economic value of aquaculture growth	Magnitude

		Specified	Y	Y	Habitat, resource availability	During the floods, increased turbidity and pollutant loads might impact water quality	Decrease	Poor drinking water quality: Siltation and sedimentation hamper the hydropower production	Magnitude
		Specified	Y	Y	Resource availability	Extreme flow events may lead to substantial erosion of riverbanks that not only place sensitive riparian ecosystems at risk but may cause water quality problems downstream due to higher suspended sediment loads.	Decrease	Increase risk to downstream people for loss of property and lives	Magnitude
Papadaki et al (2016)	Potential impacts of climate change on flow regime and fish habitat in mountain rivers of the Southwestern Balkans.	Not specified			Habitat	Results show that alteration of stream flows, especially decrease will result in a reduction in a suitable habitat available for target species.	Decrease	Decrease in fish abundance and decrease in fish products as a percentage of total animal protein in people's diet	Not specified
		Specified	Y	Y	Habitat	The smaller frequency of peak flow decreased the abundance of native fishes in the long term.	Decrease	Decrease in fish sale	Frequency
N. Poff (2002)	Ecological response to and management of increased flooding caused by climate change	Specified	Y	Y	Resource availability, diversity	More frequent larger floods will work to re-establish connections with floodplain and riparian zone wetlands. From an ecological perspective, floods are the lifeblood of rivers. Science now recognizes these extreme events as beneficial natural disturbances essential to maintaining a mosaic of dynamic **heterogeneous habitat** types that support.	Enhance	Increase the biodiversity and ecosystem services	Frequency

Poff and Zimmerman (2010)	Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows.	Specified	Y				Y	Habitat, diversity	The paper highlighted that macroinvertebrates showed mixed responses to changes in flow magnitude with **abundance and diversity** both increasing and decreasing in response to elevated flows and reduced flows.	Enhance and decrease (Means mixed)	Community perception on the importance of macroinvertebrates' habitat provision	Magnitude
		Specified	Y				Y	Habitat, diversity	Fishes' **abundance, diversity** and demographic rates consistently decline in response to both increased and decreased flow magnitude.	Enhance and decrease (Means mixed)	Increase and decrease fish production as a percent of total animal protein in people's diet, Value of fish in the market	Magnitude
		Specified					Y	Habitat, resource availability	Riparian vegetation showed both increases and decreases in response to reduced peak flows, with increases reflecting mostly enhanced non-woody vegetative cover or encroachment into stream channels.	Enhance and decrease (Means mixed)	Increase and decrease fuelwood, twigs production, air quality, local climate, carbon sequestration	Magnitude
		Not specified						Resource availability, Habitat	Riparian responses to flow frequency changes were consistently reported to decline in some papers whereas some papers reported increased.	Enhance and decrease (Means mixed)	Decrease and increase of groundwater recharge, habitat provision and corridors, bio-filtration	Not specified
		Specified				Y	Y	Resource availability, Habitat	Alterations in flow duration, mostly in the form of changes in the duration of floodplain inundation, were primarily associated with decreases in both river channel and riparian ecological variables.	Decrease	Impact abundance of aquatic organisms, water quality, Risk to people living in water hazard-prone areas	Duration

		Specified	Y	Y	Productivity	Similarly, changes in the timing of flows due to the loss of seasonal flow peaks reduced both river channels and riparian ecosystems. Whereas few studies reported mixed results of increase and decrease of ecosystem structure and functions.	Enhance and decrease (Means mixed)	Impact the nutrient regulation and decrease in aquaculture production	Timing
Rai et al (2019)	Freshwater ecosystems of the Koshi River basin, Nepal: A rapid assessment	Not specified			Resource availability	Water quality was good upper part of the basin and was Polluted lower part of the basin	Enhance and decrease (Means mixed)	Decrease and increase the proportion of people using an improved drinking water resource	Not specified
		Not specified			Resource availability	Freshwater ecosystems, the major sources for irrigation and household use have decreased over time	Decrease	Decrease in the proportion of people using improved drinking water resources, and the proportion of water supplies decrease for irrigation for agriculture, a reduction in food	Not specified
		Not specified			Resource availability	Stream banks and riparian zones were impaired with vegetation resulting in mild to severe erosion	Decrease	Loss in property value lives from declining erosion prevention, and risk to people living in a flood-prone area, sediment and silt deposits on fertile floodplains might reduce the soil fertility and reduce the agricultural products	Not specified

Sharma C M (2008)	Freshwater fishes, fisheries and habitat prospects of Nepal	Not specified		Habitat	Lowland areas are most suitable for aquaculture	Enhance	Mainly for supplying animal protein, and for generating self-employment and income of small-scale farmers.	Not specified
		Not specified		Resource availability	Hill streams have a great attraction for sport fishing	Enhance	Increase the eco-tourism and recreation	Not specified
A.B. Shrestha and R, Aryal (2010)	Climate change in Nepal and its impact on Himalayan glaciers.	Not specified		Productivity	It was found that any changes in hydrological regimes can have serious consequences for **hydroelectric projects**. For instance, the traditional water mills used by local people for various purposes (e.g., grinding grains, power etc.), might be adversely affected, especially those that are seasonally operated.	Decrease	The traditional water mills used by local people for various purposes (e.g., grinding grains, power etc.), might be adversely affected, especially those that are seasonally operated.	Not specified
		Not specified		Resource availability	The study also found various irrigation schemes along the river corridor vulnerable to climate change.	Decrease	Damage to the irrigation channel hampers on **supply of water** for agriculture and less agricultural production	Not specified
		Not specified		Productivity, habitat	Fishing an important means of subsistence will undoubtedly be affected by deglaciation in the upper catchment.	Decrease	In the long term, there will be less water in the river channel, and the abundance of fish will be reduced which impacts people's livelihoods who are dependent on fish.	Not specified

		Not specified						Resource availability	Water in the region also has important religious and spiritual uses, it might impact religious bathing and cremating. Change in flow regime, either increase or decrease, may cause inconvenience and increased risk for local people in the basin.	Enhance and decrease (Means mixed)	If no water in the river, it will hamper religious bathing	Not specified
Talbot et al (2017)	The impact of flooding on aquatic ecosystem services (Literature review from 117 papers)	Specified				Y	Y	Productivity, resource	High area inundation, Total suspended solids and dissolved organic carbon will increase connecting flowing water with floodplain, farming and fishing are especially vulnerable to food reduction during and after flooding. Recreation is negatively impacted by extreme flooding	Enhance and decrease (Means mixed)	Ecosystem services are enhanced from small floods but decrease from extreme floods, but groundwater recharge will be enhanced from extreme floods, but the quality of water will be decreased for drinking	Magnitude, duratio timing
Tonkin et al (2018)	Flow regime alteration degrades ecological networks in the riparian ecosystem	Not specified						Diversity	The finding suggests that maintaining floods under future climates will be needed to overcome the negative long-term consequences of flow modification on the riverine ecosystem. Floods, despite the negative effects and impact on human infrastructure, are associated with many beneficial and necessary processes that **enhance the diversity** of riverine systems and the robustness and resilience of ecological networks.	Enhance	Frequent links between river channels and floodplains will have a positive impact on the entire ecosystem services	Not specified
Vaughn et al (2015)	Drought-induced changes in flow regimes lead to long-term losses in mussel-provided ecosystem services	Specified	Y					Productivity, habitat, resource availability	These ecosystem services declines were directly linked to drought-induced changes in flow regimes. The increase in frequency and duration of extreme low flow declines those services.	Decrease	Decrease in agriculture productivity, aquatic organisms, water for drinking,	Magnitude and duration