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Factors influencing river discharge variability in the Himalayan mountain region: a case study of two catchments with contrasting geographical settings

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award of the Degree of Doctor of Philosophy
of the
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DECLARATIONS

To the best of my knowledge and belief, this thesis contains no material previously published by any other person except where due acknowledgement has been made.

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ABSTRACT

Variabilities in precipitation, surface air temperature and land use/land cover (LULC) over a catchment can influence surface runoff, evapotranspiration, groundwater recharge and eventually the river discharge. The headwaters originating from the Himalayan mountain region are the most important source of water for major rivers in South Asia, therefore the fragile environment of the Himalayan mountains is crucial for water availability for large population of the region. Despite the significance of comprehensive knowledge on hydro-climatic and anthropogenic changes, most of the existing studies have focused only on one or two variables or generalised results over larger regions. This study aimed at quantifying fine scale spatial and long-term variability in precipitation, temperature, river discharge and LULC changes in Bagmati and Marsyangdi sub-catchments of the Ganges River, in Nepal, in relation to their geographical settings. These two catchments represent very common but contrasting settings within the Himalayan mountain region in terms of climate, LULC, headwater source and population distribution. Association between hydro-climatic variables and the influence on river discharge for the two catchments are also examined.

Distribution and changes in LULC were examined based on historical coverage extracted from Landsat images representing mid-decade LULC since the 1970s. The Moderate Resolution Imaging Spectroradiometer (MODIS) snow cover product available between 2000 and 2017 was also used to provide supplementary information on changes in snow cover in Marsyangdi catchment. Results showed that coverage by forest, shrub/grass and snow/glacier in the catchments were highly influenced by topographic variation and climate, while agriculture and urban activities are dependent on elevation, slope and climate as well as population distribution. The main LULC change in Bagmati catchment was a 10-fold increase of urban land, while there was a remarkable decrease in snow/glacier cover in Marsyangdi catchment.

Hydro-climatic variabilities between 1970 and 2017 were examined using daily precipitation, minimum temperature (T_{min}), maximum temperature (T_{max}) observed at gauge stations within and around the two catchments, while river discharge records at multiple locations were used to examine river discharge at sub-catchment level. Daily data were homogenised and gap filled before further processing and analysis. Spatial distributions were analysed based on monthly long-term means. Long-term changes were analysed using Mann-Kendall trend test and Sen's slope estimator as well as departure from long-term means. Results of trend analysis suggested that, out of the 12 stations examined in each catchment, annual precipitation was mostly decreasing with statistically significant trends (at 95% confidence interval) at four and five stations in Bagmati and Marsyangdi catchment respectively. Monthly trends also showed that decrease in precipitation was more consistent in Marsyangdi catchment compared to Bagmati. T_{max} and the diurnal temperature range (DTR) were increasing in both catchments including significant positive trends in most of the months. T_{min} was generally increasing in Bagmati catchment and in low mountain zone (<1000 m) of Marsyangdi catchment, however it was decreasing in high mountain zone (>2500 m) of Marsyangdi catchment. The average river discharge from upper and the entire Bagmati catchment was decreasing significantly but discharge from Marsyangdi catchment was increasing significantly, including a significant trend in July and August. Even though most of the other monthly changes in minimum, average and maximum discharge were negative, maximum river discharge from the entire Bagmati catchment was increasing significantly in July. The rate of long-term changes in precipitation and temperature did not show a clear pattern in relation to elevation and topography. However, the distribution of T_{min} and T_{max} in the two catchments showed a dominant influence of elevation and topographic location, while the distribution of precipitation depends more strongly on local orography than on elevation.

Surface runoff was estimated based on precipitation, LULC and soil type data using soil curve number method. Pearson’s correlation statistics were used to examine the associations between hydro-climatic variables including the estimated surface runoff. Precipitation was seen to have a significantly positive correlation with river discharge in both catchments. T_{max} had a negative correlation with river discharge in Bagmati catchment, while the association was positive in Marsyangdi catchment. The influence of climatic variabilities and major LULC changes on river discharge in the two river catchments were examined using multiple regression analysis. Results showed that, apart from the influence of urban land use change in upper Bagmati catchment, precipitation was the dominant factor impacting discharge in the two catchments.

Considering the substantial variabilities observed in the spatial distribution and long-term changes in hydro-climatic factors and LULC, the results of this study in relation to topography and overall geographic settings allows better understanding of hydrological process and water budget in the region. Furthermore, the knowledge of hydro-climatic changes at monthly scale is also useful to manage water during low flow months as well as to minimise potential risks associated with water induced disasters such as landslides and flooding during high flow months.

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LIST OF PUBLICATIONS

Journal articles

Below are the journal articles published as part of this study and they are included in Appendices A and B.

Article 1:

> Tuladhar, D., Dewan, A., Kuhn, M., & Corner, R. J. (2019). Spatio-temporal rainfall variability in the Himalayan mountain catchment of the Bagmati River in Nepal. *Theoretical and Applied Climatology, 139*, 599-614. https://doi.org/10.1007/s00704-019-02985-8

Article 2:

> Tuladhar, D., Dewan, A., Kuhn, M., & J Corner, R. (2019). The influence of rainfall and land use/land cover changes on river discharge variability in the mountainous catchment of the Bagmati River. *Water*, 11(12), 2444. https://doi.org/10.3390/w11122444

Conference presentation

> Tuladhar, D., Dewan, A., Kuhn, M., & J Corner, R. (2018). Rainfall and river discharge variability in Bagmati river catchment of Nepal. *6th Global summit on Climate Change* 19–20 November 2018, Paris, France.

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	Article 1	**Article 2**
Conceptualisation and methodology	✓	✓
Data processing, validation, mapping and analysis	✓	✓
Draft preparation	✓	✓
Editing and revision of manuscript	✓	✓

I acknowledge that these represent my contributions to the above research.

