HI-AWARE Working Paper 21

Revisiting Key Questions Regarding Upstream–Downstream Linkages of Land and Water Management in the Hindu Kush Himalaya (HKH) Region

Consortium members

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This series is based on the work of the Himalayan Adaptation, Water and Resilience (HI-AWARE) consortium under the Collaborative Adaptation Research Initiative in Africa and Asia (CARIAA) with financial support from the UK Government's Department for International Development and the International Development Research Centre, Ottawa, Canada. CARIAA aims to build the resilience of vulnerable populations and their livelihoods in three climate change hot spots in Africa and Asia. The programme supports collaborative research to inform adaptation policy and practice.

HI-AWARE aims to enhance the adaptive capacities and climate resilience of the poor and vulnerable women, men, and children living in the mountains and floodplains of the Indus, Ganges, and Brahmaputra river basins. It seeks to do this through the development of robust evidence to inform people-centred and gender-inclusive climate change adaptation policies and practices for improving livelihoods.

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Feedback is welcomed as a means to strengthen these works: some may later be revised for peer-reviewed publication.

Authors

Santosh Nepal Santosh.Nepal@icimod.org
Avash Pandey Avash.Pandey@icimod.org
Arun B. Shrestha Arun.Shrestha@icimod.org
Aditi Mukherji Aditi.Mukherji@icimod.org

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Authors

Santosh Nepal,[1] Avash Pandey,[1] Arun B. Shrestha,[1] and Aditi Mukherji[1]

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[1] International Centre for Integrated Mountain Development (ICIMOD)

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Production team

Nagraj Adve (Editor)
Debabrat Sukla (Communication officer, HI-AWARE)
Mohd Abdul Fahad (Graphic designer)

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Contents

Acknowledgements **v**

Acronyms and Abbreviations **vi**

List of Tables **vii**

List of Figures **vii**

1. Introduction **1**

1.1. The Hindu Kush Himalaya Region 2

1.2. Geographical Characteristics Defining Upstream, Midstream, and Downstream Regions 4

2. Transnational River Basins **7**

2..1 Indus River Basin 7

2.2. Ganges River Basin 8

2.3. Brahmaputra River Basin 9

3. Environmental Conditions **11**

3.1. Monsoon Climate 11

3.2. Land Use and Land Cover 12

3.3. Glaciers and Hydrology 12

4. A Changing Environment **13**

4.1. Changes in Temperature 13

4.2. Changes in Precipitation 14

4.3. Future Trends in Temperature and Precipitation 14

4.4. Changes in River Run-off 15

4.5. A Changing LULC 16

4.6. Socioeconomic Changes 17

Revisiting Key Questions Regarding Upstream-Downstream Linkages 18

5. Review Question 1: What are the Impacts of Land Use, Land Cover Changes on Downstream Water Availability and Flooding in the HKH Region? **19**

5.1. Overview 19

5.2. Do Changes in Land Cover Affect Downstream Water Flows? 19

5.3. Impacts of LULCC on Hydrological Processes 22
5.4. Complex Relationship Between Forests and Hydrology 23
5.5. Role of Forests Beyond Hydrology 24
5.6. Discussion Related to Upstream–downstream Linkages 25

6. Review Question 2: What are the Impacts of Erosion and Sedimentation on Downstream Areas of the HKH Region? 27

6.1. Overview 27
6.2. Erosion's Causes and Processes 27
6.3. How Much Erosion is Happening in the HKH Region? 28
6.4. Erosion Leading to Sedimentation 30
6.5. Impacts of Erosion and Sedimentation 31
6.6. Discussion Related to Upstream–downstream Linkages 32

7. Review Question 3: What are the Impacts of Climate Change on the Hydrological Regime and Downstream Water Availability in the HKH Region? 33

7.1. Overview 33
7.2. Impacts of Climate Change on Water Resources 33
7.3. Impacts on Climate Change on Upstream–downstream Linkages 36
7.4. Discussion Related to Upstream–downstream Linkages 37

8. Review Question 4: What are the Impacts of Water-related Infrastructure Development on Downstream Water Availability? 39

8.1. Overview 39
8.2. The Development of Infrastructure 39
8.3. Conflicts Surrounding Infrastructure Development 40
8.4. Benefits and Risks of Infrastructure 41
8.5 Discussion Related to Upstream–downstream Linkages 43

9. Conclusions and Outlook 45

9.1. Current Understanding and Gaps in Knowledge 45
9.2. Uncertainties in Results and Methodological Differences 46
9.3. Regional Heterogeneity 47
9.4. Role of Scale 47
9.5. Future Directions 47

References 49

List of Tables

Table 1: Characteristics of the ten river basins originating in the HKH region 3

Table 2: Potential impacts of land use changes on surface and near-surface hydrological processes and relevance for the hydrological cycle 23

Table 3: Land cover and estimated erosion rates in the Koshi basin, 1990 and 2010 29

Table 4: Variation in erosion rates for different land cover types 30

List of Figures

Figure 1: Schematic diagram of a river corridor showing three zones and their upstream–downstream relationships 4

Figure 2: Ten major river basins in the HKH region 7

Figure 3: Physiographic divisions and climatic landscape zones of the Central Himalayan region 11

Acronyms and Abbreviations

AR	Assessment Report
CMA	China Meteorological Administration
CMIP5	Coupled Model Intercomparison Project 5
CORDEX	Coordinated Regional Downscaling Experiment
cu m	Cubic Metres
°C	Degrees Celsius
FMIS	Farmer Managed Irrigation Systems
ha	Hectares
GCM	General Circulation Model
GLOFs	Glacial Lake Outburst Floods
HIMAP	Hindu Kush Himalaya Monitoring and Assessment Programme
HKH	Hindu Kush Himalaya
IBA	Important Bird and Biodiversity Area
IGB	Indus–Ganges–Brahmapautra
IPCC	Intergovernmental Panel on Climate Change
LDOFs	Landslide Dam Outburst Floods
LULCC	Land Use, Land Cover Change
masl	metres above sea level
MCM	Million Cubic Metres
PRECIS	Providing Regional Climates for Imapct Studies
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
TAR	Tibetan Autonomous Region
THED	Theory of Himalyan Environmental Degradation
UDL	Upstream–Downstream Linkages
UIB	Upper Indus Basin

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1. Introduction

The activities and processes led by natural and anthropogenic factors not only change environmental variables upstream (such as land use and land cover, snowmelt, and erosion, among others), they also affect the downstream environment in terms of water availability, floods, and sedimentation. Upstream–downstream linkages (UDL) of land and water management in the Himalayan region have been widely discussed in the literature. In 1989, L. A. Bruijnzeel and C. N. Bremmer published an ICIMOD occasional paper highlighting highland–lowland interactions in the Ganges–Brahmaputra river basins (Bruijnzeel & Bremmer, 1989). It underlined the complex relationship between upstream and downstream areas in the mountainous region and shed light on the issue of Himalayan environmental degradation. Among other things, it reviewed the different facets of upstream–downstream linkages, based on evidence with respect to the physical aspects of upstream land cover and land use changes and erosion, downstream flooding, stream flows, and sedimentation.

This paper seeks to revisit that occasional paper of 1989, and expand its scope in two ways: one, the earlier paper covered "the role of forest and land use" and the effects of surface erosion. We have added two more factors – the impacts of climate change, and the development of infrastructure, on water availability downstream. Two, the earlier document only covered the Ganges and Brahmaputra basins; we also include the Indus River basin in our study.

During the 1970s, flooding and sedimentation in the Indo-Gangetic Plain were often blamed on poor land management practices of mountain farmers living in upstream regions. Eckholm (1976) discussed the environmental crisis in the Himalayan region and mainly claimed, among other things, that environmental degradation in the mountains was a major cause of flooding in the Indo-Gangetic Plain. This ecological crisis was often termed the 'Theory of Himalayan Environmental Degradation' (THED). The other main points of the THED were that accelerated erosion, sedimentation, and increasingly severe downstream flooding in the Himalayan region were driven by population growth, forest clearances, ineffective agricultural technologies, the cultivation of steep slopes, overgrazing, and the unsustainable use of forests, fodder, and fuelwood (Ives & Messerli, 1989).

The THED has been critically interrogated by a number of research studies (Bruijnzeel, 2004; Carson,1985; Hamilton,1987; Ives & Messerli, 1989; Qazi, Bruijnzeel, Rai, & Ghimire, 2017). Ives and Messerli (1989) stated that the THED drew from the assumptions, emotions, and widespread generalizations about deforestation, soil erosion, and sediment transfer linkages. They, in general, argued that the theory lacked scientific substantiation. Bruijnzeel and Bremmer (1989) stressed that the dramatic geophysical processes responsible for the very existence of the Himalaya and the plains was a far more significant factor, and that the effects of the activities of mountain farmers were insignificant in comparison. They argued that although the loss of forests could create local problems, it did not appreciably increase the danger of flooding or sedimentation in densely-populated plains in large river basins.

Hamilton (1987) further argued that even with this degree of specificity, the biophysical consequences of these actions were complex, unknown, or ambiguous. The study said that the emotive term 'deforestation' compounded the problem, and should be eliminated from both technical and popular thinking, unless used with qualification to indicate the actual pattern of changes in forest cover. The impacts of deforestation may not be significant when compared to natural erosion and mass wasting (for example, landslides). In addition, Thomson and Warburton (1985) and Thomson, Warburton, and Haltey (2006) argued that the scale of scientific uncertainty in the Himalayan region was so great that it was difficult to get objective information from existing research for use in public policy and decision-making. More focused and rigorous empirical research was required in order to confirm the many issues that had been raised as a part of the THED.

One must mention that there are also upstream–downstream economic linkages, the fundamental basis for which stem from differences in the availability of natural resources and the potential opportunities for production and exchange. Due to constraints imposed by relatively high degrees of inaccessibility, fragility, and marginality in mountainous areas, the means and mechanisms of 'capturing' niche opportunities and engaging in market exchange are limited in the region (Jodha,1997, 2000).

Many new studies have been carried out since then about these environmental issues and problems. The main purpose of this document is to review, in a comprehensive and updated manner, the information and knowledge relating to environmental degradation in the Hindu Kush Himalaya (HKH) from the perspective of upstream–downstream linkages. We have revisited, or freshly analysed, four key questions – regarding deforestation, erosion and sedimentation, climate change, and the development of infrastructure – and discussed how activities, processes, and anthropogenic impacts in upstream areas can affect environmental conditions downstream. For each question, we provide an overview of the issues and its relevance for upstream–downstream linkages and then review each of them based on the available literature. At the end of each question, we have attempted to summarize the discussions around each, in the specific frame of upstream–downstream linkages.

While this report focuses on the four key questions mentioned above, and as such is a technical report, the authors are deeply aware that issues of upstream–downstream linkages are just as much socially and politically framed, as they are through biophysical processes. The THED provides an excellent example of this political framing. The appeal of a concept like the THED lay not only in its oversimplification of complex biophysical processes, such as the role of upstream deforestation in downstream sedimentation, but more so in its simple policy formulation that involved large scale afforestation in the uplands through external aid. This also fitted the then worldview that ignorant and poor upstream farmers, knowingly or unknowingly, were responsible for unsustainable land use practices. While these myths were scientifically dismissed years ago (Ives, 2004), such simplistic notions still hold sway in popular decision-making in countries both upstream and downstream (Blaikie & Muldavin, 2004; Guthman, 1997). Many scholars have invoked a political ecology perspective in situating upstream–downstream debates and systematically explored the links with wider socioeconomic developments, including poor governance, the oppression of ethnic minorities, and neoliberal economic policies (Ives 2004; Satyal, Shrestha, Ojha, Vira, & Adhikari, 2017). Therefore, it is important to keep in mind that while many of the upstream–downstream relationships are projected as biophysical and hence understandable with a certain degree of rigour, the reality is that these interlinkages are often politically contested. In this report, we do not engage with the political contestations per se, but we urge our readers to keep this broader context in mind.

We reviewed the literature from 1985 until today, mainly from the HKH region. The scientific literature and technical reports were both consulted during the review process. Other related studies from outside the region were also consulted, mainly for issues that have seen limited research in the HKH. At the end, we also discuss the knowledge gaps around these linkages and propose the need of a framework for upstream–downstream linkages of land and water management in the HKH region.

1.1. The Hindu Kush Himalaya Region

The Hindu Kush Himalaya (HKH) region extends 3,500 kilometres (km), from Afghanistan in the west to Myanmar in the east. It is the source of ten of the largest river systems in Asia: the Amu Darya, the Indus, the Ganges, the Brahmaputra (Yarlung Tsangpo), the Irrawaddy, the Salween (Nu), the Mekong (Lancang), the Yangtze (Jinsha), the Yellow River (Huanghe), and the Tarim (Dayan) (Figure 1). The HKH region provides ecosystem services (such as water, food, and biodiversity) and a basis for livelihood to a population of around 240 million people. Nonetheless, the basins of these rivers are inhabited by around 1.9 billion people, over a fourth of the world's population (Sharma et.al., 2018). Some characteristics of these river basins are provided in Table 1. The region comprises many of the tallest mountains in the world including Mt. Everest (8,848 m) and K2 (8,611 m). The mountain system is considered relatively young and fragile (Sorkhabi & Stump, 1993).

The region is also known as the Third Pole, because it contains the highest amount of snow and glacial ice storage outside of the polar regions (Yao et al., 2012). Snowmelt and glacier melt are, to differential degrees, the major sources of water for many of the major rivers of the region (Immerzeel, van Beek & Bierkens, 2010; Lutz, Immerzeel, Shrestha & Bierkens, 2014). The river basins are an important source of food, water, biodiversity, and energy for both upstream and downstream populations (Karki et al., 2012; Rasul, 2014).

Table 1: Characteristics of the ten river basins originating in the HKH region

River	Annual mean discharge (m^3/sec)	Basin area (km^2)	Population density	Population (in millions)*	Population (in thousands)	Water availability (m^3/ person/ year)	HKH countries within the basin	Number of dams
Amu Darya	1,376	534,739	39	30.18	20,855	2,081	Afghanistan	3[a]
Brahmaputra	21,261	651,335	182	68.07	118,543	5,656	India, China, Bangladesh, and Bhutan	27[b]
Ganges	12,037	1,016,124	401	580.09	407,466	932	India, China, Nepal, and Bangladesh	795[c]
Indus	5,533	1,081,718	165	268.42	178,483	978	Pakistan, India, China, and Afghanistan	39[d]
Irrawaddy	8,024	413,710	79	42.87	32,683	7,742	Myanmar	N/A
Mekong	9,001	805,604	71	77.31	57,198	4,963	China and Myanmar	1[e]
Salween	1,494	271,914	88	17.88	5,982	7,876	China and Myanmar	N/A
Tarim	1,262	1,152,448	7	11.37	8,067	4,933	China	N/A
Yangtze	28,811	1,722,193	214	604.94	368,549	2,465	China	26[f]
Yellow River	1,438	944,970	156	198.02	147,415	308	China	8
Total		**8,594,755**		**1899.14**	**1,345,241**			

Sources: Eriksson et.al. (2009), *Sharma et.al. (2018) a. Olsson, Bauer, Ikramova, and Froebrich (2008); b. FAO (2011); WRIS (2015a); c. WRIS (2015b). d. WRIS (2015c); e. Ziv et al. (2012); f. Evans (2007).

1.2. Geographical Characteristics Defining Upstream, Midstream, and Downstream Regions

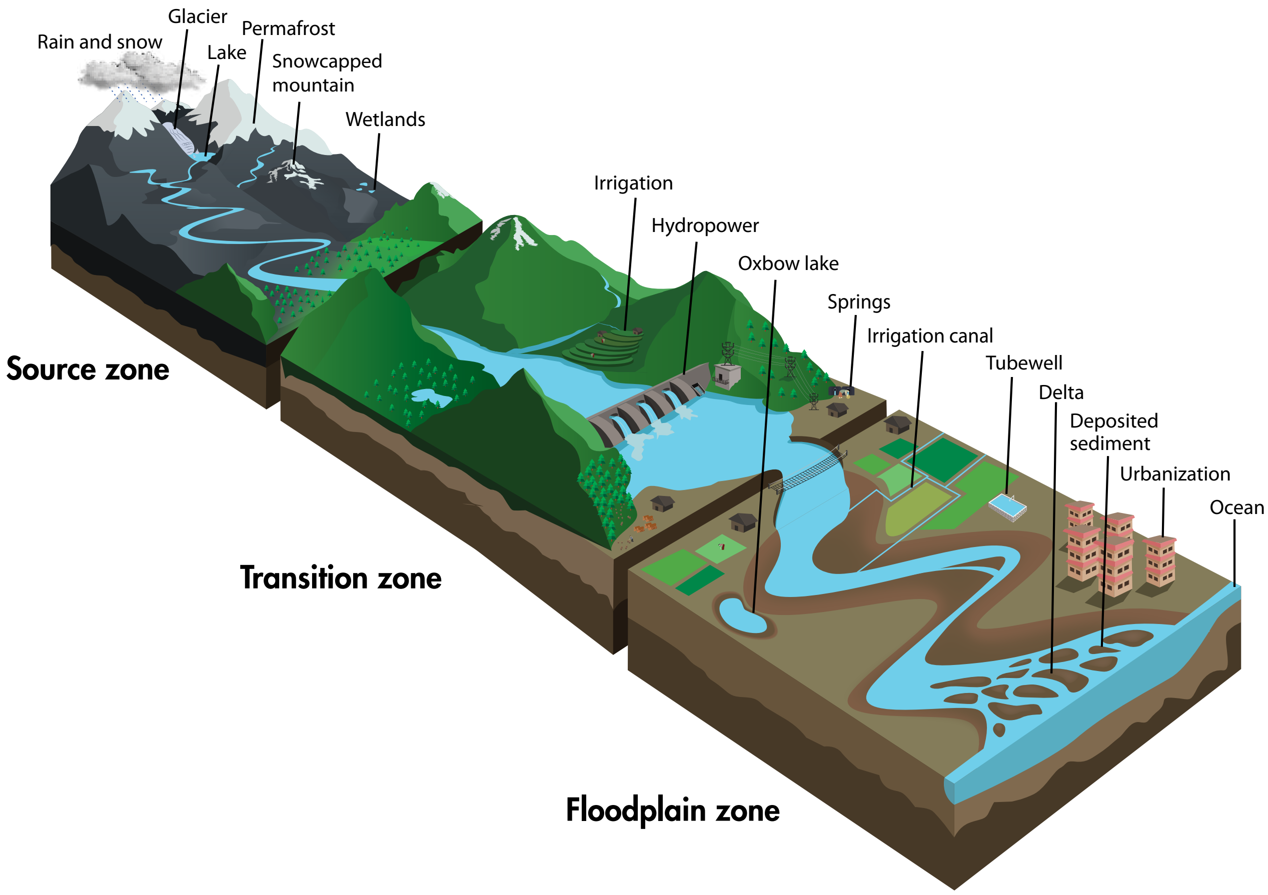

Figure 1: Schematic diagram of a river corridor showing three zones and their upstream–downstream relationships

The river basins originating in the high altitude areas of the Himalayan region (Table 1 and Figure 1) may be broadly classified into three zones as suggested by Miller and Spoolman (2012).