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	Article 1	**Article 2**
Conceptualisation and methodology	✓	✓
Data processing, validation, mapping and analysis		
Draft preparation		
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Author: M. Kuhn

	Article 1	**Article 2**
Conceptualisation and methodology	✓	✓
Data processing, validation, mapping and analysis		
Draft preparation		
Editing and revision of manuscript	✓	✓

I acknowledge that these represent my contributions to the above research.

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Author: R. J. Corner

	Article 1	**Article 2**
Conceptualisation and methodology	✓	✓
Data processing, validation, mapping and analysis		
Draft preparation		
Editing and revision of manuscript	✓	✓

I acknowledge that these represent my contributions to the above research.

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ABBREVIATIONS

APHRODITE	Asian Precipitation-Highly Resolved Observational Data Integration Towards Evaluation
ARIMA	Auto Regressive Integrated Moving Average
AVHRR	Advanced Very High Resolution Radiometer
BIC	Bayesian Information Criterion
CI	Confidence Interval
DEM	Digital Elevation Model
DHM	Department of Hydrology and Meteorology
DTR	Diurnal Temperature Range
ENSO	El Niño-Southern Oscillation
GCM	General Circulation Model
GPCC	Global Precipitation Climatology Centre
GRACE	Gravity Recovery And Climate Experiment
HADCM	Hadley Centre Coupled Model
IDW	Inverse Distance Weighting
IOD	Indian Ocean Dipole
LULC	Land Use/Land Cover
MK	Mann-Kendall
MODIS	Moderate Resolution Imaging Spectroradiometer
MSS	Multi Spectral Scanner
NOAA	National Oceanic and Atmospheric Administration
OLI	Operational Land Imager
RCP	Representative Concentration Pathway
SCN	Soil Curve Number
TM	Thematic Mapper
T_{max}	Maximum Temperature
T_{min}	Minimum Temperature
TRMM	Tropical Rainfall Measuring Mission
USGS	United States Geological Survey

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1. BACKGROUND AND INTRODUCTION

1. 1 Background

Long-term variability in river discharge represents the hydrological response of the catchment in relation to changes in hydro-climatic and physiological characteristics (Hodgkins et al., 2003; Morán-Tejeda et al., 2011). Global mean surface temperature is estimated to have increased by 0.075 ± 0.013 °C per decade between 1901 and 2012 with a higher rate of change (~0.102 °C per decade) on land surface (Hartmann et al., 2013). The rate of rise in surface average temperature, especially from the 1970s is unprecedented in human history and precipitation patterns around the world have changed noticeably as well (Hartmann et al., 2013; IPCC, 2007; Jones & Moberg, 2003). Human activities including deforestation and industrialisation are found to have a strong link to recent climate change (Stocker, 2014). Furthermore, increased human activities including land use and land cover changes (LULC) and extraction of water are also linked to changes in river discharge (Hartmann et al., 2013). Several studies modelling climate change and human activities have estimated that rise in temperature is expected to continue towards the mid to end of the 21st century (Pachauri et al., 2014).

With the warming of every 1 °C, the water holding capacity of the atmosphere increases by 6–7% (Trenberth, 2008), which tends to enhance the occurrence of intense precipitation events. On the other hand, warming of surface air can also exacerbate the intensity of droughts as a result of high evaporation (Dai et al., 2004; Trenberth et al., 2014). Studies suggest that changes in hydro-climatic variables and intensification of the hydrological cycle in the second half of the 20th century have a clear link to the warming climate (Huntington, 2006; Labat et al., 2004).

Despite a general agreement on rising temperature in most parts of the world, the rates of change are not uniform. Changes in rainfall, surface runoff and river discharge also vary significantly from one region to another. Increasing frequency and intensity of wet events are noticed in some parts of the world, whereas the frequency and intensity of droughts appears to be increasing in other locations (Dore, 2005; Trenberth, 2008). Generally, changes in heavy precipitation events influence total precipitation, however extreme precipitation events may increase even when total precipitation does not change or declines (Dore, 2005). Thus, climate warming has a multi-faceted effect on the hydrological cycle and increases the uncertainty in hydrological parameters including changes in seasonal river discharge patterns and total volume (e.g. Santini & Di Paola, 2015).

Under likely future climate change scenarios, the coverage of equatorial, arid and warm temperate climatic zones are expected to increase, while the alpine and polar climate zones are expected to shrink (Santini & Di Paola, 2015). Areas that normally receive high rainfall are very likely to receive more rainfall, while dry areas may become even drier (Pachauri et al., 2014).

In a rainfall event, groundwater retention and runoff characteristics are affected by surface condition and LULC. For instance, permanently vegetated areas such as forests will have less runoff and more groundwater recharge compared to agricultural land, while runoff is high for impervious surfaces such as road and urban areas. Therefore, together with changes in rainfall distribution, changes in LULC of a catchment can influence runoff, groundwater recharge and hence river discharge from the catchment. LULC changes are found to have significant influence on river discharge in some locations (Kashaigili, 2008; Schilling et al., 2010; Zhang & Schilling, 2006), while climatic change may play a pivotal role in influencing river discharge in other locations (Frans et al., 2013; Gerten et al., 2008; Shi et al., 2011).

Due to the complex interaction between climatic and other geographical variables, there is a considerable spatial variability in local and regional river discharge (Arnell & Gosling, 2013; Frans et al., 2013). In fact, river discharge from different sub-catchments of a large river basin can vary substantially (e.g. Villar et al., 2009). Knowledge of changes in climatic variables and human activities and their influence on river discharge is therefore very important for understanding the behaviour of the hydrological budget and for sustainable management of water resources. In addition, this information is also crucial for addressing potential loss associated with extreme events such as flooding.