The source zone, also known as the headwaters zone, is the uppermost part of the river basins. Depending on the region, a source zone could be located higher than 4,000 metres. They are characterized by steep slopes, high mountains, young landforms, extreme climate and precipitation, and hence supply heavy sediment to stream flows. Most glaciers and mountain peaks are located in this zone. Meltwater run-off and sediment generated in the glaciated headwaters here drain into streams that sustain many rivers in the Himalayan region. The main driving factor for environmental changes in this zone is global warming, which is affecting snowfall patterns, glacier dynamics, and melt run-off.

In the transfer zone, also known as the transition zone, the river begins to respond to the material received from upstream areas, as it can alter the shape and direction of its channels. This zone is dominated by vegetation and farming, but many other anthropogenic activities here rely on land and water resources. Springs are very common in this zone, and are widely used by middle mountain communities. Groundwater storage contributes to flows from springs on the hill slopes as does the collection of spring discharge as dry season flows. In places where rivers flow in the valleys, communities on the hill slopes are dependent on spring sources for domestic uses and irrigation. For this, groundwater recharge is very important, which occurs mostly in all the three zones, depending on the topography and rainfall patterns.

In this zone, water infrastructure is in the form of irrigation canals and hydropower, which sustain agriculture. The main driving factors for environmental changes in this zone are land use and land cover changes, climate change, and population dynamics, which affect the patterns of resource management.

The floodplain zone, also known as the depositional zone, consists of extensive floodplains and wide, deep channels. Eroded material from upstream is deposited on the plains because of its low gradient. The river starts meandering slowly across the floodplain zone. Flooding and depositions of sediment are the primary driving factors that cause river channels to shift continuously. At its mouth, the river may divide into many channels flowing through a delta made of river-borne sediment into the sea. As suggested by FISRWG (1998), causes and effects generally occur in all zones, but the zone concept, presented here, focuses on the most dominant processes.

Groundwater recharge is very important, and occurs in all the three zones depending upon the topography and climatic conditions. Groundwater supports a large amount of land and agriculture in the Indo-Gangetic plains. There are around 20 million wells and tube wells in India alone, and more than half of these are in the Indo-Gangetic plains. The region is the world's largest user of groundwater. Groundwater use in South Asia exceeds that of China and the United States put together. In India, 39 million hectares (ha) of irrigated land is supported by groundwater, which accounts for nearly 70% of the total area irrigated. The proportion is even higher in countries like Bangladesh. Groundwater use in irrigation is increasing both in absolute terms and in the percentage of total irrigation, leading in places to concentrations of users exploiting groundwater storage at rates above groundwater recharge (Siebert et al., 2010). Not only irrigation, urban water supply in downstream plain areas also depends heavily on groundwater.

2. Transnational River Basins

The major rivers in the HKH region mostly have their headwaters in high-altitude areas and are transboundary in nature: They reach the sea after traversing two or more countries across different climatic and geographical zones (Table 1). The region has witnessed friction and conflict over the years, between riparian states over the waters of transboundary rivers, which have been sought to be addressed through bilateral or multilateral agreements (Hanasz, 2017).

Although all these river basins have different issues of upstream–downstream linkages, for the purpose of this document, we have taken the transboundary Indus, Ganges, and Brahmaputra as representative river basins. Their upstream and downstream areas are connected with respect to various issues and effects at different scales. A short overview of these three river basins is provided below.

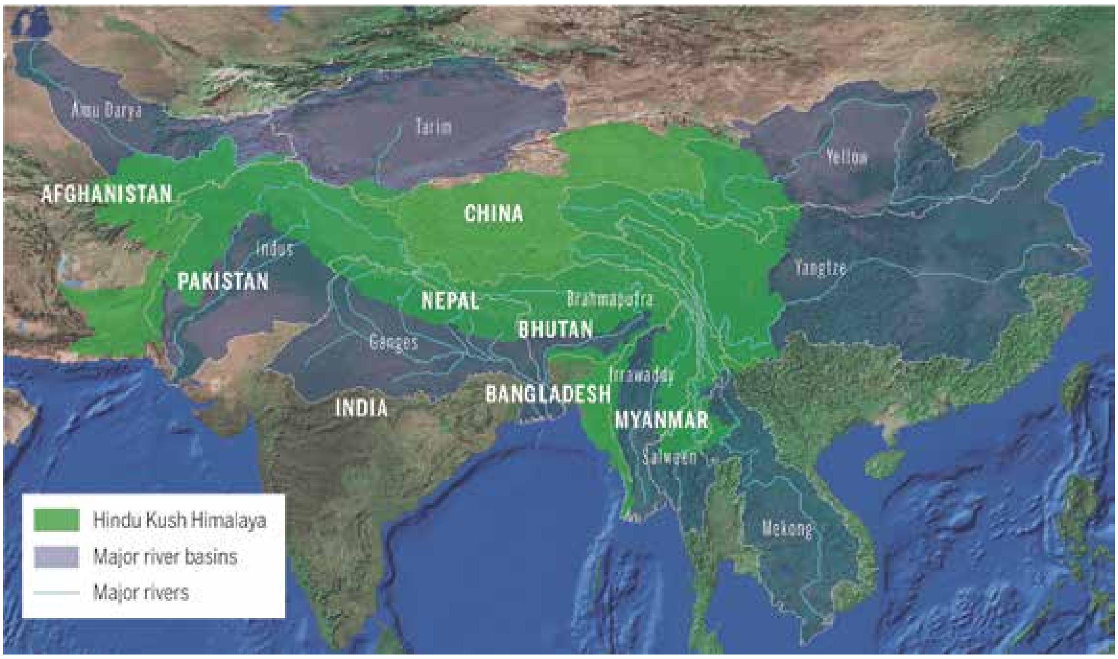

Figure 2: Ten major river basins in the HKH region
Source: Sharma et al. 2018.

2.1. Indus River Basin

With a population of around a quarter of a billion people and with very low human development indicators, the Indus basin lies in the northwestern region of South Asia. Covering a drainage area of 860,000 sq km, the Indus is regarded as one of the largest rivers in South Asia (Ali & De Boer, 2003). The largest portions of the basin lie in Pakistan (52%) and India (33%), with some of it in China and Afghanistan.

The river originates at Lake Ngangla Rinco, high on the Tibetan Plateau in China. It runs 3,200 km along northern India and along all of Pakistan and eventually empties into the Arabian Sea near the port of Karachi (Mustafa, 2010; STIMSON, 2013). Its tributaries include the Ravi, Beas, and Sutlej in India, Swat, Chitral, Gilgit, Hunza, Shigar, Shyok, Shingo, Astor, Jhelum, and Chenab in Pakistan, and the Kabul River draining parts of Afghanistan.

The Indus River basin has a range of climatic zones. It includes high-altitude catchments, with glaciers covering large areas, contributing to run-off via seasonal inputs. It also covers a mid-altitude catchment area with winter precipitation preceding summer flows, as well as the regions around the foothills dominated by winter precipitation and the summer monsoon (Archer, 2003).

The water supply in the Indus basin determines various socioeconomic aspects in Pakistan. The Indus civilization had its roots in agriculture. Even now, vast areas of the country's agricultural fields are irrigated by the Indus, and a major part of the country's hydropower generation relies on it (Young & Hewitt, 1990). In recent years, on account of Pakistan's energy and agricultural productivity needs, the Indus River has been transformed into a tightly regulated system of dams and irrigation canals (Garzanti, Vezzoli, Ando, Paparella, & Clift, 2005). According to the FAO (2011), more than 95% of Pakistan's irrigational needs are met by the Indus River basin. In 2008, the total area equipped for irrigation in Pakistan was estimated at 20 million ha.

The Indus River is also known for having the largest network of irrigation systems in the world. Their construction began as early as 1859, with the Upper Bari Doab Canal on the Ravi. The Tarbela dam, which started operations in 1975–1976, is known as the largest earth-filled dam in the world. Currently, three major dams in Pakistan and six in India are operating in this river basin (FAO, 2011).

2.2. Ganges River Basin

Extending from the high mountains to the Indo-Gangetic floodplain, the Ganges River basin system is located in four countries (Bangladesh, China, India, and Nepal) with an area of over a million sq km. Nepal lies entirely in the Ganges river basin. India occupies 79% of the basin's area. Two rivers, the Alaknanda and the Bhagirathi, which meet at Devaprayag in Uttarakhand, India, are the headwater sources of the Ganges.

Further on its course eastward, it is joined by various rivers, namely the Ramganga, Sharada, Gomti, Ghagra, Gandak, and Koshi from the Himalayan sub-basins. Other tributaries, such as the Mahananda, Yamuna, Kehtons, Son, Punpun, and Kiul, join the Ganges further downstream. The Ganges is further joined by the Punarbhaba, Atrai (Boral), and Karatoya, which originate in India. The river joins the Brahmaputra 220 km further downstream and is also joined by the Padma and the Meghna. The combined river is called the Meghna before it drains into the Bay of Bengal. The total length of the Ganges River, from headwater to the Bay, is about 2,515 km (FAO, 2011).

The Ganges river depends on large quantities of run-off, derived from snowmelt in the Himalaya upstream, and on monsoon-derived run-off in downstream hills and plains. Of all its tributaries, the Ghagra (known as Karnali in Nepal) contributes the maximum annual run-off, and the Gomti the minimum annual run-off. The Ganges River basin has relatively low precipitation northwest of its headwaters region – where it averages 760–1,020 mm annually – and high precipitation along the Bihar plains and coastal areas, with an annual precipitation of between 1,020–1,520 mm and 1,520–2,540 mm respectively (FAO, 2011).

The Ganges basin is considered one of the most fertile and densely populated areas in the world, in which 76% of the people reside in rural areas (Sulser et al., 2010). Most people here depend on the Ganges for their livelihoods. Hydropower is one major source of development in upstream regions. Downstream, the river is regulated by numerous dams, barrages, and irrigation canals for agriculture and industrial activities (Bharati et al., 2011).

The Ganges basin has an abundance of groundwater and surface water. Yet, excess demand ensures that people face water scarcity for their economic activities in eastern India, Bangladesh, and Nepal, where the majority of the population is poor and depend mainly on agriculture (Molden, Murray-rust, Sakthivadivel, & Makin, 2003; Sharma et al., 2010a). Sulser et al. (2010) state that the Ganges basin is one of the most intensely farmed areas in the world. Its total harvested area is around 68 million ha, of which approximately 52% is rainfed. The main crops in the basin are rice, wheat, millet, maize, and sorghum, the productivity of which, if increased, can significantly promote the well-being of the basin's population. But the overexploitation of groundwater and surface water has led to declining water tables, resulting in low agricultural productivity. Additionally, more and more people are significantly affected by the poor water quality in the region.

A total of 784 dams are present in the Ganges river basin within India. Most of them are already complete, while a few are still under construction. The live storage capacity of the completed projects accounts for 48,748 million cubic metres (MCM) of water (MWR, 2014).

2.3. Brahmaputra River Basin

The Brahmaputra originates from a glacier in Kailash in the Tibet Autonomous Region (TAR) of China, at an elevation of 5,300 metres above sea level (masl). It has a length of 2,900 km and joins the Ganges before draining into the Bay of Bengal (Immerzeel, 2008). The river is known as the Yarlung Tsangpo in China and flows eastward at an average height of 4,000 masl. As the river enters India, it rapidly descends and enters the plains, where it is known by the name Dihang. The river flows through Assam and Meghalaya for 650 km before entering Bangladesh, where it flows for another 240 km until its confluence with the Ganges. On its way, the Brahmaputra is fed by tributaries such as the Dibang, Lohit, Burhidihing, Dikhou, Dhansiri, Kopili, Subansiri, Kameng, Manas, Sankosh, Raidak, Dharla, Teesta, and Atrai. The basin has a total area of 543,500 sq km and encompasses four nations – Bangladesh, Bhutan, China, and India – with Bhutan lying entirely in the Brahmaputra River basin (FAO, 2011; Mahanta et al., 2014).

The average discharge of the Brahmaputra is around 20,000 m^3/s. The climate in the basin is driven by the summer monsoon (June–September), during which period it receives 60%–70% of its annual rainfall (Immerzeel, 2008). The annual regime of the river flow is controlled by climatic conditions, with two high-water periods: in early summer with melting snow, and in late summer due to run-off from the monsoon rains (Mahanta et al., 2014).

The majority of the population in Bangladesh, Bhutan, and millions in India depend on water from the Brahmaputra for irrigation, hydropower, and fisheries (Rasul, 2014). Although the river has much surface water, around 653 billion cubic metres (cu m), people in the concerned states in India suffer from water scarcity. The area under irrigation presently is less than 20% of the potential, and only 5% of the sown area is irrigated. This makes agriculture in the area highly dependent on rainfall, which itself is quite erratic (Rasul, 2015; Sharma et al., 2010b).

Three major dams have been proposed in the upstream regions of the Brahmaputra, where the Zangmu dam is already in operation. In India, a total of 18 dams have been constructed for irrigation and energy purposes in the concerned northeastern and eastern states. Three large dams are currently in operation in Bangladesh and five in Bhutan (FAO, 2011; WRIS, 2015a).

3. Environmental Conditions

As suggested by Ives and Messerli (1989), a north–south topographical transect of the Himalaya would include entire areas, or part of several areas, with aligned physiographic features: the Tibetan Plateau, trans-Himalaya ranges and intervening valleys, and the Greater Himalaya; the middle mountains; the foothills (locally referred to as the Siwaliks or Churia Hills); and the plains. This description probably best describes the central Himalaya, while some of these features may be missing in the eastern or western Himalaya.

Figure 3 describes the schematic transect of the central Himalaya in Nepal. The rapid descent in the topography, from the Greater Himalaya to the plains, within barely 100–150 km ensures a unique soil and geological profile – largely governed by altitude, slope, and vegetation cover – with the existence of varied agro-ecological zones.

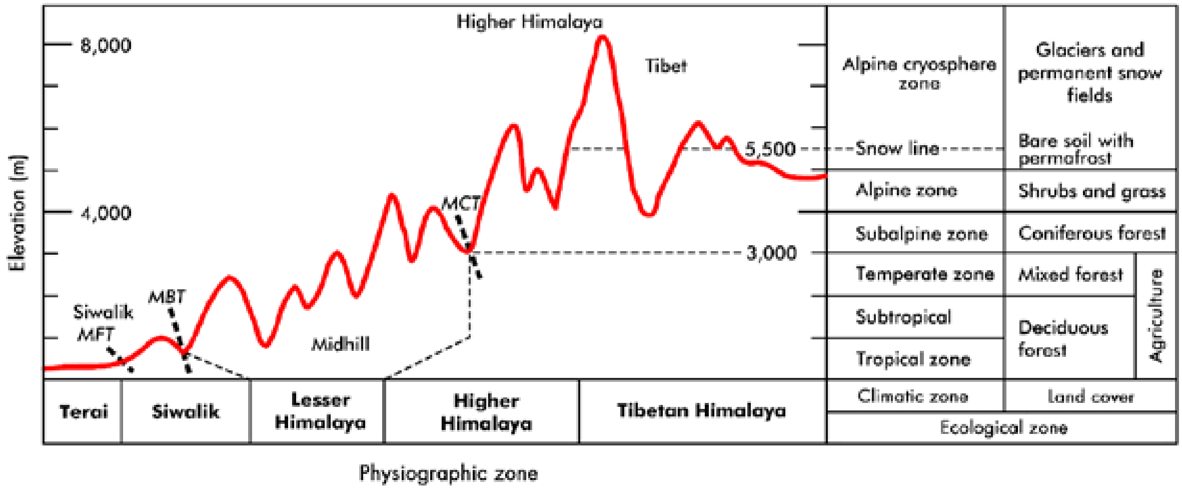

Figure 3: Physiographic divisions and climatic landscape zones of the Central Himalaya region

Note: MFT = main frontal thrust; MBT = main boundary thrust; MCT = main central thrust.
Source: Nepal et al. (2017)

3.1. Monsoon Climate

The precipitation patterns in the HKH region are influenced by the Indian summer monsoon and the westerlies. During summer, the Tibetan Plateau warms more rapidly than the Indian Ocean. The resultant low pressure over Asia and the Himalaya and relatively high pressure over the Indian Ocean give rise to a strong, low-level atmospheric pressure gradient that in turn generates the southwest monsoon (Overpeck, Anderson, Trumbore, & Prell, 1996). This brings a moist air current from the Bay of Bengal to the Indian subcontinent. When the moist flow approaches land, maximum precipitation occurs upstream and over the lower windward slopes of the west- and south-facing mountain barriers (Medina, Houze, Kumar, & Niyogi, 2010).

The summer monsoon weakens from east to west and rarely reaches the far-western Karakoram ranges. In the eastern part, 70%–80% of the annual rainfall occurs during the summer monsoon season (June–September) whereas in the western Indus basin, summer monsoon precipitation accounts for about 50% of the annual total, and the rest during winter and spring (Molden, Vaidya, Shrestha, Rasul, & Shrestha, 2014; Nepal & Shrestha, 2015). In general, the eastern Himalayan region gets an annual precipitation of around 3,000 mm, whereas the western part receives comparatively little precipitation, about 300 mm a year (Immerzeel, Droogers, Dejong, & Bierkens, 2009).