As the result of warming and changes in atmospheric circulation, snow cover in the mountain regions around the world is estimated to have decreased significantly in the last century (Huss et al., 2017; Zemp & Haeberli, 2007). River discharge patterns are also reported to have changed in mountain regions such as the Andes, the European Alps, the Rocky Mountains and the Himalayas, with predictions for near future changes in hydrological regime (Chevallier et al., 2011; Rood et al., 2005; Stewart, 2009; Vanham, 2012). Modelling results suggest that predicted climate change and LULC will continue to drive changes in discharge from rivers around the world (e.g., El-Khoury et al., 2015; Tao et al., 2014). Based on likely future climate scenarios, annual mean discharge from nearly half of the major hydrological basins of the world is expected to decrease, while increased discharge is expected from more than 35% of the basins towards the middle of the 21st century (Arnell & Gosling, 2013; Santini & Di Paola, 2015). However, on a longer term (toward the end of 21st century), discharge from 60% of the major river basins may decrease with extreme decreases in large areas of the northern hemisphere (Santini & Di Paola, 2015). In addition, due to the increased demand for freshwater associated with population and industrial growth, the proportion of the world's population under water stress has increased significantly from the 1960s (Wada et al., 2011) and is expected to increase further towards 2050 (Arnell, 1999).

Most of the major rivers of the South Asian region originate from the Himalayan Mountains. Unfortunately, due to its unique physiography and fragile ecosystems, the Himalayan region is likely to be affected most in response to climate change (Barnett et al., 2005; Dimri et al., 2018). This is emphasized by a higher rise in air temperature and observed decline of snow cover as well as thawing of glaciers and permafrost in high elevation (Bajracharya et al., 2015; Barnett et al., 2005; Immerzeel et al., 2010). There is a general perception that rainfall patterns in the region have become more unpredictable than they were in the past (Pandey, 2017; Uprety et al., 2017), supported by scientific studies (e.g. Chaudhary & Bawa, 2011). Climate models predict a higher rate of snow/glacier loss from the Himalayan region for the rest of the century under a projected warming rate of 0.06 °C per decade (Dimri et al., 2018; Immerzeel et al., 2010). Melting in glaciated areas can result in higher discharge for a period of time (Miller et al., 2012), however the depletion of glaciers and snow cover will ultimately have a negative influence on the river discharge (Cai et al., 2014; Sorg et al., 2012). The loss of snow/glaciers can also have a critical impact on water availability during winter and spring seasons for domestic use, agriculture and hydropower generation as well as affect aquatic habitat and biotic communities (e.g. Huss et al., 2017).

Considering that it supports the livelihood of more than 655 million people across Bangladesh, China, India and Nepal, the Ganges river system is one of the most important transnational rivers in south Asia (Jeuland et al., 2013; Sadoff et al., 2013; Shahjahan & Harvey, 2012). Discharge from Himalayan headwaters have a substantial contribution to the Ganges River (Siderius et al., 2013). On average, rivers flowing from Nepal contribute 45% of its annual flow with contributions as high as 70% during dry seasons (Upreti, 2005 cited by Shahjahan & Harvey, 2012). Within the Himalayan region also, some rivers are snow fed and perennial, while others are fed by mountain springs and depend directly on the amount of rainfall received. Higher populations are located on the plains and valleys compared to slopes and high mountains. Therefore, the type and intensity of human activities within the Himalayan region vary significantly in relation to geographic conditions.

The Indian Summer Monsoon (hereinafter referred to as monsoon) originating from the (northern) Indian Ocean delivers most of the precipitation between June and September in the South Asian and Himalayan region. However, its spatio-temporal distribution depends on many factors including climatic, topographic and orographic variations within the region. The westerly systems, originating from the Arabian Sea and Mediterranean regions, bring occasional precipitation in winter (Barros, 2004; Krishnan et al., 2019). The monsoon is also known for high inter-annual variability and precipitation patterns may also be affected by other large-scale climate forcing such as El Niño-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) (Krishnamurthy & Kinter, 2003; Pervez & Henebry, 2015). Thus, the seasonal imbalance and dynamic nature of Himalayan rivers, together with climate change effects pose a significant challenge in efficient management of water resource in South Asia (Jeuland et al., 2013; Sadoff et al., 2013). Furthermore, groundwater extraction and LULC changes associated with increasing population can also alter the rate of groundwater recharge and hence the seasonal availability of water resources in the region (Rodell et al., 2009; Tiwari et al., 2009; Wada et al., 2011).

Several studies have examined historical changes in one or more components of precipitation, temperature and river discharge in the Himalayan region and major river basins of South Asia including the Ganges river basin using traditional in-situ data (Collins et al., 2013; Mirza et al., 2003; Pattnaik & Dimri, 2020; Shekhar et al., 2010; Sun et al., 2017; Yang et al., 2013). Some studies have used gridded data such as Asian Precipitation-Highly Resolved Observational Data Integration Towards Evaluation (APHRODITE), Tropical Rainfall Measuring Mission (TRMM), Global Precipitation Climatology Centre (GPCC), Gravity Recovery and Climate Experiment (GRACE) derived from remote sensing and generalised regional data to study precipitation and water availability in the region (e.g. Anders et al., 2006; Fu & Freymueller, 2012; Khandu et al., 2016; Sinha et al., 2014). Results from these studies generally agree on increasing surface air temperature and extreme precipitation events in the region, while changes in seasonal and annual precipitation show significant spatial variations.

Similar to the spatially variable rate of historical temperature change, future rises in temperature are also predicted to vary spatially with a higher rate in high elevation of mountain regions (Liu et al., 2009; Palazzi et al., 2017). Several studies have attempted to predict the effect of future climate change on precipitation and water availability in major river basins of South Asia (Immerzeel et al., 2010; Jeuland et al., 2013; Masood & Takeuchi, 2015; Pervez & Henebry, 2015). However, climate predictions in the

Himalayan region and the Ganges basin have significant uncertainties associated with lack of uniform data and rugged topography (IPCC, 2007; Jeuland et al., 2013). Based on 16 general circulation models (GCMs) for the A2 emission scenario, Jeuland et al. (2013) concluded that precipitation and runoff predictions in the Ganges basin differ widely both in terms of water availability (increase/decrease) and spatial variation. Results indicate that temperature rise, together with uncertain precipitation changes can alter the water cycle of the Ganges basin significantly (Immerzeel et al., 2010; Jeuland et al., 2013).

In Nepal, some studies have examined trends in temperature (e.g. Kattel & Yao, 2013; Nayava et al., 2017; Poudel et al., 2020; Thakuri et al., 2019) using historical data at up to 30 stations. Shrestha et al. (2019) analysed 0.5° × 0.5° gridded data produced by National Oceanic and Atmospheric Administration (NOAA) to study temperature variation between 1979 and 2016. Similarly, precipitation trends in Nepal, have been examined by Bohlinger and Sorteberg (2018) and Karki et al. (2017) using data at 40 to 76 stations. Some studies have focused on precipitation variability in parts of Nepal (e.g. Barros & Lang, 2003; Panthi et al., 2015; Pokharel & Hallett, 2015), while Kansakar et al. (2004) focused on classifying precipitation regimes in Nepal. Using APHRODITE data for 1951–2007, Pokharel et al. (2020) suggested that frequency and intensity of extreme precipitation events is increasing in Nepal and future precipitation is expected to increase especially during the second half of the 21st century. Hannah et al. (2005) analysed flow regimes of 28 river basins of Nepal and trends in streamflow at 33 river stations were analysed by Gautam and Acharya (2012). Chalise et al. (2003) examined a method to estimate low flow in the mountainous regions and attempted to estimate discharge for ungauged areas of Nepal using precipitation data related to 52 mountain catchments. LULC maps of Nepal have been prepared for various periods including 1978, 1986, 1994 and 2010 (DFRS, 1999; LRMP, 1986; Uddin et al., 2015), while some studies have focused on mapping LULC of Kathmandu valley (Ishtiaque et al., 2017; Thapa & Murayama, 2012). However detailed comparisons of LULC, based on these results are difficult due to the use of different methods and limitations associated with spatial accuracy. A few studies have modelled future water availability under various climate change scenarios for some of the mountain catchments in Nepal (e.g. Neupane et al., 2015; Shrestha et al., 2016). Studies on long-term climatic variability mostly focus at annual or seasonal scales with very limited assessment at monthly resolution (e.g. Bohlinger & Sorteberg, 2018; Karki et al., 2017; Kattel & Yao, 2013; Poudel et al., 2020; Thakuri et al., 2019).

Most of the existing studies on hydro-climatic changes covering large river basins or major parts of the Himalayan region do not highlight detailed variations associated with local topography but instead generalise the results over larger areas (e.g. Curtis et al., 2018; Pervez & Henebry, 2015; Shekhar et al., 2010). This, together with non-uniform temporal changes in hydro-climatic variables and human activities highlights the need for spatial assessment at finer resolutions for improved understanding of hydrological behaviour in the river catchments of the region (Diodato et al., 2010; Guhathakurta & Rajeevan, 2008).

Some studies have also analysed one or more hydro-climatic variables (e.g. rainfall, temperature and river discharge) specific to a smaller river catchment in Nepal (Babel et al., 2014; Dhital & Kayastha, 2013; Dhital et al., 2013; Gautam et al., 2010; Mishra & Herath, 2014; Neupane & Dhakal, 2017; Sharma & Shakya, 2006). Other studies have examined LULC changes in different parts of the country with a special focus on urban growth (e.g. Ishtiaque et al., 2017; Pradhan, 2004; Thapa & Murayama, 2012). Yet most of these studies have not provided detail on spatial variability within the catchments in relation to topographic variation. Furthermore, knowledge on the linkage between hydro-climatic variability and human activities is very limited in the Himalayan mountain region including that in Nepal.

To address these limitations, this study aims to look at changes in rainfall, temperature, LULC and their influence on river discharge from the Bagmati and Marsyangdi catchments in Nepal that are part of the Ganges system. The geographical settings of these two catchments are contrasting in terms of topographic variation, hydro-climatic behaviour and importantly LULC and population density. A focus is also put on to compare similarities and differences in hydro-climatic and anthropogenic components of the two river catchments. Specifically, this study attempts to quantify how river discharge in Himalayan mountain catchments with specific geographic characteristics are responding to climate change and increased anthropogenic activities. The questions that have motivated this study are:

(a) Are there any significant long-term changes in surface air temperature, precipitation and river discharge in the two mountain catchments?

(b) How do long-term changes in these hydro climatic variables at monthly scale relate to annual changes?

(c) Have there been any major LULC changes in the two catchments?

(d) Are the changes in climatic variables and LULC influencing river discharge from the catchments?

(e) Is there any spatial patterns in results from these two river catchments in relation to their geographical settings?

1. 2 Objectives of the study

This thesis aims to examine the influence of climatic variations and anthropogenic activities on river discharge in the two Himalayan mountain catchments of the Bagmati and Marsyangdi rivers. Based on this aim and the research questions formulated above, the objectives of this study are to:

(a) Quantify long-term changes in hydro-climatic variables and LULC in the two Himalayan mountain river catchments. This will be achieved by studying long-term (1970–2017) changes and spatial variabilities in precipitation, temperature and river discharge using in-situ records and historical LULC changes extracted from satellite images. This is expected to improve the understanding of hydro-climatic and anthropogenic changes in the Himalayan mountain region which can assist in sustainable management of natural resources as well as adaptation to climate change.