The precipitation pattern is characterized by two gradients: (i) a north–south gradient due to an orographic barrier, which prevents air masses from going further north, and (ii) an east–west gradient due to the weakening of the Indian summer monsoon as it moves westward from the Bay of Bengal, implying greater humidity in the eastern HKH (Bookhagen & Burbank, 2010).

The height and extent of the Tibetan Plateau and Higher Himalaya constitute a significant barrier to atmospheric circulation patterns (Yao et al., 2012). The climatic controls are quite different in the western Himalaya from the central and eastern Himalaya; in the western part, precipitation is dominated by westerly disturbances and a significant amount of precipitation occurs during winter and spring (Bhutiyani, Kale, & Pawar, 2010).

3.2. Land Use and Land Cover

The HKH region has very diverse climatic zones, mainly due to sharp altitudinal differences, ranging from 500 metres to more than 8,000 metres. These altitudinal differences create diverse climatic and ecological zones. The vegetation in the region varies from subtropical broadleaf forests to alpine meadows in stretches of only a few hundred kilometres.

An inventory by Bajracharya and Shrestha (2011) identifies 54,000 glaciers in the ten river basins of the HKH region, with a total area of 60,000 km^2 (1.4% of the total area). The glaciers melt during the summer season and feed the rivers like the Indus, Ganges, and Brahmaputra. The glaciers and snowmelt also feed natural wetlands, which have a total area of about 665 sq km in the HKH. Of these wetlands, 28 are designated as Ramsar sites and play a vital role as natural systems of water storage (ICIMOD, 2009). Forest cover is approximately around 20%, while 39% of the area comprises grasslands (Chettri, Shakya, Thapa, & Sharma, 2008).

The countries in the HKH region have set aside 488 biologically important areas, covering 39% of the land, as protected areas. This includes 33 Ramsar sites, 15 UNESCO world heritage sites, and 330 important bird areas (IBAs). Yet, there is also an alarming rate of deforestation in some places where vast areas of forest have been cut down primarily for agricultural uses and the need of local people for fuel.

Sharma, Bhuchar, Xing, and Kothyari (2007) emphasized that the conversion of forest land into other land cover types, mainly for agriculture, is quite a common phenomenon in the Himalaya. Most people in the HKH use mixed crop-livestock farming systems, which include grain, horticultural crops, cash crops, and livestock (Tulachan, 2001). Agriculture, covering about 26% of the total land area, is the main source of livelihood for most people, but they are mainly dependent on the rainfall for it.

3.3. Glaciers and Hydrology

The hydrological regime of the Himalayan rivers is governed by run-off from snow, glaciers, and rain, depending on the location of the river basin and the type of precipitation. On the eastern side of the HKH, the climate system is dominated by the summer monsoon, and by the winter monsoon in the western part.

According to Lutz, Immerzeel, Shrestha, and Bierkens (2014), the eastern basins (such as those of the Ganges and Brahmaputra) are dominated more by rainfall run-off than melt run-off. In the Ganges river basin for instance, Immerzeel, van Beek, and Bierkens (2010) estimated that snow and glacier melt contribute merely 10% to the overall volume of streamflow of the river. In contrast, the Indus basin is dominated by glacier run-off. It provides an estimated 40% of the total streamflow in upstream areas of the Indus basin. Edwards et al. (2010) estimated the contribution of melt run-off in the Indus and Tarim at around 40%–45%. Singh and Jain (2002) estimated that, on average, snow and glacier melt contributes 59% of the annual flow at Bhakra Dam in the Sutlej sub-basin. It must be pointed out that the contribution of melt run-off may vary, depending on the model chosen (Siderius et al., 2013), the location of the point at which the melt run-off is calculated, and the location of the basins themselves (Alford & Armstrong, 2010; Nepal, Flügel, & Shrestha, 2014).

4. A Changing Environment

The effects of climate change in the HKH region can already be observed in the form of increasing temperatures, accelerated glacial melt, and extreme weather events such as floods, heat waves, and droughts. These various ongoing environmental changes may have physical, environmental, and socioeconomic consequences for the 1.9 billion people living in the HKH river basins (Sharma et.al. forthcoming). In particular, the higher temperatures and greater variability in precipitation may have adverse effects on livelihood-related activities. They may also affect cultural practices. As suggested by Mukherji, Scott, and Molden (2018), the two megatrends in the HKH, of climate change and urbanization (and related outmigration), will impact water, energy, and food in the region in varied ways.

4.1. Changes in Temperature

Analyses of the past climate for the HKH region have not been conducted until recently (Ren & Shrestha, 2017). Ren et al. (2017) analysed past climate trends based on the Global Land Surface Air Temperature (GLSAT) data sets developed recently by the China Meteorological Administration (CMA). According to this study, generally, from the early 20th century through the beginning of the current one, the HKH has experienced warming from 1901 to 1940, cooling from 1940 to 1970, and warming from 1970 to the present. From 1901 to 2014, annual mean surface air temperature significantly increased in the HKH, at a rate of about 0.10 °C per decade – while the warming rate over the last 50 years has been 0.2 °C per decade ($p>0.05$) (Ren et al., 2017). According to Shrestha, Gautam, and Bawa (2012), the overall average warming in the HKH region over 1982–2006 was 1.5 degrees Celsius (°C) (at an average rate of 0.06 °C/year), in comparison to a rise of 0.6 °C for the global mean surface temperature over the same period.

The recent warming trend in the climate of the Himalayan region has been observed explicitly by Gautam, Timilsina & Acharya (2013), with varied trends in different regions and seasons. The literature review done by them provides observations that indicate a higher rate of rising temperatures in Nepal and the Chinese part of the Himalaya as compared to the rest of the Himalayan region. In the higher regions of the HKH, such as the Tibetan Plateau, observations show an average rise in temperature of 1.8 °C over the past 50 years (Wang et al., 2008). In the eastern Himalaya, western Himalaya, and the Gangetic Plain, the rise in mean temperature has been slightly lower (0.01–0.03 °C/year) than that of the central Himalayan region such as Nepal (0.04–0.09 °C/year) and Tibet (0.03–0.07 °C/year) (Kulkarni, Patwardhan, Kumar, Ashok, & Krishnan, 2013).

In the Upper Ganges river basin, the maximum temperature has increased at a rate of 0.06 °C/year between 1978 and 1994 for the whole of Nepal. In the Koshi catchment, a sub-basin of the Ganges, the maximum temperature increased 0.058 °C/year over the last four decades (Nepal, 2016; Shrestha, Wake, Mayewski, & Dibb, 1999). According to Shrestha, Bajracharya, Sharma, Duo, and Kulkarni (2016), the frequency and intensity of weather extremes are increasing. The daily maximum temperature increased by 0.1°C/decade on average between 1975 and 2010 and the minimum by 0.3 °C/decade in the Koshi River basin.

The maximum temperature has been increasing during the last century over all the regions of India and particularly in mountainous regions (0.9 °C in the western Himalaya and 1°C in the northeast) (Dash, Jenamani, Kalsi, & Panda, 2007). More recent data for India indicates a rise in mean temperature of 0.6 °C/100 years over 1901–2010. The rise has been mainly in maximum temperature (1 °C/100 years), with the rise in minimum temperature of 0.17 °C/decade over 1981–2010 (Srivastava, Kothawale, & Rajeevan, 2017).

In the Upper Brahmaputra River basin, the average annual temperature rose 0.28 °C per decade from 1961 to 2005 (Bongartz, Flügel, Pechstädt, Bartosch, & Eriksson, 2008). Average winter, autumn, spring, and summer temperatures increased by 0.37, 0.35, 0.24, and 0.17 °C per decade respectively. Immerzeel (2008) found a temperature increase of 0.6 °C over a hundred years in the Brahmaputra river basin, with a higher increase in spring, based on Climatic Research Unit data over 1900–2002. In the Indus river basin, Fowler and Archer (2006) showed a consistent lowering of mean and minimum summer temperatures between 1961 and 2000, without a consistent trend in maximum summer temperatures.

A study, by Sun et al. (2017), suggests that extreme indices have changed over the past 50 years in the region: the occurrence of extreme cold days and nights has declined (days by 0.85 per decade, nights by 2.40 days per decade), while the occurrence of extreme warm days and nights has increased (days by 1.26 days per decade, nights by 2.54 days per decade). Warm nights have increased throughout the region, and extreme absolute temperature indices have changed significantly. Frost days show a significant declining trend in most parts of northern India and the Tibetan Plateau. The length of the growing season has increased by 4.25 days per decade, a positive change for agriculture ($p>0.05$).

4.2. Changes in Precipitation

A direct influence of global climate change is changes in precipitation patterns. Increased warming leads to greater evaporation, which results in the land surface drying, and an increased intensity in rains and droughts (Trenberth, 2010). The climatic situation is constantly changing in the Himalaya, as the mountains are known to act as a barrier to atmospheric circulation. This eventually affects the Asian Monsoon (Eriksson, 2009).

Zhan et al. (2017) analysed past precipitation trends in the HKH region using the Global Land Monthly Precipitation (GLMP) and Global Land Daily Precipitation (GLDP) data sets developed recently by the CMA. The study suggests that, while precipitation trends for the HKH are inconclusive over the past century, extreme precipitation has increased overall over the last five decades, and extreme precipitation has changed markedly since 1961: rising trends appear in the intensity of annual extreme precipitation and also in the frequency of annual intense precipitation days (Zhan et al., 2017). Across the HKH region as a whole, average annual precipitation has increased by 163 mm, or 6.52 mm/year, over 1982–2006 (Shrestha, Gautam, & Bawa, 2012). There are no changing trends in winter precipitation in the northwestern Himalaya over 1866–2006, whereas a significant decrease in summer monsoon precipitation is observed (Bhutiyani, Kale, & Pawar, 2010).

Archer and Fowler (2004) found no significant long-term trends from 1895 to the early years of this century for the Upper Indus basin, although a statistically significant increase in annual precipitation was suggested at several stations from 1961 to 1999. In the Ganges River basin, historical annual precipitation has remained stable, with no distinct precipitation trends in the Nepalese Himalaya between 1954 and 1994 (Shrestha, Wake, Dibb, & Mayewski, 2000). In the Koshi catchment, significant changes were found only in three stations with two increasing trends and one decreasing trend (Nepal et al., 2016). Karki, Schickhoff, Scholten, and Böhner (2017) suggested that precipitation extremes are increasing all over Nepal.

In the Brahmaputra basin, Bongartz et al. (2008) reported a slight increase in the mean annual precipitation over 1961–2005, as well as in autumn, spring, and summer, but no statistically significant trends.

4.3. Future Trends in Temperature and Precipitation

Many studies of the HKH region have suggested that its temperature is likely to increase in the future, and it will face changes in precipitation.[2] A detailed review of these projections in the Indus–Ganges–Brahmapautra (IGB) river basins has been carried out in Nepal and Shrestha (2015). A short overview and main findings are presented here.

[2]Until the IPCC's *Fourth Assessment Report* in 2007, these scenarios were based on the *Special Report on Emissions Scenarios* (SRES), whereas for and after its *Fifth Assessment Report*, they are based on Representative Concentration Pathways (RCPs).

In the Indus river basin, studies have suggested that precipitation may increase in the future. Immerzeel, van Beek, and Bierkens (2010) report an increase in precipitation by 25% by 2046–2065, compared to the baseline (2001-2007), based on general circulation model (GCM) data. Akhtar, Ahmad, and Booij (2008) suggest an increase of up to 21% using data from the PRECIS high-regional climate model (RCM). Using A1B scenarios, Rajbhandari, Shrestha, Kulkarni, Patwardhan, and Bajracharya (2014) also projected an increase in precipitation over the upper regions of the Indus basin for the A1B scenario by the end of the century using PRECIS, but they projected a decrease in its lower regions, and thus no overall pattern for the whole basin. They also projected a decrease in winter precipitation, particularly over the southern part of the basin. Forsythe et al. (2014) also project an increase in precipitation of 18% in the Upper Indus basin.

An increase in precipitation is projected by many studies for the Ganges river basin as well. One study, using the A1B and A2 scenarios, mentions an increase of 10%–12% during the monsoon season by the end of the century (Pervez & Henebry, 2014). Immerzeel, van Beek, and Bierkens (2010) suggest an 8% increase in precipitation in upstream regions of the Ganges. One study also reported an increase in summer, autumn, and annual precipitation, but a decrease in spring precipitation in the Koshi River basin (Agarwal, Babel, & Maskey, 2014). In the Brahmaputra river basin as well, an increase in precipitation is projected by various studies: Pervez and Henebry (2014) suggest an increase of 12%–16% by the end of twenty-first century, while Immerzeel (2008) mentions an accelerated increase in precipitation, with a greater increase over the Tibetan Plateau than over the plain areas.

While most of the studies suggest that precipitation will increase in the future, differences in their magnitude of changes reported are likely, due to different GCM and RCM scenarios, methods of analysis, and data periods covered.

As part of the Hindu Kush Himalaya Monitoring and Assessment Programme (HIMAP), an analysis of climate projections was conducted for the HKH based on a Coupled Model Intercomparison Project 5 (CMIP5) multi-model ensemble mean (a subset of 25 models). These projected changes in surface temperature are higher than the likely ranges reported for the globe and South Asia by IPCC's Fifth Assessment Report. They indicate a continuous warming over the entire HKH in the twenty-first century. The projected temperature increase is 2.5 ± 1.5 °C by the end of the twenty-first century for the moderate scenario, corresponding to the representative concentration pathway RCP4.5. For the more extreme scenario RCP8.5, the projected temperature increase is 5.5 ±1.5 °C by the end of the twenty-first century. The simulation data of the CMIP5 models suggest that the projected changes in the surface mean temperature over the HKH are larger than the global mean change by the end of the twenty-first century. Further, similar analysis for the HKH was conducted based on the Coordinated Regional Downscaling Experiment (CORDEX) models (Sanjay, Krishnan, Shrestha, Rajbhandari, & Ren, 2017). The study projected significant warming over the HKH region in the future. In the near term (2036–2065), the region is projected to warm by 1.7–2.4 °C for RCP 4.5 and 2.3–3.2 °C for RCP 8.5. In the long term (2066–2095), regional warming is projected to be 2.2–3.3 °C for RCP 4.5 and 4.2–6.5 °C for RCP 8.5. Winters are projected to warm up relatively more. The CMIP5 GCM projections and CORDEX projections are similar in trends but are different in magnitude. Both studies suggest that the Tibetan Plateau, the central Himalayan Range, and the Karakoram will see a rise in temperature higher than the HKH's average rise.

According to the report prepared for National Adaptation Plan (NAP), the mean temperature in Nepal could increase by 0.9–1.1 °C in the medium-term period (the 2030s) and by 1.3–1.8 °C in the long-term period, corresponding to the 2050s. The highest rates of mean temperature increase are expected for the post-monsoon season (1.3–1.4 °C in the medium-term period, and 1.8–2.4 °C in the long-term period) and the winter season (1.0–1.2 °C in the medium-term period, and 1.5–2.0 °C in the long-term period) (MOFE, 2018).

4.4. Changes in River Run-off

The hydrological regime of the Himalayan river basins is affected by a number of factors including climate change. The precipitation that takes place at higher elevations falls as snow, which sustains flows for a longer period of time during the year (Bookhagen and Burbank, 2010). These processes may be severely affected by the warming temperature trend, as a consequence of which precipitation will occur more as rain rather than snow than it does presently, and the snow storage capacity of these basins will diminish (Nepal, Flügel, & Shrestha, 2014; Nepal, 2016). In the case of higher evapotranspiration, soil water content decreases, especially in the forested catchments, reducing the water available for stream flows (Greminger et al., 2003). Other environmental changes, such as land use and land cover changes, and infrastructure development, may also affect hydrological processes.

Lutz, Immerzeel, Shrestha, and Bierkens (2014) suggested that annual run-off would increase by 7%–12% in the Upper Indus basin by 2050. This would primarily be due to rapid glacier melt in the upper reaches of the rivers, along with an increase in precipitation. Laghari, Vanham, and Rauch (2012) suggested that there might be a possible increase in water availability in the short-term, but it would decrease in the long run.

A decrease in the mean upstream water supply in the Ganges and Brahmaputra basins has been pointed out by Immerzeel, van Beek, and Bierkens (2010) for 2046–2065, by 17.6% and 19.6%, respectively. But in downstream regions of the Ganges in Bangladesh, there will be an increase in peak discharge, leading to an increase in the severity of extreme events (Mirza, Warrick, & Ericksen, 2003).

Nepal and Shrestha (2015), based on a review of the impacts of climate change in the Indus, Ganges, and Brahmaputra river basins, concluded that the magnitude of impacts might differ from one basin to another. Different studies may yield varied results in terms of changes in run-off, primarily due to a selection of different climate models and related output, and their choice of hydrological models. A more detailed discussion of the impacts on run-off is discussed in a later section (Section 7).

4.5. A Changing LULC

The HKH region is highly heterogeneous, with a wide range of habitats, diverse micro climates, and varied ecological conditions, resulting in a high level of biodiversity. The headwater zones are covered with snowpack, glaciers, and permafrost. In the Karakoram region, more than 50% of the glaciers are advancing or stable (Gardelle, Berthier, & Arnaud 2012; Zemp, Hoelzli, & Haeberli, 2009) whereas, in central and eastern areas of the HKH, most of the glaciers show a negative mass balance. Permafrost and snow cover can also retain water that freezes in the winter and thaws in summer, providing much-needed water to people in downstream areas. The linear trend of snow cover in the HKH over 2000–2010 has been found to be −1.25% ± 1.13%, with similar trends in its western, central, and eastern parts. The snow cover varies in different areas, according to the seasons and atmospheric circulation (Gurung, Amarnath, Khun, Shrestha, & Kulkarni, 2011).