(b) Investigate the influence of climatic and anthropogenic changes on river discharge from sub-catchments of the two rivers. This will provide insight on the hydrological response of each catchment to climate change, human activities and geographical settings. Considering the vast topographical diversity within the Himalayan mountain region, knowledge of these associations specific to their geographical settings can be crucial for management of the water resource as well as in mitigation of the impact of water induced disasters.

1. 3 Significance of the study

This study is significant as it provides a comprehensive insight into the long-term hydro-climatic variability of the Himalayan river system exemplified by the Bagmati and Marsyangdi river basins. This will be useful in modelling/predicting future water availability for sustainable planning of this vital natural resource (Chalise et al., 2003; Neupane et al., 2015). As mentioned above in Section 1.1, the Himalayan mountain region is the origin for most of the major rivers in South Asia and it is identified as being particularly vulnerable to climate change (Shah et al., 2013; Sharma & Shakya, 2006). Any changes in climatic and anthropogenic activities can have significant impact on ecology, hydrology and socio-economic condition in the Himalayan and South Asian region (Dimri et al., 2018). Changes in precipitation patterns, rising temperature and the resulting decrease in snow cover as well as glacier retreat can influence availability of water resources for agriculture, domestic/industrial use and hydropower generation (Bajracharya et al., 2015; Barnett et al., 2005; Bolch et al., 2012; IPCC, 2007; Shekhar et al., 2010). This highlights the significance of comprehensive knowledge of long-term hydro-climatic variability in the Himalayan river systems, which is still limited due to various reasons including complex topographical variability and lack of uniform hydro-meteorological data (Moench, 2010; Savéan et al., 2015). Therefore, understanding long-term changes of hydro-climatic variables and LULC in relation to the specific geographic characteristics within the two river catchments can provide valuable insights into the hydro-climatic variabilities in the region.

Considering the dependency on the Indian summer monsoon, accurate knowledge of hydrological changes at monthly scale will also be significant to minimise the potential risks associated with water induced disasters as well as to manage water scarcity during low flow months (Brown et al., 2014; Sharma & Shakya, 2006). Monsoon is reported to be retreating later in Nepal (Panthi et al., 2015) indicating that monthly rainfall distribution in the region might have changed, even if seasonal and annual precipitation are unchanged. River discharge in the region largely depends on the monthly distribution of precipitation, while contribution from release of subsurface water and snow/ice melt are important during dry season. Moreover, occasional rainfalls in November and December are essential for winter crops, while regular rainfall in the months between May and June is crucial for rice seedlings, in Nepal. On the other hand, increased precipitation in September and October can have an adverse impact on rice production. Similarly, surface air temperature changes in different months may have varying degree of influence on mountain environment and hydrological outputs of the catchment.

1. 4 Thesis outline

This thesis has seven chapters. This chapter introduced the aim and objectives of the study after providing some background on river discharge variability and potential influence of climatic and anthropogenic changes.

Chapter 2 describes the materials and methods of the study. Introduction of the Bagmati and Marsyangdi river catchments is provided including a brief description of their geographical settings. It also provides detail of the datasets as well as the overview of processing and analysis techniques used.

Chapter 3 examines spatial and temporal variabilities in LULC, which in fact represent the most important components of human activities, in terms of potential impact on runoff and river discharge in the two river catchments. LULC changes in the Bagmati river catchment have been published in (Tuladhar et al., 2019a)[1], therefore only a brief summary of the results are provided for Bagmati river catchment, followed by detailed results for the Marsyangdi river catchment. Furthermore, a discussion of the results from the two catchments in relation to their geographical settings and existing studies is provided.

Chapter 4 analyses spatio-temporal variabilities in precipitation and surface air temperature at the stations in and around the two catchments. Results on precipitation variability in terms of spatial distribution, precipitation regime as well as long-term trend and 5-yearly departure from long-term mean at annual and monthly scale are provided. Since the spatio-temporal variability in precipitation in the Bagmati River catchment has already been published in (Tuladhar et al., 2019b)[2] only a brief summary is provided in results section for Bagmati catchment. Variabilities in temperature are presented in terms of spatial distribution and long-term trend results in daily minimum and maximum temperature as well as the diurnal temperature range at annual and monthly scales. The chapter then provides a discussion of the results on temperature and precipitation variability for the two catchments in relation to topographical variabilities as well as comparison with results of other studies.

Chapter 5 presents a detailed assessment of spatio-temporal variabilities in river discharge from the two river catchments and their sub-catchments. Results of long-term trends in average, minimum and maximum discharge at monthly and annual scales as well as decadal departures from long-term mean are presented. Results are also

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[1] Tuladhar, D, Dewan, A, Kuhn, M, Corner, R.J (2019) The Influence of Rainfall and Land Use/Land Cover Changes on River Discharge Variability in the Mountainous Catchment of the Bagmati River, **Water** 11.12 (2019), 1-21.

[2] Tuladhar, D, Dewan, A, Kuhn, M, Corner, R.J (2019) Spatio-temporal rainfall variability in the Himalayan mountain catchment of the Bagmati River in Nepa, **Theoretical and Applied Climatology** 139.1 (2020): 599-614.

discussed in relation to the geographic characteristics of the sub-catchments and existing studies.

Chapter 6 analyses and discusses associations between the hydro-climatic variables and LULC changes in the two river catchments. Results of correlation between precipitation, minimum temperature, maximum temperature, estimated surface runoff and river discharge for the two catchments and their sub-catchments are presented. Influence of the climatic variables and major LULC changes are also analysed using results of multiple regression.

Chapter 7 provides the conclusions of the study. Main conclusions related to the objectives of the study are followed by some specific findings. Limitations of the study and few recommendations for further works are also provided.

2 MATERIALS AND METHODS

The Himalayan river systems play a significant role in fulfilling the demand for water resources of a massive population in the South Asian region. The Ganges is one of the major rivers in this region in terms of its catchment size and the population that depends on it for water. The importance of water resources for various purposes and dependence on naturally available freshwater is even higher in developing countries, such as Nepal. As described in Chapter 1, the two mountain river catchments selected for this study, the Bagmati and Marsyangdi river catchments (Figure 2.1), represent two very common but contrasting cases of the Himalayan mountain region in terms of physiographical settings (e.g. elevation range, general climate) and the level of human activities (e.g. agriculture, urbanisation). Apart from these, the availability of a reasonable number of hydro-meteorological stations with long-term data (>30 years) was also taken into consideration while selecting the two river catchments.

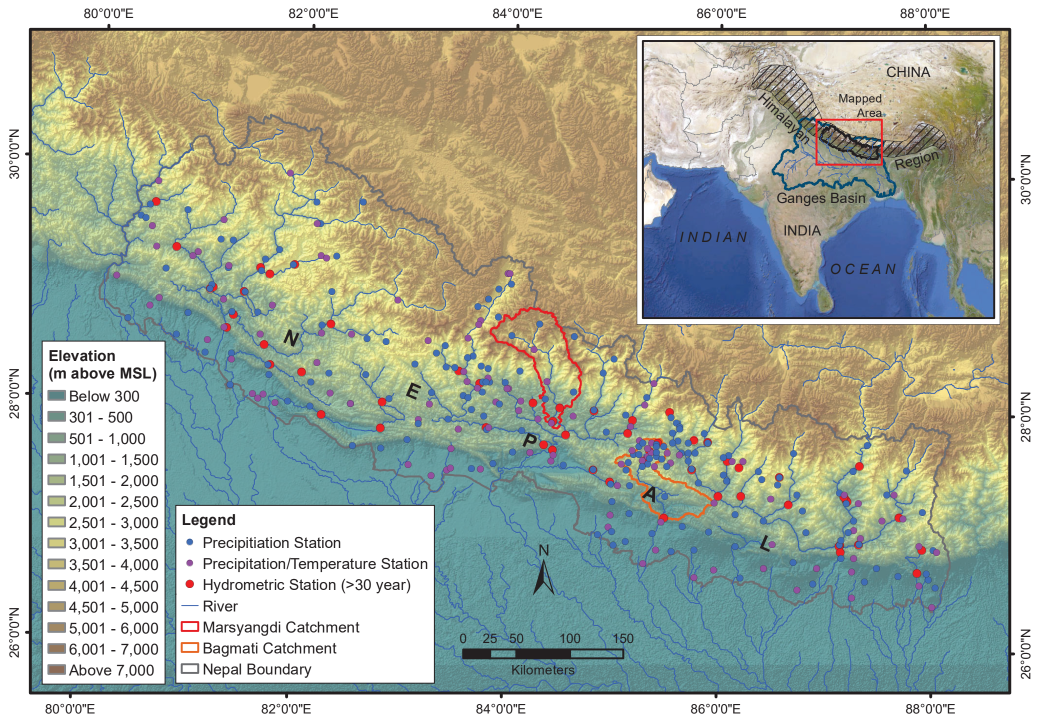


Figure 2.1 Hydro-meteorological stations in Nepal and location of Bagmati and Marsyangdi catchments

Next section provides an introduction of the two river catchments in terms of their geographical settings. This is followed by descriptions of the data sources used in the study. Section 2.3 provides details on processing and analysis techniques used for the examination of precipitation, surface air temperature, river discharge and LULC variabilities as well as association between these variables. The description of the Bagmati river catchment provided here is taken from Tuladhar et al. (2019a) with minor modifications as appropriate.

2. 1 Description of the study areas

2.1.1 Bagmati catchment

Located in Bagmati province of Nepal, the Bagmati River originates from the mountain springs north of Kathmandu valley. It flows south through the valley, a mid to low elevation mountain region, and the Terai plain, to eventually converge with the Ganges River system. This study focuses on the 2806 km^2 area of the middle and upper Bagmati River catchment in Central Nepal (Figure 2.2). For sub-catchment analysis, the 15 km^2 catchment of the Bagmati River, upstream of Sundarijal hydrometric station is defined as headwater catchment. This area is within the Shivapuri-Nagarjun national park and has been protected since 1976 (ADB, 2013). The 605 km^2 area upstream of Khokana station mostly consisting of the Kathmandu valley and surrounding mountains is defined as upper catchment (Babel et al., 2014; Panthi et al., 2017; Thakur et al., 2017). The 2201 km^2 area downstream of Khokana but upstream of Pandheradovan station is described as middle catchment (Babel et al., 2014; Panthi et al., 2017). Thus, the three sub-catchments of Bagmati River, delineated based on the three available river gauge locations, represent contrasting geographical settings within the catchment.

The Bagmati catchment covers the Kathmandu, Lalitpur and Bhaktapur districts entirely, and parts of the Kavre, Sindhuli, Makwanpur, Rautahat and Sarlahi districts of Nepal. Based on Shuttle Radar Topography Mission (SRTM) data (Jarvis et al., 2008), the elevation of the Kathmandu valley ranges between 1170 and 1400 m, whilst the surrounding mountains extend up to 2780 m. Elevations in the lower parts of the middle catchment range between 140 m and 600 m, while higher parts of the Kavre, Sindhuli, upper Makwanpur and southern Lalitpur range from 1500 m to 2800 m.

The climate in the southern parts of the middle catchment, including lower hills and valleys (<1000 m), is sub-tropical. The mid-elevation mountain ranges and valleys (1000–2000 m) have a warm temperate climate whilst the higher mountain parts experience a cold temperate climate (Kansakar et al., 2004; Mishra & Herath, 2014; Pokharel & Hallett, 2015).