In the transition zone, the land surface is dominated by vegetation, forests, and agricultural land. Here, the forests provide numerous ecosystem services to the people living in the mountainous regions. Agricultural land dominates the middle mountain region where lots of anthropogenic activities (such as farming and irrigation) are carried out. The climate and socioeconomic changes have a direct impact on land cover. To tackle these problems, countries such as Nepal have stipulated that 40% of the land be devoted to forests (FAO, 2012). The contrast across the region is noteworthy: Data sets from 1987, 2000, and 2014 show that forests and rangeland in northwest Pakistan have shrunk on average by 15% and 7.5% respectively over that period (Hussain, Haq, & Rahman, 2018), but in Nepal one sees an increase in forest cover by 7.6% in the central region from 1976 to 2000. Bhutan – where over 60% of the total area is forest land – has had a very stable forest cover over the last three decades, going by Landsat images from 1990, 2001, and 2011 (Bruggeman, Meyfroidt, & Lambin, 2016; Gautam, Shivakoti, & Webb, 2004).

The Himalayan wetlands constitute an important ecosystem, providing diverse ecosystem services to people living in nearby and downstream areas. The source of the Yangtze River has the largest cluster of wetlands, covering 3.29×1,010 square miles (sq mi.). Despite their importance, high-altitude wetlands and the catchments draining into them are under increasing threat from climate change, land use changes, modifications in upstream flows, unsustainable exploitation, overgrazing, and tourism-related problems (Chatterjee et al., 2010; ICIMOD, 2009).

Due to the overexploitation of wetlands, a 30% decrease in the extent of wetland area has been observed in the HKH over the past few decades (Sharma, Chettri, & Oli, 2010). Such degradation can also be seen in the western Himalayan Hokersar wetland, where the area decreased from 18.75 sq km in 1969 to 13 sq km in 2008 (Romshoo and Rashid, 2014). Research in the same wetland revealed that the silted area had increased from 0 ha in 1969 to 221 ha by 1995 (Alam, Rashid, Bhat, & Sheikh, 2011). Interestingly, the silted area reduced from 221 ha in 1995 to 90 ha in 2005, due to the emergence of plants over the silted area.

4.6. Socioeconomic Changes

The HKH region is undergoing rapid changes, but among the most important socioeconomic changes is the spread of capitalist relations in agriculture and other sectors across large portions of the HKH. This has meant greater mechanization, yields, risk, and the use of high-yielding seeds and fertilizers. This has been accompanied by the greater use of technologies to tap groundwater, which has resulted in declining groundwater levels, particularly in northwestern India and parts of Pakistan (Rodell, Velicogna, & Famiglietti, 2009) and Bihar (Sinha, Gupta, & Nepal, 2018). These changes have been accompanied by the twin megatrends of climate change and urbanization (Mukherji, Scott, Molden, & Maharjan, 2018).

Socioeconomic and demographic changes (such as migration and urbanization) have put unprecedented pressure on water resources, leading to uncertain supplies, increased demand, and a higher risk of extreme events such as floods and droughts, which can adversely affect people's livelihoods (Mukherji, Molden, Nepal, Rasul, & Wagnon, 2015). Rapid urbanization is occurring across the entire HKH region. In all eight HKH countries, urban populations are increasing. Rural populations will decline, by 2050, in six HKH countries (Bangladesh, Bhutan, China, India, Pakistan, and Myanmar), and more than 50% of the population will live in cities. In the other two HKH countries (Nepal and Afghanistan), urban populations are growing rapidly despite the projected demographic balance remaining less than half urban by 2050 (UN-DESA, 2014; Mukherji et al., 2018). Water availability in rivers and springs are crucial for mountain communities for agricultural production, downstream irrigation systems, urban water supply, and ecosystem services (Mukherji, Scott, Molden, & Maharjan, 2018).

Revisiting Key Questions Regarding Upstream–downstream Linkages

In this section, we revisit key questions related to upstream–downstream linkages of land and water management in the HKH region. We have analysed four key questions – regarding deforestation, erosion and sedimentation, climate change, and the development of infrastructure – and discussed how activities, processes, and anthropogenic impacts in upstream areas can affect water availability and environmental conditions downstream. For each question, we provide a quick overview of the issues and its relevance for upward–downward linkages and then reviewed based on the available literature.

5. Review Question 1

What are the Impacts of Land Use, Land Cover Changes on Downstream Water Availability and Flooding in the HKH Region?

5.1. Overview

Land use, land cover change (LULCC) has been identified as one of the major drivers of change induced by anthropogenic activities in global change analysis. A better understanding of cause–effect relationships between upstream land use changes and how such changes contribute to the generation of river run-off, downstream water availability, flooding, and ecosystem services is essential for an impact analysis of a changing LULC.

Land use, land cover (LULC) controls hydrological run-off generation and evapotranspiration, which affect the temporal and spatial variability of run-off and storage. Over large land areas in temperate zones, about two-thirds of the annual precipitation evaporates; the remaining one-third runs off in streams, or percolates to replenish groundwater. In arid regions, on the other hand, evapotranspiration may be even more significant, returning up to 90% or more of the annual precipitation to the atmosphere (Rodda, 2011). Within the global hydrological cycle, evapotranspiration feeds into the intercontinental transport of water vapour and energy, inducing precipitation, for example within the monsoon system (Ellison, Futter, & Bishop, 2012). Research in particular is focused on the transfer of precipitation to stream flow, which is controlled by topography, LULC, soils, and geology. The temporary storage of water in different forms, in soils, as groundwater, snow, or glaciers, where different residence times influence the hydrological cycle, is also very important (Andermann et al., 2012a).

The downstream regions of the Himalaya, located in the large plains of the Indus, Ganges, and Brahmaputra, have the highest population densities in the world. Those living downstream are dependent on water sources from upstream mountainous areas for various livelihood activities such as domestic agriculture, transportation, and industry. However, activities and processes – such as changes in land management, precipitation, and snowmelt and glacier melt – in upstream areas affect the spatial and temporal distribution of water in downstream regions (Nepal, Flügel, & Shrestha, 2014). The upstream–downstream relationship occurs at different scales, and generates both opportunities (such as water availability) and threats (flooding and sedimentation).

5.2. Do Changes in Land Cover Affect Downstream Water Flows?

LULC controls local hydrology, and substantially affects terrestrial hydrological budgets, through processes of interception, evapotranspiration, infiltration, soil-water storage, and surface run-off. This has complex effects on downstream areas, as water, food, energy, and climate are all linked through complex action–reaction systems comprising direct and indirect effects and feedbacks (Stonestrom, Scanlon, & Zhang, 2009).

The impacts of a changing LULC occur at multiple spatial scales, ranging from the catchment to the river basin scale (Bossa, Diekkrüger, & Agbossou, 2014; Krishnaswamy et al., 2013). The presence of vegetation provides opportunities for interception and infiltration and delays the response of precipitation to run-off. On the other hand, vegetation enhances evapotranspiration because of the presence of root zone in the soil from where soil moisture is transpired. Combining these complex processes, forest cover influences hydrological processes and the resulting run-off from hill slopes. This has been described for different run-off processes as follows:

Average flows: Many studies have suggested that deforestation in catchment areas results in greater stream flows, and that, conversely, afforestation leads to a corresponding decrease (Douglass & Swank, 1975; Gilmour, 1977;

Hamilton & King, 1983; Ives & Messerli, 1990). Hibbert (1967) made an experimental study of the effects of altering forest cover on water yields in 39 catchments. The results suggested that forest reduction increases water yields and reforestation decreases water yields. Bosch and Hewlett (1982) extended Hibbert's experiments and found similar results. These results indicate that increases in average annual flows are mainly caused by less evapotranspiration as a result of deforestation. This was confirmed by a respective model analysis published by Sun et al. (2005) from 38 forested catchments in the US and by Croke et al. (2004) from Thailand.

Peak flows and flooding: Peak flow occurs when precipitation flows over the surface due to saturation and limited scope for infiltration. LULCC is one of the factors that influences peak flows in downstream areas. The peak flow can decrease to some extent by providing more opportunity for infiltration (longer lag time and shallower rising limbs). Even so, infiltration is also dependent on soil properties, the type of vegetation, and the slope of the catchment. As suggested by Bruijnzeel (2004), reforestation and soil conservation measures can reduce enhanced peak flows and storm flows.

A study of the middle hills of Nepal also demonstrated that overland flows are reduced in natural forests as compared to degraded pasture (Ghimire, Bonell, Bruijnzeel, Coles, & Lubczynski, 2013; Ghimire et al., 2014a). In turn, Ilstedt et al. (2016) suggested that rainwater falling in an area near trees has more chances of percolation than that falling further away, which is likely to evaporate. For small catchments and moderate rainfall, vegetation can play a role in reducing the peak flow slightly (Nepal, Flügel, & Shrestha, 2014).

Contrary to popular belief, upstream vegetation has been shown to have only a limited role in downstream flooding, especially in large-scale events (FAO & CIFOR, 2005; Ives, 2004). On the other hand, when the capacity of the soil for infiltration is reduced, peak flows might increase (Bruijnzeel, 1990, 2004). But such effects are overshadowed when there is high intensity rainfall (Brooks, Folliott, Gregersen, & Thames, 1991; Bruijnzeel, 1990) along with saturated soil conditions. As suggested by Hamilton (1987), reforestation might not prevent flooding to any great extent in the lower reaches of major rivers, or significantly reduce flooding during major storm events. The impact of land use on peak flow generation is less visible in a large basin because of the differences in the basin's time lag between the different tributaries and spatial and temporal variations in rainfall and land use (Nepal, Flügel, & Shrestha, 2014).

Dry season flows: The infiltrated water, after meeting the field capacity requirements in soil water, further percolates into shallow and deep groundwater aquifers. The water from these aquifers gets released to the surface over time, which sustains the river's base-flow run-off, especially during the dry seasons. The impact of land use change on dry season flow depends on the infiltration capacity of the land cover and evapotranspiration by plants.

Studies point to the complex relationships between LULC changes and dry season (base) flows. Most of the experimental evidence in rainfall-dominated regimes suggests that forest removal (or a change from plants that need more water to those that need less) enhances dry season flows (Brooks, Folliott, Gregersen, & Thames, 1991). Bruijnzeel (2004) argued that there is a lack of documentation on the effects of reforestation on the increase of base flows. He also indicated that it may depend on the water use of the newly-planted trees and cumulative soil erosion during the post-cleaning phase, which may reduce soil water storage.

On the other hand, if the soil infiltration capacity is reduced after deforestation (as a consequence of anthropogenic processes such as machinery work, compaction of soil, or an increase in areas that are impervious to infiltration such as roads and settlements) in the rainy season, it might cause less water to go into an underground storage and, subsequently, the dry season flow is reduced (Beven, 2001; Bruijnzeel, 1990; Bruijnzeel & Bremmer, 1989).

In contrast, if the soil surface is maintained after deforestation and there is enough infiltration, the dry season flow will increase due to the lower evapotranspiration associated with forest removal (Bruijnzeel, 2004). Bruijnzeel (1990) summarized to the effect that dry season flows diminish in case infiltration opportunities are reduced and less water reaches groundwater storage reservoirs.

As reported in Kiersch (2000), a large-scale pine afforestation in 60,000 ha of watershed previously covered by grassland resulted in a reduction in dry season flows of 50%–60% in Fiji (FAO and CIFOR, 2005). A pine forest tends to reduce undercover vegetation – due to the acidic nature of pine needles – which enhances overland flows. A surface with fallen needle leaves causes more surface run-off (and less infiltration) than in a deciduous forest. This may cause a reduction of dry season flows, which is reported widely through the middle hills in Nepal. For instance, Ghimire et al. (2014b), based on their study in the middle hills of Nepal, reported that the limited amount of infiltration allowed by the pine plantation proved insufficient to compensate for the higher levels of water used by pine trees through transpiration, which get reflected in the observed declines in dry season flows. The pine forests' vegetative water use was found to be 580 mm (compared to 225 mm by pasture, and 525 mm by natural forests). In contrast, the extra infiltration afforded by the pine plantations was just 90 mm (compared to 285 mm in natural forests). This may be the cause of the drying springs in the mid-hills of Nepal, especially below a pine forest. However, more studies are required to conclusively establish a firm relationship between pine plantations and their effects on dry season flows.

Helmschrot (2006) showed that after afforestation, the low (base) flow during the dry season decreased by 48% in the Weatherley catchment in South Africa. A scenario of deforested land in eastern Nepal indicates that evapotranspiration will decrease, but because of a low infiltration rate – realized through the model application – the dry season flow might decrease as well (Nepal, 2012).

Schilling and Libra (2003) reported a significant increase in base flow components (annual base flow, annual minimum flow, and annual base flow percentage) in the Iowa catchment in the United States. The improvement was attributed to improved land management and conservation practices, greater artificial drainage, increasing row crop production, and channel incision. This had improved infiltration into the underground storage and thereby sustained a higher base flow in streams.

Vegetative cover, springs, and hydrology: Springs – which are underground water systems – constitute a very important component of the hydrological cycle in the mid-hills of the Himalaya. Springs are groundwater discharge points in the mountains where the water-bearing layer (the aquifer) intersects with the surface, and water seeps out of rock pores, fissures, fractures, or depressions. Springs are the main source of water for millions of people in the mid-hills of the HKH. There is, however, increasing evidence that springs are drying up, that they are becoming seasonal, and their discharge is reducing over the years. A study found that around 45% of the springs in one catchment in the central Indian Himalaya had dried or become seasonal (Tiwari, 2000). A survey of villages in another catchment in the same region found that there has been a decline in spring discharge by 25%–75% in the preceding 50 years (Valdiya & Bartarya, 1991). Chapagain, Ghimire, and Shrestha (2017) found that spring discharge in a mid-hill region in Nepal has declined by over 30% over the last 30 years. Given the paucity of long-term data, most of these results are based on the perceptions of local people. However, a recent study by Kumar and Sen (2017) used instrumentation and long-term monitoring to derive the flow duration curve of spring discharge and concluded that spring discharge had declined during the dry season in their study region in Uttarakhand (in the central Indian Himalaya), thereby confirming decades of anecdotal evidence.

A number of studies, based on people's perceptions, have attributed the drying of springs to an increase in temperature (Pandey et al., 2018); the late onset of rains and erratic rainfall patterns (Macchi, Gurung, & Hoermann, 2015); changes in land use, mostly the conversion of forests to agricultural land (Joshi et al., 2014); and the degradation of forests (Pandey et al., 2018; Rautela, 2015), including changes in forest types (Ghimire, Bruijnzeel, Lubczynski, & Bonell, 2012; Naudiyal & Schmerbeck, 2017).

Of particular interest to us in this paper is the relationship between springs and types of vegetation. The traditionally held view that tree roots, leaf litter, and soil act as a sponge and facilitate a greater infiltration of water than bare surfaces (Bruijnzeel, 2004) meant that a major proportion of the existing literature on springs attributed their drying to deforestation or the degradation of forest cover. Much of the argument as to whether or not having a good forest cover leads to better infiltration and recharge, and therefore higher spring discharge, and also what species of trees are most conducive for recharge, has so far been made using the perceptions of local communities and the expert judgement of authors. It is only in recent years that studies based on experimental and modelling data have been carried out to support these claims, but such scientific studies are still too few in number.

Birch et al. (2014) conducted a modelling study in Phulchoki forest – a well-preserved community forest and Important Bird and Biodiversity Area (IBA) on the outskirts of Kathmandu in Nepal. This forest has around 50 springs and provides drinking water to a large section of the population of Lalitpur city in the Kathmandu Valley. This study found that the replacement of the current state of community forests with an alternative state (incorporating other land uses such as agriculture and urbanization) would lead to only a marginal decline in the water quantity because the decrease in evapotranspiration would be neutralized by a decline in cloud water interception, leading to only a 5% decline in the overall water balance. However, the replacement of community forests would far more significantly impact water quality and both organic and inorganic non-point sources of pollution, as well as increase the overall sediment load several-fold. Joshi and Kothyari (2003) found that springs located in reserve forests yielded water that was suitable for drinking, whereas the water quality of springs in irrigated land and densely populated areas had a higher electrical conductivity, a lower dissolved oxygen concentration, higher nitrate content, and was unfit for human consumption.

To the best of our knowledge, papers by Ghimire, Bruijnzeel, Lubczynski, and Bonell (2012), Ghimire, Bruijnzeel, Lubczynski, and Bonell (2014), and Ghimire et al. (2014) are the only ones that use long-term experimental data to look at the hydrological impacts of natural, broad-leaved forests and mature planted pine forests. The large-scale plantation of pine forests started in Nepal in the early 1980s with the introduction of community-based forestry programmes. Pinus species were preferred by local communities and international donors due to their high survival rates and quick growth (Gilmour, 1990). Local residents in the mid-hills of Nepal have long believed that it was the introduction of pine species in the upper reaches (in recharge areas) that led to the drying of springs. This perception has been confirmed by various studies by Ghimire et al. (2012) who found that as a result of higher evapotranspiration of planted pine forests – particularly during the dry season – combined with the high use of forest products by local communities and a poor hydrological function of planted pine forests, there was an overall decline in dry season stream flow volumes and spring discharge in their study area in Central Nepal. The main conclusion of their work is that it is not enough to reforest a degraded forest and expect that hydrological functions would be restored. The species that has been planted, its water interception rates, and ongoing forest management practices are just as important a determinant of the restoration of hydrological functions, as the act of reforestation itself.

Based on the studies summarized in the above paragraphs, it is evident that the effects of land cover changes on downstream flows are complex. The removal of vegetation causes less evapotranspiration, which adds more water to the soil storage. However, if infiltration is compromised, dry season flows can reduce. There are also examples which show that having improved land management practices which allow better retention of water on the land surface improves base flows. Some recent literature links forest cover with the continental hydrological cycle and hence the need to look beyond the immediate watershed and further downwind.

5.3. Impacts of LULCC on Hydrological Processes

Bronstert, Niehoff, and Bürger (2002) highlighted the potential impacts of land use changes on hydrological processes and water availability (Table 2). They suggested that vegetative cover and management practices largely affect the different components of the hydrological cycle. For example, forest cover improves the dry season flow in streams via infiltration, which helps meet the water demands of riparian communities. At the same time, reforestation can lead to interception losses – as studies below suggest – indicative of the complex processes involved.