Precipitation, mostly in the form of rainfall, is the main source of water input to the catchment and none of the rivers are snow fed. The Indian summer monsoon delivers more than 80% of the annual rainfall between June and September (Nayava, 1980; Tuladhar et al., 2019b). The westerly systems originating from the Mediterranean region deliver occasional winter and spring precipitation between November and March (Nayava, 1980). River discharge in the region is related to rainfall pattern, peaking in July/August and reaching a low between January and April.

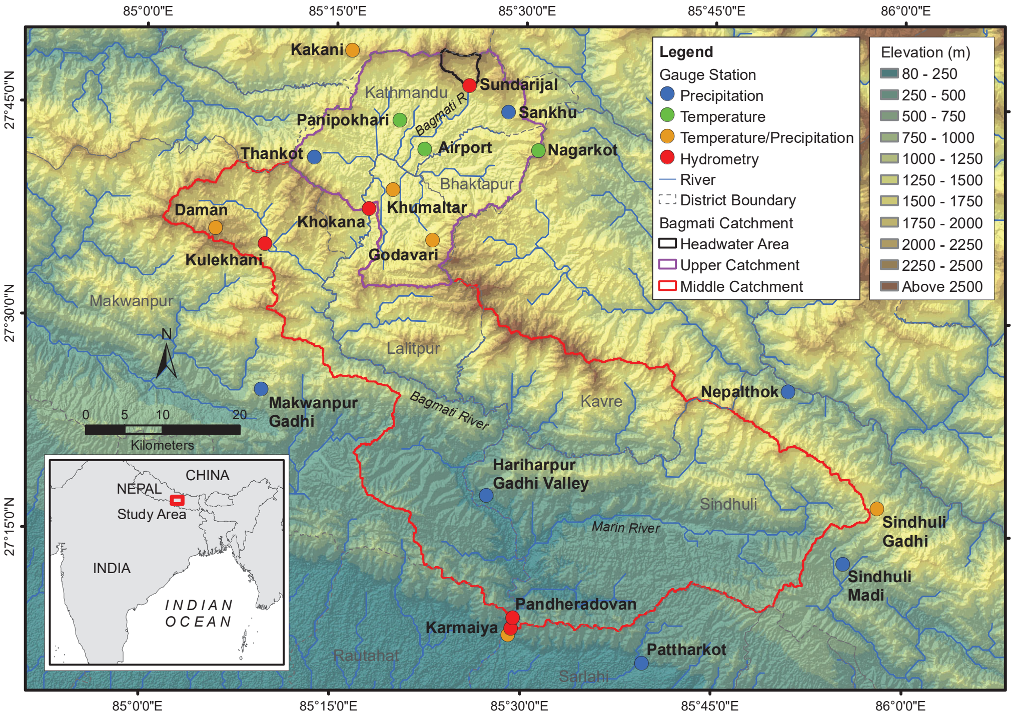


Figure 2.2 Bagmati River catchment and location of hydro-meteorological stations used

The lower parts of the Kathmandu valley are generally covered by agriculture and urban lands. Based on the area-weighed population (Section 2.2.2) estimated from district level census data (CBS, 2014), the permanent population of the Bagmati catchment was 2.7 million in 2011. However, at least 30% more people are estimated to live in the Kathmandu valley temporarily (KUKL, 2010; Shrestha, 2012) and the total population was estimated to be over 4 million (NRB, 2012). Outside the Kathmandu valley, agricultural activities not only take place on valley bottoms and lowlands, but also on the mountain slopes that would otherwise be covered by forest and shrubs (Bastakoti et al., 2017; Lamichhane & Shakya, 2019; Tuladhar et al., 2019a).

2.1.2 Marsyangdi catchment

Located in Gandaki province of Nepal, the Marsyangdi River is one of the major rivers of the Himalayan region (Bookhagen & Burbank, 2010). As shown in Figure 2.3, this catchment consists of mid mountain ranges in the south and high Himalayan ranges in the north. The Marsyangdi River originates from the slopes of a glacial region near Tilicho lake (4919 m) in the north-western part of the catchment and flows southeast along the Manang valley before turning south across the high to mid mountains. It is joined by several other tributaries originating from glaciated mountain regions. The Marsyangdi River then feeds into the Gandaki River, which flows south through the Terai region to the Ganges River system. This study focuses on the 4114 km^2 catchment of the Marsyangdi River upstream of Bimalnagar gauge station. The mid to high mountain catchment (3003 km^2) upstream of Bhakundebesi is described as upper catchment. The 308 km^2 catchment of Chepe tributary, upstream of Garambesi gauge station is described as Chepe sub-catchment.