Processes like interception and evapotranspiration can affect hydrological processes at different scales. Ghimire et al. (2012), based on a study in the middle hills of Nepal, suggested that the interception losses of incident rainfall from planted and natural forests could be as high as 19% and 23% respectively. The study indicated that the high interception losses could be a contributory factor in the decline in dry season flows following the reforestation of degraded hills slopes in the middle hills of Nepal. Such observations were marked in the case of reforestation with pine trees. Liu, Yao, Huang, Wu, and Liu (2012) showed that evapotranspiration accounted for about 80% of run-off changes in the Yarlung Zangbo river basin in South-Central Tibet, the combined effects of increased forest land and air temperature.

Table 2: Potential impacts of land use changes on surface and near-surface hydrological processes and relevance for the hydrological cycle

Processes	Potential impact of land use change
Canopy interception storage	Greatly affected by changes in vegetation (for example, crop harvest, cutting of forests); relevant for evapotranspiration and energy balance
Litter storage	Affected by changes in vegetation, in particular the cutting of forests; relevant for evapotranspiration and energy balance
Root zone storage	Affected by crop and land management practices like tilling; relevant for evapotranspiration and storm run-off generation
Infiltration excess over land flow	Affected by crop management practices; relevant for storm run-off generation in the case of intense rainfall and low soil conductivity; may be enhanced by soil siltation and crusting
Saturation excess over land flow	Only slightly affected by land use changes (the process is controlled by topography and sub-surface conditions)
Interflow	Only slightly affected by land use changes (the process is controlled by topography and sub-surface conditions)
Run-off from urbanized areas	Highly affected by the sewer system and sewage retention measures; relevant for storm run-off from urban areas

Source: Modified from Bronstert, Niehoff, & Bürger (2002).

5.4. Complex Relationship Between Forests and Hydrology

Of all the major types of land use, the literature on the links between forest cover and hydrology is the most abundant, and indeed, forest hydrology is a distinct sub-discipline (Brooks, Folliott, & Magner, 2012). Three major strands of the relationship between forests and water have been distilled from the literature. These are paraphrased as: 'no forest-no water' or, alternatively, 'more forest-more water'. This is on the lines of the THED debate discussed earlier. The second perspective is 'more forest-less water', according to which it is argued that forests consume more water than other vegetation and large-scale afforestation decreases stream flows, especially dry season flows. The third and newly emerging perspective is that the forest–water relationship is much more complex, is usually quite context-specific, and varies according to spatial scales. This means that blanket policies like afforestation are not appropriate without understanding the wider context of climate change and other land use practices (Creed & van Noordwijk, 2018).

As suggested by Lorup, Refsgaard, and Mazvimavi (1998), various factors should be taken into account in assessing the impacts of land use changes on hydrology, such as a change in cropping and other management practices and a change in the area of land use categories. Bruijnzeel and Bremmer (1989) suggested that an important issue is whether the reforestation of severely degraded soils in the Himalayas would eventually lead to such improved infiltration conditions.

As discussed in Bruijnzeel (2004) and Krishnaswamy et al. (2013), there is a complex relationship in the nature of an 'infiltration–evapotranspiration trade-off'. The hypothesis predicts a net gain or net loss of base flows and dry season flows under both forest degradation and reforestation. It indicates that under certain conditions of land use and land cover changes in the tropics, the ability of a degraded forest to allow sufficient infiltration may be impaired to such an extent that the effects on delayed flows or dry season flows would be detrimental, even after accounting for the gains from reduced evapotranspiration.

A study by Roa-García, Brown, Schreier, and Lavkulich (2011) showed that natural forests have a larger capacity to store and release soil moisture than grasslands. This study supports the 'infiltration–evapotranspiration trade-off' hypothesis for tropical environments, which holds that after forest removal, soil infiltration rates are small, and water losses through quicker flows are larger than the gains from reduced evapotranspiration.

Further, as suggested by Krishnaswamy et al. (2012, 2013), a higher proportion of rain converted into run-off is associated with degraded forests, whereas natural forests showed the slowest run-offs. They also reported much higher quick-flow volumes from degraded forests and reforested, formerly degraded land, compared to less disturbed, natural forests, including much longer durations of low flows from natural forests, in contrast to degraded forests.

On the other hand, according to Ghimire et al. (2014b), in the middle hills of Nepal, the water use of natural forests and degraded pastures indicated that replacing the latter by mature broad-leaved forests would have a near-neutral effect on dry season flows, because the gains in infiltration and evaporative losses approximately balance out. However, as we have seen in the case of pine forests above, the effect is very different.

5.5. Role of Forests Beyond Hydrology

Mountain forests play a pivotal role in hydrology. The essence of a mountain forest has been highlighted in Lexer and Budgmann, (2017). However, the relationship between forests and water in the context of an upstream–downstream relationship is not linear. Complexity prevails as a result of many factors, including anthropogenic activities (Sun & Vose, 2016), ecosystem services (Luque & Iverson, 2016), and air quality-induced climate change (Keenan et al., 2014). This complexity is a consequence of various drivers, including climate change (Sheil, 2018).

The climate can influence water dynamics in forested ecosystems; one study suggests that changes in climate, forest structure, and species composition in unmanaged forests – brought about by disturbance and natural community dynamics – can result in large changes in water supply over time (Caldwell et al., 2016). There are studies on the effects of beetle attacks on forests (which may be getting more virulent or spreading into new areas because of climate change). The strong relationship between overall net ecosystem productivity, water flux, and water availability supports the argument that large-scale disturbance events are dependent not only on tree mortality but also on the responses of the remaining and new vegetation, "because mortality and recovery occur at the same time" (Reed et al., 2014). There is evidence of the direct influence of land use and land cover changes on water (Pan et al., 2015) and phenology (Mishra & Mainali, 2017) influencing ecosystem dynamics. Monocultures bring additional challenges for maintaining natural ecosystems (Chen et al., 2016).

Similarly, vegetation has a very strong role to play in controlling erosion in hill slopes. When soil cover is reduced, erosion accelerates in the absence of roots binding the soil. The transition zone in the Himalayan region is particularly likely to be affected by intense and continuous rainfall during the monsoon. When soil cover gets eroded, the ability of the soil to hold water and enable it to percolate to the groundwater level declines. In such a scenario, more water will flow overland, and dry season flows might decline. And during the monsoon season, when there is already excess water in the river channels, additional water is likely to amplify the magnitude of floods. The essence of the argument is that the linkage between forests and water is complex and influenced by many factors simultaneously, with complex interconnections between them. It is not prudent to draw conclusions from results derived from individual aspects of the forest hydrology processes.

The role of the forests should also be seen from a wider perspective. They provide wider benefits like controlling erosion and maintaining the soil profile, and supporting biodiversity and ecosystem services that can influence forest hydrology. This can also benefit local communities through income-generating activities. There is still a limited understanding and some uncertainty about this at larger scales. However, it is by now amply clear that forest ecosystems are vital to human well-being and there is a need to work on strong trade-offs among different functions (Diaz et al., 2018).

Recent research is increasingly more sophisticated and can better assess the impact of forest cover on a wider, continental scales, well beyond the smaller catchments that have traditionally been the unit of study of the forest–

hydrology relationship (Ellison, Futter, & Bishop, 2012; Ellison et al., 2017). These studies have shown that forests can impact water balance at a continental scale, and more conventional strategies like the thinning of forests to improve hydrological flows in the immediate downstream may indeed impact the overall continental water balance (Ellison, 2018).

5.6. Discussion Related to Upstream–downstream Linkages

- It is common understanding in forest hydrology that, on an annual scale, a reduction in forest cover increases stream flows, and afforestation decreases stream flows. But after deforestation, the overland flow may increase and the base flow decrease due to reduced soil infiltration rates in degraded lands. This has been explained as the 'infiltration–evapotranspiration trade-off' by Krishnaswamy et al. (2012, 2013) and Roa-García, Brown, Schreier, and Lavkulich (2011).

- The effects of vegetation on water flows are more prominent in smaller catchment areas, and less prominent in large-scale river basins. The role of vegetation in reducing floods might be prominent in low-to-moderate rainfall situations, in which the canopy allows for more infiltration. But during intense rainfall, as occurs in the monsoon season, the role of vegetation is overshadowed by the intense rains. After a few hours of rain, the soil likely gets saturated, and little or no water can infiltrate further. As a result, almost all additional precipitation generates surface flow and river run-off. Therefore, the infiltration and saturation access run-offs dominate the hydrological processes during such times of year.

- There are clear indications that deforestation might adversely affect the capacity of vegetation to control erosion. In the absence of roots binding the soil, soil erosion accelerates. When soil cover gets eroded, the ability of the soil to hold soil water and allow it to percolate to the groundwater level declines. In such a scenario, more water will flow overland and dry season flows might decline. It may also amplify floods. Therefore, the wider aspects of the role of forests should be taken into account.

- For these reasons, that one should remove forests in order to increase average water availability should not be taken as a justifiable argument. The issue and its complexity should also be considered, and over time. Although the average volume of water might increase, the increase would be in the monsoon because of a higher volume of overland flows. This means more flooding events might occur. Besides, the short-term benefits of an increase are likely to be outweighed by the medium-term loss of soil water storage capacity, due to the high erosion rate of exposed soil, and a potential longer-term loss of the entire soil profile (Nepal, Flügel, & Shrestha, 2014).

- Upstream–downstream linkages created by land use, land cover changes have a wider dimension. While most of the knowledge generated about this is through experiments at the catchment level, their effects and impacts may vary at a large scale. The quantification of the impacts of land use, land cover changes on stream flows might be more visible in small-scale catchments than large-scale ones.

- The combination of forest species and soil type predominate the forest–hydrology relationship, along with other factors. The complexity and combination of these variables need a thorough analysis to understand LULCC and changes in ecosystem services, particularly the provision of water.

6. Review Question 2

What are the Impacts of Erosion and Sedimentation on Downstream Areas of the HKH Region?

6.1. Overview

Many factors influence erosion processes in the HKH region – climate, topography, soil types, and vegetation cover, to name the most important ones. Studies across the globe suggest that the presence of forests and other types of vegetative cover are the most important factors in reducing soil erosion (Ochoa et al., 2016; Zuazo & Pleguezuelo, 2009). A changing land use, land cover affects surface erosion primarily through the exposure of the soil surface to rainfall. The removal of trees and shrubland from the fragile soil of the Himalaya has accentuated erosion and, to some degree, has had an adverse effect on slope stability and surface erosion as well (Ramsay, 1987). Surface erosion on gentle and moderate slopes and mass movement in steep slopes are quite common in the tropics (Sentis, 1997).

Erosion in the Himalaya is probably higher than in most other mountain systems in the world (Ives & Messerli, 1989). Jain, Kumar, and Varghese (2001) documents the fragile environment of the Himalayan region. Its steep slopes, constantly reducing forest cover, and high seismic activity, have led to rapid soil erosion and sedimentation downstream. Particularly in upstream areas – as in the Nepalese mountains – where 80% of the total land is mountainous and the areas are still tectonically active, soil erosion is a critical problem (Shrestha, 1997). People in upstream regions of the Himalayan river basins are vulnerable to landslides, mudslides, avalanches, and the collapse of built structures, which add to the rapid loss of topsoil there.

The midstream region, which comprises the Siwaliks and the Lesser Himalaya, is also prone to rapid erosion (Jain, Kumar, & Varghese, 2001). In the mid-hills of the Himalayas in Nepal, the key kind of LULC over the past 20 years has been a shift from forest cover to agricultural land. It has intensified the rate of erosion, raising concerns in downstream regions (Gardner & Gerrard, 2003). In India's Central Himalaya, Rao and Pant (2001) drew attention to the fragile ecosystem there, also threatened with constant erosion and landslides, especially during the monsoon.

The eroded material carried by the Himalayan rivers is deposited in the plains as the rivers enter the floodplains. In downstream areas, sediment deposition can affect the river morphology, and has the potential to shift river channels, as occurs in the transboundary Koshi River basin (Chakraborty, Kar, Ghosh, & Basu, 2010). This would affect agricultural land and human settlements.

6.2. Erosion's Causes and Processes

High seismic activity, the relatively young and fragile geology (Shrestha, 1997), and intense precipitation in particular are the major forces triggering land erosion in the HKH (Bookhagen, 2010).

Erosion caused by water, including raindrops, comprises sheet erosion, linear erosion, and mass movement (FAO, 2008a). The kinetic energy created by raindrops impacts the soil when it strikes the bare surface. This intensifies the process of erosion (Hebel, 2006). This phenomenon takes place in areas that lack forest cover and hence where the bare soil is exposed. The intensity of precipitation would influence the rate of erosion. During the monsoon season, when continuous rainfall for a few hours, and even days, is not uncommon, the soils get saturated, and get detached from mountain slopes. The soil particles lose their capacity to stay together. Therefore, mass wasting and landslides become quite common.

In high-altitude areas, processes such as freeze-thaw cycles and frost-cracking accelerate erosion by breaking down hill slope materials, as observed in the Bhutanese high Himalaya (Portenga et al., 2015). In the case of riverbank erosion in the Brahmaputra in Assam, Kotoky, Bezbaruah, and Sarma (2015) identified three active processes: (i) mass failure; (ii) fluvial entrainment; and (iii) sub-aerial weathering and weakening. This mass failure may come about because of the heterogeneity of the bank material.

Seismicity also influences erosion in the Himalayan region. In a study in the Greater Himalaya of Nepal, Burbank et al. (2003) suggested that the convergence of the Indian and southern Tibet Plates has caused persistent lateral and vertical transport of rock into the orogen. They concluded that this convergence along with the geometry of overthrusting strongly influenced the pattern of denudation across the Himalayan region.[3]

A number of overtly anthropogenic causes also contribute to or accelerate the process of erosion. Soil erosion may accelerate due to overgrazing (mainly trampling), agricultural activities, and deforestation. In an impact assessment in the Phewa watershed in western Nepal, Regmi and Saha (2015) found that the degradation of the watershed had mainly been brought about by deforestation, unplanned construction, landslides, and LULC changes, which all lead to erosion. Studies in the upper catchment areas of the Sindhupalchowk district in Nepal have shown that excessive grazing and the lack of vegetative cover have led to extreme erosion (Jackson and Tamrakar, 1998). The unplanned extension of mountain road networks has also contributed to a massive amount of soil erosion and landslides, which can be seen in many places in the middle hills of Nepal.

Erosion is a major threat to land resources and degrades water quality. It eventually causes the transport of sediment in rivers (Bookhagen, 2010). In the HKH region, landslides probably contribute the bulk of sediment load in the river, and they are quite frequent in the middle hills of the Himalaya (Bruijnzeel & Bremmer, 1989).

Erosion is also indirectly accentuated by the demand for firewood for fuel consumption, which is rising in the Himalayan region along with its population. The high consumption of fuelwood is likely to increase forest degradation, which in turns leads to high erosion. Wood and non-wood based biomass is the chief source of energy in rural areas of the Nepalese Himalaya (WECS 2011), and other countries in the HKH region. According to a study in South Asia (Rasul, 2014), 70% of the total population use biomass for cooking and heating. An IEA report (2006) estimated that 87% and 55% of the rural population in India and China respectively are dependent on biomass as their primary fuel for cooking. A study by The Energy Resources Institute (TERI) in 2005, summarized in Patil and Garud (2010), says that 91% of the total demand for energy of the residential sector in Bhutan was met by biomass, mainly firewood.

The extension of infrastructure is another factor contributing to an increased erosion rate in the HKH region. Recent developmental activities, especially the construction of new roads in hill areas, have made the already fragile geography of the area more fragile. Roads are being extended in many parts of the hills to facilitate economic activities and social traffic, but the price to pay for this development is hefty. Rural road construction in hilly areas may also be contributing to erosion. A study of the Trishuli–Kathmandu highway in the mid-hills in Nepal (Johnson, Olson, Manandhar, & May, 1982) found that highway construction had caused many changes in the geography of the area. The effects included cutting through terrace series, thereby interrupting the gradient and damaging fields, the removal of soil and stones, leading to disruption, changing the course of natural streams, and discarding waste soil in fields. Similarly, in the northern and eastern parts of the Indian Himalaya, Kothyari (1996) found that rapid road construction and mining had led to an increase in the rate of erosion.

6.3. How Much Erosion is Happening in the HKH Region?

The rate of erosion depends on many factors such as soil type, topography, vegetative cover, and precipitation. The rate of erosion may vary in space and time across the Himalayan region due to the variation in climatic and

[3] The recent earthquake in Nepal in April 2015 caused many landslides and mass movement in districts around the epicentre.

physical conditions. LULC changes, such as the shifts from forested land to other forms of land cover for agriculture, urban structures, or as barren land, increase the soil erosion rate considerably.

In a study in the Hilkot watershed, Pakistan, results from experimental plots showed that almost 50% of the run-off and loss of soil occurred during the monsoon season, whereas it was negligible in the winter or dry periods (Zokaib & Naser, 2011). Rapid erosion is observed in the Bhutanese Himalaya in the steep catchments. This is most likely facilitated by the high amount of rainfall associated with the summer monsoon (Portenga et al., 2015). The three major rivers of Nepal, the Gandaki, Karnali, and Koshi, transfer low volumes of sediment in the pre-monsoon season, because the rainfall normally only replenishes the groundwater table then. But during the monsoon, run-off on the hill slopes results in the transportation of a large amount of eroded materials to the rivers (Andermann et al., 2012b).

Erosion rates in the transboundary Koshi river basin show an increasing trend (Uddin, Murthy, Wahid, & Matin, 2016). For example, annual erosion increased from 40 million tonnes (mt) in 1990 to 42 mt in 2010. Table 3 shows the land cover, annual loss of soil, and mean soil erosion rates in the Koshi basin in 1990 and 2010. It shows a significant increase in built-up area. Among the types of land cover, barren land has the highest rate of soil erosion, nearly 22 tonnes per hectare a year (t/ha/yr), whereas the forested and built-up area has the lowest.

The HKH region, with its growing population and rapid urbanization, is facing an acute problem of the conversion of forested land into other land types, with subsequent higher rates of erosion. For example, the transboundary Koshi river basin has lost 205 km^2 of forest to other types of land cover between 1990 and 2010 (Table 3).

Table 3: Land cover and estimated erosion rates in the Koshi basin, 1990 and 2010

Land cover	Land cover area (km^2)		Annual soil loss ('000 tonnes)		Mean erosion rate (t/ha/yr)	
Year	1990	2010	1990	2010	1990	2010
Forest	20,032	19,827	601	991	0.3	0.5
Shrubland	679	670	231	261	3.4	3.9
Grassland	23,463	23,486	10,793	11,743	4.6	5
Agricultural land (kharif)	17,927	15,691	4,482	5,335	2.5	3.4
Agricultural land (rabi)	11,708	14,715	5,269	8,240	4.5	5.6
Barren land	8,245	7,081	18,057	15,437	21.9	21.8
Built-up area	99	268	0.5	2	0.05	0.08
Water bodies	793	572	56	11	0.71	0.19
Snow/glaciers	4,595	5,235	5	5	0.01	0.01
Total	87,542	87,542	39,495	42,025	-	-

Source: Uddin, Murthy, Wahid, and Matin (2016).

Regarding erosion from snow and glaciated areas, very few studies have taken into account the erosion induced by glaciers and other cryospheric processes. Burbank et al. (2003) suggested that the glaciated Upper Marssyangdi in Nepal has the potential to erode at rates of more than 5 mm/year despite relatively lower precipitation. Such rates in glaciated areas are equivalent to fluvial incision rates on the southern Himalayan flank, where precipitation is higher.

Table 4 refers to erosion rates for different soil types, mainly in the Nepalese Himalaya. In the protected and dense forests of the mid-hills, the erosion rate is as low as 1 t/ha/yr (Shrestha, 1997). Plots under farmers' control with good and bad land management practices give an erosion rate that varies between 2.8 t/ha/yr and 131.6 t/ha/yr (Ya & Nakarmi, 2004). The variation in the erosion rates in agricultural land may be related to the timing of crop cultivation and the intensity of precipitation. Controlled pastures may have a lower erosion rate of 1 t/ha/yr, while the rate for overgrazed pastures comes to 9.88 t/ha/yr.

Table 4: Variation in erosion rates for different land cover types

Land cover type	Location	Erosion rate	Source	Remarks
Rain-fed terraces	Likhu Khola catchment, mid-hills, Nepal	2.7–12.9 t/ha/yr	Gardner and Gerrad (2003)	
Farmers practice control plots	Mid-hills, Nepal	2.8–131.6 t/ha/yr	Ya and Nakarmi (2004)	Timing of crop cultivation and precipitation
Dense forest	Mid-hills, Nepal	1 t/ha/yr	Shrestha (1997)	Soil erosion assessment model from Morgan et al. (1984)
Overgrazed pastures	Mountains of Nepal	9.85 t/ha/yr	Impat (1981); Ramsay (1987)	
Controlled pastures	Transition zone of Nepalese mountains	1 t/ha/yr	Impat (1981); Ramsay (1987)	
Yak pastures	Mountains of Nepal	0.43–2.95 t/ha/yr	(Watanabe, 1994)	Intensive grazing during the growing season
Barren land	Koshi basin	21.9 t/ha/yr	(Uddin, Murthy, Wahid, and Matin, 2016)	Highest rate of all land cover types
Forests	Koshi basin	0.3 t/ha/yr	(Uddin, Murthy, Wahid, and Matin, 2016)	Lowest rate of all land cover types

6.4. Erosion Leading to Sedimentation

Eroded material from the mountain slopes collects in streams and constitutes a sediment load that is transported downstream. Downstream sediment yield is a complex function of upstream erosion processes, transport, deposition, and remobilization in the transition zone of the channel system. A constant interchange of sediments between floodplain and river occurs in the plain areas (Kotoky, Bezbaruah, & Sarma, 2015). Hence, the sediment load in downstream areas is the product of upstream erosion processes, land use practices, and the resulting rate of erosion. The complexity of erosion, transport, and sedimentation from upstream to downstream in a basin involves the fragile mountainous region, intense river flows at a high gradient, and plain areas where the sediment is deposited.

The denudation that happens in the Himalaya eventually contributes to the sediment transport in rivers such as the Ganges, Indus, and Brahmaputra. Wasson (2003) categorized the source regions of the sediment in order of significance: High Himalaya, Middle Himalaya, Siwaliks, Plains, and Tethyan (Tibetan) Himalaya. These regions have a complex network of rivers to carry the sediments further downstream. The rate of sedimentation in Himalayan rivers is even higher than the Amazon, the largest river in the world, which has an annual discharge of 6,300 cubic km/year and sediment yield of 195 t/sq km/year. On the other hand, the Ganges and the Brahmaputra have a combined annual discharge of only 971 cubic km/year but an exceptionally high sediment yield of 716 t/sq km/year (McLennan, 1993).

The Koshi River in the Nepalese Himalaya carries about 100 million cu m of sediment load each year, most of it during the monsoon (Dixit, 2009). This is indicative of the heavy monsoon that the southern side of the Himalayas faces, and its effects on erosion and sediment transport by various rivers. The sediment load deposited in the plains has formed the world's largest active alluvial fan (Gohain & Prakash, 1990) and also resulted in the Koshi River shifting by 113 km across Bihar over the past two centuries (Chakraborty, Kar, Ghosh, & Basu, 2010). This shifting of major rivers may be explained by the rising of riverbeds due to excessive in-channel sedimentation.

Wasson (2003) and Wasson et al. (2008) suggested though that the relationship between land use practices in upstream areas and the resulting sediment load in downstream areas in the Himalayan region was not clear, and that it was difficult to identify the role of human activities in the erosion and sediment transport system.

Wasson (2003) observed that in the Ganges river basin, around 62% of the sediment load for discharge had been measured. This would leave around 40% of the tributaries unaccounted for with respect to measuring sedimentation. The link between upstream erosion and downstream sedimentation is as complex and unclear as that of the effects of a changing land cover and deforestation on erosion at river basin scales.

6.5. Impacts of Erosion and Sedimentation

The intensive erosion and sedimentation that occur in the HKH region have various impacts on upstream and downstream populations. Excessive erosion leads to degradation of the soil. A direct impact of this is on food production, as land provides around 99% of the food humans consume (the remaining 1% comes from aquatic sources) (Pimentel, 2006). More specifically, with the degradation of land in the upstream HKH region, agricultural land is getting scarce and yielding a lower productivity. Agricultural productivity declines by around 4% for each centimetre of soil lost due to erosion (Bakker et al., 2005), as was found in an experiment on cereal farmland in Greece. Agricultural productivity declines as the supply of water, nutrients, and rooting space deteriorates. Farmlands have been converted to rangeland in the past century as a result of erosion (Bakker, Govers, Jones, & Rounsevell, 2007).

This erosion leads to sediment deposition, sometimes also referred to as silt. Depending on how much sedimentation occurs, it can have beneficial or deleterious effects. Sedimentation is mostly beneficial to farmers, as it increases productivity, but excessive sediment deposition will reduce the fertility of the land immensely. Silt can be trapped by dams that are constructed upstream. Nevertheless, over time, intense sedimentation has a detrimental effect on infrastructure like dams and canals, reducing their lifespan. In some cases, sediments are transported to the downstream side of a dam to provide farmers much-needed silt as fertilizer (Richter & Thomas, 2007).

The silt deposited by Himalayan rivers also impacts river channels. The rise of a riverbed due to siltation causes the river channel to shift and endangers human settlements by causing flood-related disasters. Studies have shown that villages in the Bagmati River basin in Bihar, India, are often in grave danger of being inundated because of the rising riverbed, which is decreasing the relative height of the embankments built to protect them (Jain & Sinha, 2003, 2004; Mishra, 2011).

Sedimentation resulting in rising riverbeds is also found in other major rivers that flow into the plains from the Himalaya. Sinha (2008) suggested there is enough evidence to show a siltation of canals and sediment budgeting related to rising riverbed levels in the plains. Sedimentation deposition contributed to the Koshi floods of 2008 which hit eastern Nepal and Bihar, and was believed to be the reason for a breaching of embankments (Dixit, 2009).

6.6. Discussion Related to Upstream–downstream Linkages

The role of vegetation and land cover, and their influence on erosion and sedimentation, has been intensely debated in the past. It included the processes that influence erosion in the headwater and transition zones, and the eventual deposition of sediments on the plains. Many studies have shown that reduced land cover increases the rate of erosion, especially when the soil is exposed to heavy rainfall. Vegetative cover reduces splash erosion from raindrops, and less surface run-off is generated, in favour of increased infiltration. The details about the erosion rates of various kinds of land cover have been presented in Table 4. Well-managed pastures and farmlands are known to stabilize erosion. Certain kinds of human activity, such as having unmanaged agricultural terraces, and overgrazing, tend to erode more than other forms of land use management. We focus below on the key issues of the discussion, pertaining to upstream–downstream linkages:

- The HKH region is geologically very fragile, and its rivers carry large sediment loads because of the intense rainfall during the monsoon. Soil erosion caused by human activity is likely to be very low compared to natural processes. However, much research is needed to quantify the attributions of overall human activities.
- The eroded materials from mountain slopes are deposited as silt in downstream plain areas, where it is considered to be a very fertile input for agriculture. On the other hand, the deposition of sediments in the reservoirs of large rivers has reduced the operational lifespan of the reservoir. The role of infrastructure in trapping sediment from the mountains is explained in Section 8.
- Disasters such as floods are common in downstream regions of the HKH, whereas in upstream regions, phenomena such as landslides are triggering erosion and contribute to sediment deposition rates. These landslides are caused by factors like intense rainfall, which is becoming more intense due to climate change (discussed in the next section), and steep slopes in upstream regions. Landslides can be countered by the proper management of soil through well-planned vegetation.
- Sediment downstream is not always the result of upstream land use practices (Wasson, 2003). In regions with high-intensity rainfall, a steep terrain, and a fragile geology, the relative impact of land use may be very low (Kiersch, 2000). In the Himalayan region, a combination of many factors is likely to be responsible, such as intense rainfall, bank erosion, landslides, and steep and unstable terrain (Bruijnzeel, 1990). Because of the complex terrain, not all the eroded materials reach the plains; a major part is stored or deposited in the stream network itself.
- The Higher Himalayan region is likely the major and dominant source of sedimentation. The Higher Himalaya contributes about 80% of the total suspended load budget in the Ganges–Brahmaputra catchment (Wasson, 2003).

7. Review Question 3

What are the Impacts of Climate Change on the Hydrological Regime and Downstream Water Availability in the HKH Region?

7.1. Overview

The last three decades have been the warmest at the global level, since 1850. Combined land and ocean surface temperature data show an average warming of 0.85 °C [0.65 °C–1.06 °C] over 1880–2012 (IPCC, 2014). More recent NASA/GISTEMP data suggests warming has reached 1.07 °C over that baseline by 2017 (Hansen et al., 2018).[4]

The impacts of climate change on different sectors have been widely discussed in recent years. A warming climate can affect the environmental system in different ways. It can cause changes in land cover, affect biodiversity and ecosystem composition, accelerate evapotranspiration, affect rainfall, and increase snowmelt and glacial melt. Its effects include variations in river flows, floods and flash floods, and altered groundwater recharge (Eriksson et al., 2009). All these would have major impacts on the water resources sector, which in turn would have implications for other related sectors, such as irrigation, drinking water, energy generation, and infrastructure.

Climate change affects all regions of the river basins in the HKH. The source zone and the transition zones depend on glacial melt – which is altering, as we shall see – during the dry season for agriculture. The floodplain zone is affected in the form of flooding, related erosion, and sediment load (Nepal, Flügel, & Shrestha, 2014). Climate change would influence land cover changes in the transition zone, the demand for water in the floodplain areas, and, importantly – given their significance in the HKH region – cryospheric processes in the headwater zone.

About 9% of the HKH region is covered with glaciers. The region has nearly 0.76 million sq km of snow cover on average, which is about 18% of the total land area. Snow cover varies in different seasons, between 4% and 43% of the total land area (Gurung et al., 2011). Rising temperatures, in combination with atmospheric pollutants (such as black carbon), have begun and will continue to accelerate cryospheric processes such as snowmelt and glacial melt. These changes will affect water supply and availability across time and space. Many glaciers in the region are losing ice volume. This has serious implications for downstream water availability, both in the short run and the long run (Eriksson et al., 2009). This is particularly pressing in the Indus basin, where discharge generated by snow and glacial melt is very significant (Miller, Immerzeel, & Rees, 2012; Lutz et al., 2014; Kraaijenbrink, Bierkens, Lutz, & Immerzeel, 2017).

7.2. Impacts of Climate Change on Water Resources

Climate change's impacts on water resources are due to changes in the patterns, state (solid or liquid), and amount of precipitation, and in temperature, and the resulting changes in evapotranspiration and melt rates of glaciers and snow cover. We present in this subsection some key impacts of climate change on water resources in the HKH region.

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[4]Greenhouse gas emissions from the HKH region are, overall, quite low. The contributions of countries that constitute the HKH vary widely, with China and India being the largest and third-largest greenhouse gas emitters in the world respectively. Others, such as Bhutan and Nepal, have extremely low carbon emissions.

Effects on snowfall: The duration of snow cover is very heterogeneous along the Himalayan mountain range: There is snow cover for about half the year in the western and eastern parts of the Himalaya, while it is very low in the Tibetan Plateau (Ménégoz, Gallée, & Jacobi, 2013). However, changes in climate and precipitation affect its distribution.

Due to an increase in temperature, the patterns of precipitation will change in high-altitude areas, with it occurring more as rainfall and less as snow. Consequently, basins can lose their overall snow storage capacity (Nepal, 2016). Having snowfall and snow storage in a basin means a longer retention time of water; gradual melting provides sustained flows to a river, particularly during the dry season, whereas rainfall can reach a nearby stream relatively faster and earlier than snowfall. Eriksson et al. (2009) stated that these changes in the form of precipitation in the higher regions of the Himalaya have decreased the storage of water in the form of ice and snow.

Global warming leads to a decreasing snowfall pattern in winter, early spring precipitation, and the reduction of snow-covered areas, as noticed in the Pir Panjal range in the western Himalaya (Bhutiyani, Kale, & Pawar, 2010). Snow cover has substantially decreased in most of the Tibetan Plateau from 2000–2011 during January to April (Wang, Peng, Lin & Chang, 2013). Similarly, in Nepal, a negative trend in winter snow cover between 3,000–6,000 masl and a positive trend in autumn snow cover above 4,000 masl have been observed (Maskey, Uhlenbrook, & Ojha, 2011).

Changes in evapotranspiration: Climate change has a direct impact on evapotranspiration, through an increase in solar radiation, a rise in temperature, and an increase in the water vapour deficit (Abtew & Melesse, 2013). As suggested by Chattopadhyay and Hulme (1997), future warming seems likely to lead in general to increased potential evapotranspiration in India, although this increase will be unequal between regions and seasons. In contrast to this, both pan-evaporation and potential evapotranspiration have decreased constantly in the northern hemisphere (Chattopadhyay & Hulme, 1997; Golubev et al., 2001; Peterson, Golubev, & Groisman,1995). Besides reducing water availability in downstream areas in general (discussed below), higher evapotranspiration could cause greater stress on soil moisture.

Melt run-off and streamflows: The upstream preservation of water, in the form of snow and ice, is of extreme importance for water supply to people downstream when they need it. An important impact of climate change on water resources in the HKH is a change in melt run-off from snow- and glacier-dominated basins in high-altitude areas. Any changes in the melting processes at high altitudes will directly affect the water availability in downstream regions.

Snowmelt and glacier melt contribute significantly to streamflows in downstream areas, in some rivers more than others.[5] The Indus in particular depends heavily on run-off originating from snow and glacier melt. It accounts for around 50% in the eastern Hindu Kush, Karakoram, and Western Himalaya (Winiger et al., 2005). In the Upper Indus Basin (UIB), glacial meltwater contributes 40.6% of the total run-off (Lutz, Immerzeel, Shrestha, & Bierkens, 2014). Water flows from the Indus are set to increase in the short term, but will decrease in the long run (Iqbal, Akhter, Ashraf, & Ayub, 2018; Miller, Immerzeel, & Rees, 2012).

Meltwater contributes about 11.5% of the total run-off generated in the Upper Ganges basin and 16% in the Upper Brahmaputra. Despite a lower annual contribution, the contribution of meltwater during the pre-monsoon season can be significantly high. For instance, the annual contribution of meltwater from the glacial area in the eastern Dudh Koshi River in Nepal was found to be 17%, but during the pre-monsoon season, it was as high as 65% (Nepal, Krause, Flügel, Fink & Fischer, 2014). Melt run-off is generated mainly in the summer season when the downstream water demand is high (Singh & Bengtsson, 2004).

[5]The snow-dominated Kabul River peaks in spring, whereas the glacier melt-dominated Indus peaks in summer. Similarly, in the central and eastern river basins, the melt run-off coincides with the summer monsoon period.

Under a future glacier scenario for 2046–2065, mean upstream water supply decreases in all three major basins, the Upper Indus (–8.4%), the Ganges (–17.6%), and Brahmaputra (–19.6%) (Immerzeel, van Beek, & Bierkens, 2010). In contrast, the mean upstream rainfall increases in these basins (Indus +25%, Ganges +8%, Brahmaputra +25%), compensating for the reduced melt flows. A more recent study by Lutz, Immerzeel, Shrestha, and Bierkens (2014) indicated that the modelled results based on RCP 4.5 and RCP 8.5 suggest that the annual run-off will increase by 7%–12% by 2050, primarily because of accelerated melting in the Upper Indus basin and increased precipitation in the Ganges and Brahmaputra basins. Laghari, Vanham, and Rauch (2012) suggested that water availability might increase in the short term in the Indus, but would decrease in the long term. Nevertheless, the projected future hydrology depends mainly on projections about precipitation. These projections have a large uncertainty and variation between annually averaged and seasonal projections among the GCMs.

Other studies of individual river catchments suggest similar patterns. In the eastern Dudh Koshi river basin, climate change might increase the annual discharge by 13% by the end of the century. However, the increase in discharge is most likely to be in the form of surface run-off, which might cause more flooding events than the baseline period 2000–2010 (Nepal, 2016). In the larger Koshi River basin, little impact is projected at the full-basin scale, but sub-basin scale precipitation is projected to decrease in the lower sub-basin in the 2030s, and increase in the upper basin in the 2050s (Bharati, Gurung, Jayakody, Smakhtin, & Bhattarai, 2014). This study suggested that projections regarding impacts are likely to be scale-dependent.

In the Sutlej river basin, changes in the distribution of melt run-off were found to be more pronounced in summer, when the decrease is expected to be about 10% for a projected temperature increase of 2 °C (Singh & Bengtsson, 2004). In the Brahmaputra river basin, Prasch et al. (2011) suggested that glacial ice melt will accelerate from 2011 to 2040 due to the increase in air temperature and longer melting periods, and that as the volume of glacial ice reduces, ice melt will decrease.

For the Brahmaputra, Mirza (2002) projected a substantial increase in mean peak discharge (although less than in the Ganges) based on climate change scenarios from four GCMs, which indicated more frequent flooding of different magnitudes. Ghosh and Dutta (2012) estimated an increase in both peak discharge and flood wave duration for the Lower Brahmaputra under the regional climate model PRECIS's A2 scenario, in both the pre-monsoon and monsoon seasons. The increment in peak flows in the monsoon season is likely to be greater for moderate events and lesser for extreme events with higher return periods. Gain, Immerzeel, Weiland, and Bierkens (2011) too indicated that there will be a strong increase in peak flows, both in size and frequency, in the Lower Brahmaputra, although dry-season conditions are likely to increase. Wijngaard et al. (2017) suggested that there will be increases in the future mean discharge and high flow conditions towards the end of the twenty-first century in the upstream Indus, Ganges, and Brahmaputra river basins. The 50-year return period discharge level in particular will increase in magnitude and frequency.

Overall, studies suggest that while the total annual water availability may increase, at least in the short to medium term, the increase in hydrological extremes and shifts in seasonal peaks may counteract these benefits to some extent. For example, an increase in precipitation in the monsoon might accelerate flooding events in downstream areas. Similarly, a short-term increase in streamflows might occur due to enhanced melt run-off from glaciated areas, but when glacial storage reduces, the dependent streamflow might decrease as well.

Recent studies suggest that the extreme flows are likely to increase in the future due to climate change. While climate models have large uncertainties in projecting extreme events, available information suggests the likelihood of a significant increase in extreme hydrological events in the HKH basins (Mirza, 2011; Lutz, Immerzeel, Kraaijenbrink, Shrestha, & Bierkens, 2016; Wijngaard et al., 2017). Wijngaard et al. (2017) suggests that on average there will be a roughly 100% increase in the 50-year return period floods in the upstream parts of the HKH river basins. Similar changes are projected in the Upper Indus Basin (Lutz, Immerzeel, Kraaijenbrink, Shrestha, & Bierkens, 2016).

7.3. Impacts of Climate Change on Upstream–downstream Linkages

Downstream populations rely on run-off from mountain areas to meet their water requirements. However, climate change causes fluctuations in water availability for these downstream communities.[6] For instance, changes in precipitation and snowfall into run-off have a direct impact on water availability in downstream areas (Eriksson et al., 2009).

The impacts of climate change on water availability in downstream areas indicate that its impacts could vary in river basins, based on different factors such as climate and precipitation patterns. In the Upper Indus basin, increasing early melt season discharge from most of the sub-regions is reported, which is likely due to more rapid snowmelt. Similarly, a decreasing or weakly increasing discharge is observed from the corresponding sub-regions during the mid-to-late melt season (Hasson, Böhner, & Lucarini, 2017). Another study in the same basin revealed that hydrological change is highly dependent on the season in which the change occurs (Archer and Fowler, 2006). These changes include summer cooling and winter warming. This affects the rapid run-off from snow and glaciers and reduces the duration of storage as ice and snow.

Reservoir systems such as in the Indus River store meltwater generated from upstream areas, for use in downstream regions, for instance as much-needed irrigation water. Any changes in the hydrological regime are likely to impact downstream irrigation water users (Immerzeel, van Beek, & Bierkens, 2010).

Another kind of linkage pertains to warming-induced changes in evapotranspiration. It may affect the water balance and water availability in downstream areas. Basically, higher evapotranspiration will cause more water to be lost through water vapour and less water would be available downstream.

Water-induced hazards in both upstream and downstream areas are an important aspect. The rapid melting of glaciers has not only affected flows downstream, but also swelled glacial lakes in upstream areas of the HKH region, mainly in Nepal, India, Pakistan, Bhutan, and the Tibet Autonomous Region, China. Most of the glacial lakes are dammed behind unstable moraines. These lakes are a serious threat to downstream communities due to a phenomenon known as glacial lake outburst floods (GLOFs) (Mool, Bajracharya, & Joshi, 2001). There are many instances in which GLOFs have significantly damaged downstream properties and affected communities. For example, a 1985 GLOF in the Dudh Koshi River basin in eastern Nepal damaged the nearly completed Namche Small Hydroelectric Project and caused other damage further downstream (ICIMOD, 2011). Similarly, landslides blocking rivers and causing landslide dam outburst floods (LDOFs) have become more frequent, such as at the Sunkoshi dam (in eastern Nepal) in 2014.

In Nepal, the glaciated area decreased by 25% from 1980 to 2010, and the number of glaciers rose, from 3,430 to 3,808 (11%). In Bhutan, about 23% of the glaciers have decreased in area (Bajracharya, 2014). In both cases, small glaciers increased in number because of fragmentation, whereas larger glaciers have become smaller. From 2001 to 2009, the number of glacial lakes in Nepal had reduced by 37% and the glacial area by 14%. Very small supra-glacial lakes had appeared and merged to form a larger glacial lake (ICIMOD, 2011). The same study identified 21 potentially dangerous glacial lakes in Nepal.

Potential GLOF events may directly impact communities living downstream near riverbanks and floodplain zones. Infrastructure such as dams, bridges, and houses may also be destroyed. The bursting of unstable moraine dams of these glacial lakes releases a huge amount of sediment. These may be deposited downstream and damage structures such as dams, irrigation canals, and fields. Khanal et al. (2015) calculated that the cost of a GLOF of the Imja glacial lake could be about USD 11.8 million; the subsequent flooding could cause serious damage downstream.

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[6]Upstream regions are also regarded as vulnerable and sensitive to climate change, because meltwater and glacier run-off are important factors in run-off dynamics, subsequently affecting agricultural practices (Chaudhary & Bawa, 2011).

7.4. Discussion Related to Upstream–Downstream Linkages

The following points can be underlined in relation to the impacts of climate change and its effects on upstream and downstream areas:

- Overall, in all three river basins of the Indus, Ganges, and the Brahmaputra, projections indicate a reduction in snow (and thus snowmelt) and an increase in glacial melting approximately until the mid-century, followed by a decrease. Although there is likely to be an increased volume of meltwater available for the next few decades, this amount might decrease abruptly thereafter as glacial storage is reduced. The exact timing remains uncertain.
- Many studies indicate that climate change has effects on the hydrological regime of the river basin in terms of water availability and disasters. In the HKH region, snowmelt and glacier melt run-off play a significant role in water availability. There is evidence that the rapid melting of glaciers and snow increases the amount of run-off in the short-term, but this will eventually lead to reduced run-off in the long-term.
- Climate change impacts will not only be limited to gradual changes in water availability, hydrological extremes will also become more common in future, towards the end of the twenty-first century. In Nepal, intense precipitation events are likely to increase in frequency, with extremely wet days expected to increase at a higher rate than very wet days. This will occur in combination with an increase in the intensity of precipitation. Hydrological extremes can cause widespread damage in downstream areas in the form of landslides and flash floods that damage property and infrastructure. Downstream communities can suffer huge losses in the event of flash floods and GLOFs.
- Climate change may affect the type of vegetation and its dynamics in upstream regions, such as vegetation shifting upwards due to rising temperatures. Specifically, this may affect the hydrological cycle with respect to infiltration, evapotranspiration, and interception.
- River basins such as the Ganges are less affected by climate change as far as hydrology is concerned, because it is mainly rainfall-dominated, but the Indus is highly affected, being fed heavily by glaciers and snowmelt.
- The IPCC's Fifth Assessment Report (AR5) suggests that warming is likely to continue. This trend will likely extend for long, which will pose threats to downstream areas in the form of variability in streamflows, floods and flash floods, and potential GLOF events.
- New issues are emerging such as the deposition of black carbon on snow and glaciers, causing a possible acceleration of melting processes. Concerns have also been raised about the impacts of climate change, not only on water availability in general, but on hydrological extremes such as seasonal shifts, and the frequency and magnitude of floods. An improved understanding of such processes would help design better mitigation measures and adaptation practices.

8. Review Question 4

What are the Impacts of Water-related Infrastructure Development on Downstream Water Availability?

8.1. Overview

The HKH region stores water in the form of glaciers, snow, permafrost, natural lakes, wetlands, and groundwater aquifers. It holds the largest amount of ice outside the polar regions. Besides these natural storage systems, human-made reservoirs such as dams also store some amounts of water. They have been widely used for irrigation, hydropower, navigation, and drinking purposes (ICIMOD, 2009). Water infrastructure in a broad sense are systems of water supply, treatment, storage, water resource management, flood prevention, and hydropower. It can also include water-based transportation systems such as canals.

The region in general receives a large amount, and proportion, of its precipitation during the summer monsoon season, even as water shortages with respect to agricultural and domestic uses regularly occur in the remaining months (Merz et al., 2003). The high dependence on agriculture makes the demand for irrigation water relatively high in the region. For example, the Indus river basin supplies water for 90% of the food production in Pakistan, which contributes 25% of the country's gross domestic product (Qureshi, 2011). This is largely possible due to the largest irrigation network in the Indus which is regulated through two major dams.

Balancing too-much and too-little water variability is crucial for water-related developments. Sustained water availability in the region demands adequate water infrastructure such as irrigation canals, dams and other water-storage structures. There are mainly two types of water storage practised in the HKH region: (i) local-scale water storage structures, such as ponds, used mainly for domestic purposes and irrigation; and (ii) dams and water reservoirs for multi-purpose objectives. These structures can store water during the monsoon or periods of rainfall, and can enable its use when and where there is a water shortage. The construction of dams for hydropower and for irrigation is gaining pace in the entire HKH region.

8.2. The Development of Infrastructure

Water scarcity is a major concern for the people living in the HKH region. To adapt and help build resilience, various measures have been taken in this region for centuries, such as the construction of irrigational canals.

Despite the fact that the region is rich in water resources, the inability to harness those resources has led to water shortages, especially for upstream communities. Traditionally, mountain communities had developed their own methods of storing water, by building terraces on their fields, along with small-scale irrigation systems (Molden, Vaidya, Shrestha, Rasul, & Shrestha, 2014). This kind of infrastructure can still be found in upland areas of the HKH, and has the added advantage of helping in holding back the soil. But with the increasing demand for water, better and larger irrigational infrastructure was required.

This led to the construction of larger irrigational structures as early as 1848, when the Upper Ganga Canal System was built in the upstream region of the Ganges in Uttar Pradesh, India (FAO, 2008b). Pakistan has two large storage dams, the Tarbela in the Indus and the Mangla in the Jhelum, both situated in the Upper Indus basin (STIMSON, 2013), and the world's largest contiguous irrigation system that millions of people downstream rely on (Kahlown, Khan, & Azam, 2006). The existence of such dams has become more important in recent periods for upstream and downstream communities to manage and store excess water during the monsoon and distribute water for irrigation during the dry season.

Embankments have also been built on a massive scale to control river flows and reduce flooding during the monsoon season. About 34,000 km of flood embankments has been constructed in India, especially in the North and North-East (Mazumder, 2011). This region is most often affected by floods, when the rivers come coursing down from the Himalaya to the plains downstream.

The development of hydropower is also expanding in the development of HKH nations. The region's combined hydropower capability exceeds 500 GW (Vaidya, 2012), with infrastructure development encouraged by governments of the region. In the upstream regions of the Ganges River basin, for instance, especially in India, Nepal and Bhutan, the construction of dams for hydropower and irrigation is gaining pace (Bharati et al., 2011). In India alone, there are 5,254 large dams[7] overall, and a further 447 large dams are under construction. The Indian states that lie in the HKH region – Bihar, Himachal Pradesh, Jammu and Kashmir, West Bengal, and Nagaland – have 24, 19, 14, 29, and 1 dam respectively (CWC, 2017). Pakistan has 12 dams with a total capacity of 43.35 MW (WAPDA, n.d.). In the transboundary Indus River basin, around 60 barrages and 43 canal heads with 48 off-takes have been built since the Indus Water Treaty of 1960. These structures contain thousands of canals and a water-course network irrigating around 42 million acres of land (Laghari, Abbasi, Aziz, & Kanasaro, 2015).

Due to the heavy demand for power, countries such as Pakistan, India, Bhutan, and Nepal have initiated large hydropower development in the Himalaya. This could lead to a capacity addition of over 150,000 MW over the next 20 years (International Rivers, 2008). Both medium and large-scale hydropower, either small raised dams (for run-of-the-river projects) or large dams of a few hundred metres in length can affect the environment of upstream and downstream areas, though the impact of the former is considerably less than the latter. However, the impacts of run-of-the-river projects, on altered flows for particular ecosystems, could be huge.

Clean energy such as hydropower is needed to maintain economic growth sustainably and improve the livelihoods of mountain people, who still rely on firewood for fuel. However, producing power and energy for urban centres and industry at the expense of mountain livelihoods and landscapes will bring great unevenness in the distribution of costs and benefits of such development (ICIMOD, 2011). Economic development should recognize the role of the mountain communities in maintaining and conserving the mountain environment, which contributes to sustaining river flows for the development of energy sources. This necessitates the design and implementation of appropriate benefit-sharing mechanisms (Shrestha, Lord, Mukherji, & Shrestha, 2016).

8.3. Conflicts Surrounding Infrastructure Development

As suggested by Merz et al. (2003), too much and too little in the middle mountains of Nepal gives rise to problems such as floods, surface erosion, landslides, and droughts. This problem not only triggers the existing water scarcity but may also lead to conflict during the dry season, especially when the supply is less than demand.

Water infrastructure helps reduce the spatial and temporal variability in water availability. This can however also create problems of access, deprivation, inequity, and environmental impacts. The development of infrastructure, especially dams, has a long history of politics and controversy, and has given rise to ethical questions related to the environment and the people living in their vicinity. The debates around large dams have been especially polarized. Critics point to a wide range of negative environmental and related social effects, from the destruction of biodiversity to the displacement of people (Ledec & Quintero, 2003).

The Three Gorges dam in China, for example, is a project that has attracted various criticisms about its environmental impacts. It was said to have affected the lives and habitats of around 20 million people upstream and 300 million people downstream, and in particular the biodiversity of the Yangtze River through the immense reduction of fish species such as carp, which is essential to the livelihoods of local communities (Jackson & Sleigh, 2000; Stone, 2008).

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[7]According to International Rivers, a dam higher than 15 metres is categorized as a high dam.

In the Indian Himalaya, there have been numerous instances in which locals have staged anti-dam struggles protesting their negative effects on biodiversity, ecology, and their livelihoods. For instance, such struggles have been waged in the Jongu region of Sikkim with respect to the Lower Subansiri dam on the Brahmaputra, and against various dams on the Tirthan river in Himachal Pradesh, and other hydropower projects in Rajasthan, and in Uttarakhand (Blue Planet Project, 2013). Some of these struggles against these dams are still being waged by local communities.

Transboundary tensions: Dams built on transboundary rivers can cause frequent tensions between nation states. For example, the construction of the Farakka barrage on the Ganges River has given rise to persistent friction between India and Bangladesh regarding water sharing. India's motive for building the dam was to reduce mud and silt emission from the Bhagirathi–Hooghly canal and the Kolkata harbour (Haftendorn, 2000), thereby overlooking the economic benefits it could get from navigation. Bangladesh had earlier opposed a plan proposed by India as a riparian country to divert water from the Brahmaputra River to the Farakka by a link canal, for it would have adverse effects on the fertility of agricultural lands downstream (Hossain, 1998). There are numerous examples of water infrastructure built by downstream countries for their benefit in the upstream countries, such as irrigation infrastructure built in Nepal by India and hydropower infrastructure in Bhutan built by India. The case of Indo-Nepal water infrastructure development is marred with dissatisfaction, with both parties having deep concerns (Gyawali & Dixit, 1999; Malhotra, 2010).

Such conflicts related to hydropower infrastructure are mainly due to the lack of a basin-wide impact assessment and poor governance arrangements. It is useful to consider other dimensions, such as multiple uses and users of water, transboundary basin agreements, and risk management (Ahlers, Budds, Joshi, Merme, & Zwarteveen, 2015; Erlewein, 2013). As indicated by Hanasz (2017), transboundary water issues in South Asia have been addressed through bilateral, rather than multilateral approaches. This framework lacks the capacity for problem-solving through collective action by stakeholders.

8.4. Benefits and Risks of Infrastructure

Similar to the conflicts that surround the construction of dams, the benefits and risks associated with the development of infrastructure are highly polarized by the common person and policy makers alike.

There are advantages and disadvantages to the development of large infrastructure (such as dams and embankments) in upstream and downstream contexts. Structures such as barrages and reservoirs can address the problem of water scarcity and flooding in downstream regions. For instance, the Aswan high dam in Egypt has saved the region from both droughts and floods. From 1981 to 1987, the high dam storage allowed 55 billion cu m of water to be released annually downstream, and during the 1975 floods, the third-highest on record, excess water was contained within the reservoir, thereby saving downstream areas from catastrophic damage (Scudder, 2003). The dam has also increased the availability of water for agricultural planning, and the cropping area has expanded (Abu Zeid & El-Shibini, 1997). In the Indian part of the transboundary Koshi river basin, massive embankments have been constructed since 1959. The region is divided into many sub-basins with embankments, which are protecting infrastructure, such as roads, irrigation channels, and the railways, from flooding (Dixit, 2009). However, thousands of people are residing inside the embankments and flood-prone areas, making them vulnerable to annual flooding, river cutting, and the shifting of river channels.

New water resource infrastructure could also have other benefits. It may reduce the risks associated with climate change, hydrological variability, and their impacts on water resources and systems (UNESCO, 2012). Hydropower generation in countries such as China and India has led to an increased interest in the potential of mountainous areas to generate renewable energy. There is a resurgence of large hydropower dams that supply surrounding downstream areas with low-carbon energy (Erlewein and Nüsser, 2011). The Three Gorges Dam on the Yangtze River in China, the largest project of its kind in the world, has three main purposes: to control recurring floods, to improve internal navigation, and to generate hydropower (Xi, Hwang, Feng, Qiao, & Cao, 2007). It is designed for an expected generation of 84.7 billion kilowatt-hours of electricity annually, equal to, and hence avoiding, burning 50 million tonnes of coal (Stone 2008). Another purpose was to help the unnecessary siltation of reservoirs like the Dongting Lake, whose capacity for holding excess water is decreasing (William & Freeman, 2005).

Irrigation canals, which form the backbone for agricultural livelihoods in the HKH region, are providing much-needed water for millions of hectares of agricultural land. Traditional irrigation, such as spate irrigation and farmers-managed irrigation systems (FMIS), is still prevalent. In the arid province of Punjab in Pakistan, the construction of small-scale dams has resulted in higher crop yields and earnings of farmers (Ashraf, Kahlown, & Ashfaq, 2007). Canals and dams also have the capacity to replenish groundwater recharge.

Small-scale water storage options (such as rainwater harvesting) could offer storage of monsoon precipitation for agricultural and household uses for an entire year. A rainwater harvesting system may ensure local water availability and ecosystem services in a watershed and help build mechanisms to facilitate upstream and downstream linkages. On a local scale, both upstream and downstream communities may benefit via a compensation mechanism from the use of water resources. And given that the externalities are positive, these storages can yield a higher aquifer recharge (Vaidya, 2015).

Negative effects: Notwithstanding all these benefits, the construction of big dams or related infrastructure does not come without a hefty price, which affected communities often have to pay. Hydropower development affects the resource use patterns by communities, since extensive alterations of fluvial systems happen in the process (Erlewein, 2013). Large-scale dams can alter natural flows downstream which may affect the river morphology, ecosystem, and water-dependent livelihoods. For instance, in downstream regions of the Ganges River basin, the construction of dams and irrigation canals upstream is altering the flow of the river and adversely affecting the water quality and availability, indeed the riverine ecosystem itself (Bharati et al., 2011). Singh (1990) stated that the Farakka barrage had cost people in downstream regions of Bangladesh by reducing the silt flow. This has affected soil fertility, even as the ingress of salt water up the river has had negative consequences.

Countries in the HKH region rely heavily on agriculture for their economic activities, so interference with fluvial flows can have potentially adverse effects. For instance, in Pakistan, downstream discharge into the sea has reduced sharply in the Indus River basin due to the construction of a vast network of irrigation canals, barrages, and associated structures. After the development of the Indus basin irrigation system, the water and sediment transported decreased from 108 billion cubic metres (bcm) and 225 billion tonnes (Gt) respectively, to 48 bcm and 50 Gt respectively (Laghari, Abbasi, Aziz, & Kanasaro, 2015). Such negative impacts are also illustrated by Tahmisciolu and Anul (2007), in situations in which dam construction and sediment contained in reservoirs in general will lead to a change in the water regime.

In the case of embankments, their use to control floods has been strongly critiqued, in particular in the case of rivers with a high sediment load. The sediments tend to get deposited in plain areas downstream, and raise the level of the riverbed. In the long run, the river channel may shift due to riverbed aggradation. In another kind of adverse effect of embankments, communities inside the embankments, for instance in the Koshi river basin, have been complaining that their livelihoods and infrastructure are constantly at risk due to flood waters.

Therefore, overall, the trade-off between the benefits of water resources, such as hydropower and irrigation, and the costs to different sectors – such as the ecosystem, agricultural productivity, and natural flows – needs to be balanced in a sustainable way.

The growth in structures such as dams and the expanding execution of large-scale water projects reduce water availability downstream in transboundary watersheds (Al-Faraj & Scholz, 2014). An example may be found in the Nathpa Jakhri project in the Sutlej River basin, where the diversion of the river for the project left the downstream riverbed with a stretch of rocks and debris (Erlewein, 2013).

The effects of upstream dams on dams downstream in the same river basin have also been highlighted by Erlewein (2013). He observed that, unless the dams are run by the same company, not much consideration and attention was being paid to cooperation in their operation. Upstream dams may adversely affect downstream dams by holding or releasing too much water, or holding or discharging sediment.

There are other, indirect and deleterious effects of dams. An example is the situation in the Romaine River in Canada, where a proposed dam would open the indigenous land to exploitation by big mining and forestry corporations. Such exploitation would have a huge impact on the hydrological regime of the region, especially in the form of massive deforestation and degradation of land. The Kariba dam in southern Africa forced the evacuation of 130,000 people due to the rise in water levels in March 2010 (Karunananthan, 2013). In Ethiopia, a large-scale irrigation project under the name of the Water Sector Development Program had been initiated in 2002 and concluded in 2016. Ruffeis, Loiskandl, Spendlingwimmer, Schönerklee, & Awulachew (2006) concluded that the impacts of these projects in two locations included a rise in the water table, waterlogging, and changes to the low-flow regime, with the causes listed as improper irrigation management and seepage losses.

Finally, widespread infrastructure-building can also have grave effects on biodiversity. In the HKH region, this would be substantial: for instance, Grumbine and Pandit (2013) said that dam-building in the undisturbed forests of the Indian Himalaya could lead to the loss of 22 angiosperms and seven vertebrate taxa by 2025. The Mekong River basin, the biggest inland fishery in the world, is undergoing massive changes due to the construction of several massive hydropower plants upstream. This has led to the loss of diversity in fish species, attributable to the blocking of their migratory routes by the infrastructure constructed in the upstream tributaries (Ziv, Baran, Nam, Rodriguez-Iturbe, & Levin, 2012).

8.5. Discussion Related to Upstream–downstream Linkages

The importance of river systems in the Himalayan river basins and their effects on ecosystems depends largely on the availability of water. The deposition of silt and sediment by these rivers has created the deltas in downstream regions that are immensely fertile and support the livelihoods of tens of millions. As discussed in the previous section, there are numerous advantages and disadvantages of water infrastructure in terms of economic benefits, as well as adverse effects on natural flows, ecosystems, people, and the environment. The following can be underlined with respect to upstream–downstream linkages in this context:

- The Himalayan region is a hotspot in terms of the development of mega hydropower projects. The construction of various kinds of infrastructure in recent years to control the flow of water in upstream regions has subsequently affected the downstream regions.
- Regarding infrastructure on transboundary rivers such as the Farakka and the Gandak barrages, there are ongoing disputes between the countries involved on water resource sharing and management.
- Special consideration should be given by the involved countries to solve issues of water quality and availability for downstream populations. Agricultural productivity can be improved by infrastructure such as dams and irrigational canals, and their proper management.
- The construction of infrastructure to retain water upstream might diminish the amount of sediment, leading to the loss of precious silt required for the fertility of lands downstream. This reduction in silt is also found in areas where embankments have been constructed to mitigate the effects of floods. The villages in which agriculture was once thriving are now struggling to maintain the fertility of their land, because of less silt reaching their fields.
- Various mitigative measures such as the transfer of required sediment to downstream regions and sediment flushing through dams could be adopted in the HKH to benefit both upstream and downstream communities. For transboundary rivers, strategies for cooperation are needed between the riparian nations on the issues of building water-harvesting structures for the successful management of water resources. This will enhance the benefits that the upstream and downstream regions will derive. Downstream populations will benefit from flood control measures and upstream people from improved water availability and hydropower generation.

- Strategies about cooperation shared between upstream and downstream stakeholders can be an answer to an equitable benefit-sharing for both upstream and the downstream communities. Further, governance strategies for a basin-wide assessment of water uses in upstream and downstream areas should be formulated, along with transboundary agreements and the management of risks associated, in order to minimize the cascading negative effects of infrastructure development. In this regard, addressing water issues – minimizing risk and maximizing benefits – through multilateral rather than bilateral approaches can provide additional benefits. This will also help to minimize conflicts and grievances.

9. Conclusions and Outlook

9.1. Current Understanding and Gaps in Knowledge

The issue of upstream–downstream linkages in the Hindu Kush Himalaya region has been widely discussed, documented, and reviewed. Since the 1980s, a vast amount of knowledge has been generated through field investigations, remote sensing, and data assimilation, which have contributed to an increased process understanding. The new dimensions of climate change and infrastructural development have been added to discussions about upstream–downstream linkages, which were missing earlier, when land use, land cover changes (LULCC), and erosion and sedimentation dominated the discourse.

Issues related to LULCC have slowly progressed, but have generated a wealth of knowledge about process understanding regarding the middle hills region. With the advent of hydrological models, impacts of land cover changes on the hydrological regime have been investigated at the meso and macro river basin scale. However, these models have difficulties assessing the impacts of land use change on hydrology at a large scale due to simple conceptualization modelling processes related to land use change (such as infiltration and root depth). The effects of land use changes tend to be less important at the scale of large river basins, whereas the effects of rainfall variability and heterogeneity of the basins tend to dominate the process at that scale.

Apart from run-off, land use and land cover changes need to be viewed from the angle of erosion and sedimentation. While many small-scale studies suggest that overall annual water availability might decrease under vegetation (or reforestation) scenarios, the important information pertains to a change in flooding patterns and dry season flows due to land cover changes. Deforestation also needs to be seen together with erosion. In the long run, the loss of soil profile through erosion will reduce soil water holding capacity and groundwater recharge, and dry season flows might suffer gravely. Also, the role of vegetation and forests needs to be viewed from a wider perspective, one of erosion control, biodiversity, and ecosystem services.

In spite of many years of research in this field, the quantification of the erosion rate and sediment yield, and sources and causes of erosion (both natural and anthropogenic) at the scale of large river basins remains a challenging task. The sediment loads from isolated events such as landslides, or infrastructural activity such as road construction in the mountains, may contribute more significantly and overwhelm that of deforestation and LULC changes. However, little research has taken place in this direction. Similarly, the impacts of erosion and sedimentation on infrastructure (dams, hydropower, canals, and agriculture), and consequently on livelihoods, need to be assessed from an integrated physical and socioeconomic perspective.

There is also a gap in the understanding of forest type, species, and patterns in relation to water availability. There is a need to understand the vegetation and water relationship in the perspective of upstream–downstream linkages. Despite a number of research studies on vegetative cover and soil erosion, and sedimentation, having been done and being available, there is still a gap related to understanding the complexity of other variables such as soil type, soil aspect, and species pattern.

Climate change has added another dimension to upstream changes (in land cover, snow cover, glaciers, and permafrost) and downstream water availability. Published studies indicate that glaciers are already melting and receding across numerous river basins of the HKH. Due to further rises in temperature (projected by most GCMs), glacier shrinkage in the future is almost unequivocal. Shrinking glaciers may produce more melt per unit area for a few decades. However, when the glacial storage diminishes in the longer run, flows may decrease in downstream areas.

Although a few studies have indicated that glacial melt flows may increase up to the mid-century and then decrease, more concrete research is required to indicate the timescale from when there would be an abrupt change in water flows downstream. It is almost unambiguous that the high-altitude/headwater catchments, exclusively fed by meltwater, will be affected in the future. Topics such as climate change's impacts on the cryosphere, permafrost, solifluction and related erosion and sedimentation, and hydrological extremes need more attention, particularly to obtain more granular information about space–time variations in water availability and extremes. Information on changes in water availability at an annual or decadal scale might not be sufficient to design adaptation practices. Similarly, issues such as the deposition of atmospheric pollutants, such as black carbon, on glacier surfaces and its impact on melting need more research. In spite of intense research over the past two decades in this field, the impact of climate change on downstream water availability requires unbundling in terms of timing, magnitude, and scale. Furthermore, climate projection inputs in the form of higher resolution is always useful to understand local-scale impacts.

Given the growing scarcity of water resources in the context of increasing demand and its socioeconomic drivers, managing water resources is, and will be, a challenging task. Water storage infrastructure, both at the small scale (such as ponds and irrigation structures) and the large scale (dams) have their benefits and risks. While the former is found to be quite beneficial at the local scale in dealing with too much and too little water, the latter imposes costs on the ecosystem and the surrounding environment. But water resources management at large basin scales needs bigger storage infrastructure able to regulate flows at longer time scales (seasons). However, downstream water use may be impacted as a consequence, and this may impact people's livelihoods. For instance, if sediment is blocked in the upstream reservoir, soil fertility may reduce in downstream areas and adversely impact agriculture productivity. For this issue as well, understanding erosion rates and sedimentation of major reservoirs is very important and vital for water resources management.

Another knowledge gap pertains to climate change and groundwater. While groundwater plays a crucial role in supporting agriculture, mostly downstream, there has been very little research on the effects of climate change on groundwater availability and storage.

The four key questions related to upstream–downstream linkages are interlinked. Understanding these issues in a more holistic fashion requires an integrated systems analysis approach, bringing together disciplines that deal with both the natural environment and the human system. There are great challenges in linking the local-scale and case-based studies with river basin scales. We suggest that a framework for assessing upstream–downstream linkages could address this. Such a framework should be flexible enough to address the varied linkages, which occur at different scales.

9.2. Uncertainties in Results and Methodological Differences

The quantification of these upstream–downstream linkages is a prerequisite to understanding the magnitude and scale of the problems, in order to design and plan effective and sustainable water resources management. However, understanding the issues through quantification requires a robust representation of data and information at both the temporal and spatial scales. However, the HKH region lacks good quality, representative data, especially in high-altitude areas, due to the constraints of remoteness and logistics. In addition, not all countries of the region are equally interested in sharing data and information with neighbouring countries, which hinders understanding at a regional and transboundary level.

About quantification related to climate change assessment, data pertaining to future projections have uncertainties at a different level, from emission scenarios to socioeconomic development trajectories. Applying data and information from these GCM scenarios to regional studies requires further downscaling to a fine resolution, so that regional heterogeneity (such as mountains, vegetation, etc) is taken into account. The outcomes of these scenarios are applied to different tools, say to a hydrological model to understand changes in future hydrological dynamics. The outcomes need to be interpreted with caution, especially while designing adaptation strategies. In addition, the results tend to differ due to differences in methodological approaches, variation in data periods used, and the quality of the data.

9.3. Regional Heterogeneity

Upstream–downstream linkages in the HKH region are complex, and it is not always possible to generalise understanding from one basin to another. Parts of the region have many similarities, but also differences. For instance, the climate and hydrology in the eastern part are dominated by the summer monsoon, whereas winter rains dominate in the western region. The variability in climate can primarily alter the magnitude of rainfall run-off processes. Snow and glacial meltwater are very important in the western region, and is stored in reservoirs. For example, the irrigation system of the Indus is regulated through two major storage dams, for which the supply is mainly from melt-dominated rivers. In contrast, in the east, irrigation in the Ganges river system is regulated by barrages.

There has been, and will likely continue to be, considerable differences in the rate of warming at different altitudes, with higher altitudes warming at a significantly higher rate than the plains. There is also considerable heterogeneity in the pace and rate of glacial melting across river basins. Clearly, the impacts of climate change and other changes on water resources and availability in downstream areas are likely to vary across the region. All of these factors, and the upstream–downstream linkages, are strong reasons to encourage countries located in upstream and downstream areas to develop mechanisms and processes to both understand commonalities and regional heterogeneity, and effectively address extreme events such as floods and droughts, which are expected to hit the region with greater intensity in the future.

9.4. Role of Scale

The review of the key questions shows that the magnitude of upstream–downstream linkages, and our understanding of it, depends on the scale at which the assessment is carried out. Hydrological processes occur at a wide range of scales, from unsaturated flows in a soil profile to floods in river systems of thousands of square kilometres. The spatial and temporal scales of hydrological processes play an important role in the upstream–downstream dimension of impact analysis. While some issues are prevalent at the local scale, their impact might be less visible at a large scale.

As the scale of the catchment changes from small plots to the river basin, the nature and complexities of the linkages and related impacts change as well. For example, the impact of deforestation and afforestation on water downstream is most visible in the small-scale catchment/watershed. However, its effects might dissolve at the large scale, because of the spatial variability of a catchment and run-off contributions from different sources such as groundwater. Assessment tools such as hydrological models have difficulty in differentiating these changes at the large river basin level, as the impact of LULCC tends to dissolve under the influence of basin heterogeneity arising from different elevations and related differences in climate, land use, and ecosystems.

Issues of scale become complicated when the system's components interact with each other, which influences the behaviour of processes in space and time. Therefore, while analysing upstream–downstream linkages, it is important to clarify the relevant scale for assessing the particular problem or issue. Issues of scale need to be an integral part of developing a framework for upstream-downstream linkages.

9.5. Future Directions

This review has highlighted some key elements of upstream–downstream linkages related to land and water management in the HKH region with a focus on the river basins of the Indus, Ganges, and the Brahmaputra. It has encompassed some of the relevant literature pertaining to climate change and infrastructure development as well, in addition to LULC and erosion and sedimentation. It is clear that more scientific research needs to be designed at different scales, with representation from different physiographic and ecological zones. As the issues of upstream–downstream relationships are integrated in nature and consist of multidisciplinary sciences and inherent cause–effect relationships, an integrated systems analysis approach needs to be adopted. For this, a framework for upstream–

downstream linkages of land and water management is required, which can guide assessment and analysis of these linkages and their relationships at different scales.

The sharing of data and information is a prerequisite for such a comprehensive assessment, as the effects and processes in one upstream country might affect a downstream one. Scientific collaboration will lag behind in the absence of accurate data and information-sharing.

Monitoring the infrastructure of the region needs to be strengthened, especially in high-altitude areas. Finer and higher resolution datasets help us understand these issues at various scales better, and provide better validation and assessment of uncertainty.

To conclude, as already underlined at the beginning of this paper, upstream–downstream interlinkages are just as social and political as they are physical. Hence, there is an urgent need to frame the upstream–downstream discourse within a political ecology perspective that takes into account issues of unequal state power and how that shapes various interactions between upstream and downstream countries in the context of the Himalaya. While this paper does not do so explicitly, it identifies this as a knowledge gap that needs to be filled in the near future.

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Himalayan Adaptation, Water and Resilience (HI-AWARE) Research
c/o ICIMOD
GPO Box 3226, Kathmandu, Nepal
Tel +977 1 5275222
Email: hi-aware@icimod.org
Web: www.hi-aware.org

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