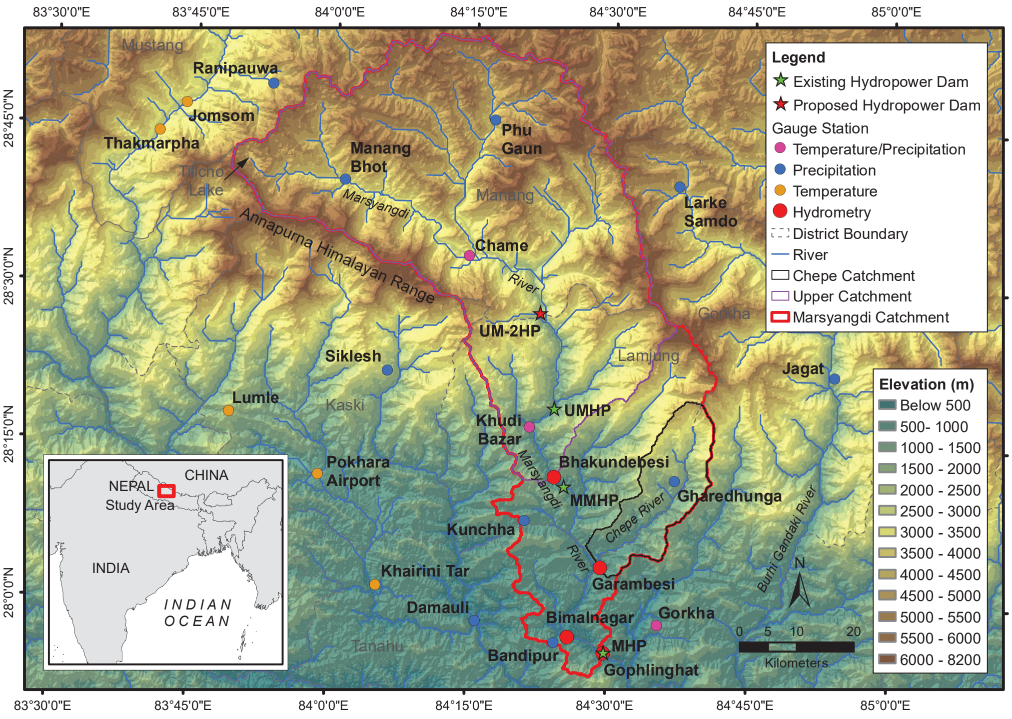


Figure 2.3 Marsyangdi River catchment and location of hydro-meteorological stations used. Abbreviations: Marsyangdi Hydropower (MHP), Middle Marsyangdi Hydropower (MMHP), Upper Marsyangdi Hydropower (UMHP), Upper Marsyangdi-2 Hydropower (UM-2HP).

The Marsyangdi River has a higher discharge compared to the Bagmati River and has been used to generate hydropower in a few locations. Currently, three run-of-river type hydropower projects viz. Marsyangdi Hydropower (MHP), Middle Marsyangdi Hydropower (MMHP) and Upper Marsyangdi Hydropower (UMHP) with capacities of 70, 60 and 50 megawatts respectively, are operational along the Marsyangdi River

(Chiluwal et al., 2021). In addition, development of Upper Marsyangdi-2 Hydropower project (UM-2HP) with a capacity of 500 megawatts is approved for construction in the near future. Hence, the river discharge is not only important for the catchment and downstream region but also has socio-economic implications for the whole country.

Marsyangdi catchment covers Manang district as a whole and parts of Lamjung, Gorkha, Tanahu and Kaski districts of Nepal. This catchment features a diverse range of climatic condition, due to substantial topographic variations. Elevation within the catchment ranges from 340 m to 8091 m above mean sea level and generally increases from south to north. The majority (66%) of the catchment area is above the elevation of 3000 m and 28% is above 5000 m.

The general climate in the foothills (<500 m) and low mountains (<1000 m) as well as valley bottoms of the mid mountain region (1000–2000 m) is subtropical, while it is warm temperate on valley slopes. The climate on higher slope and ridges above 2000 m is cool temperate, while the high mountain regions above 3000 m are alpine (Diodato et al., 2010; Kansakar et al., 2004). As in the case of Bagmati catchment, the Indian summer monsoon delivers most of the annual precipitation in the region. Higher parts of the mid mountain region receive occasional snowfall, while the higher Himalayan region above (5000–6000 m) receives most of the precipitation in solid form (Kansakar et al., 2004; Nayava et al., 2017; Singh & Kumar, 1997). The westerly systems deliver most of the winter precipitation in the region, which is crucial for the accumulation of snow/ice in the high mountains and glaciers.

Approximately half of the catchment, especially in the upper west, is covered by a nature conservation area with limited human activities. Additionally, more than half of the catchment area is above 4000 m elevation with very little human activities. Above the elevation of 2000 m, only small settlements and some agricultural activities exist on valleys and lower slopes. In the lower parts of the catchment (<2000 m), however human settlements and substantial agricultural activities take place on flat land and valley locations as well as higher parts of mountain slopes. Based on the area-weighed population estimated from district level census data (CBS, 2014), the total population within Marsyandi catchment was just over 0.2 million in 2011.

2. 2 Data sources

2.2.1 Historical gauge records

Observation data recorded over a long period (e.g. >30 year) are required to assess long-term changes in hydro-climatic variables as well as to evaluate likely changes into the near future. Hydro-meteorological data collected in Nepal are managed by the Department of Hydrology and Meteorology, Nepal (DHM). Daily precipitation and temperature records from selected stations within and in the proximity of the two river catchments were acquired from DHM. Due to limited resources, meteorological stations do not have uniform coverage across Nepal and the stations are very sparse in remote parts of high mountain regions (Kansakar et al., 2004).

Alternative data derived from remotely sensed products (e.g. TRMM, GRACE) have been used to study hydro-climatic variabilities in Nepal (Barros, 2004; Fu & Freymueller, 2012; Pokharel et al., 2020). However, due to the shorter historical coverage and limitations related to coarse spatial resolutions (Andermann et al., 2011), such data are not suitable for long-term change analysis and fine scale spatial variability within these river catchments. Therefore, despite the lack of ideal distribution of meteorological stations, the precipitation and temperature records available at all suitable stations have been acquired and used in the study.

Daily precipitation records from 12 stations (cf. Table 2.1 and Figure 2.2 were used to examine precipitation changes in the Bagmati catchment, while records from 13 stations were used for the Marsyangdi catchment (cf. Table 2.1, Figure 2.3). Since not all the precipitation stations had temperature data, slightly different sets of stations were used for the study of temperature and precipitation. For the Bagmati River catchment, daily minimum and maximum temperature data from nine climatic stations were used, while the temperature data from eight stations were used for the Marsyangdi catchment (Table 2.2).

Table 2.1 Details of stations used for the study of precipitation. Note: * indicates that the data are only used for analysing spatial distribution and not for long-term change.

Station	Short Name	Index No.	Latitude	Longitude	Elevation (m)	Data Used	Missing Data (%)
Bagmati catchment							
Daman	Dam	905	27.60486	85.09417	2265	1970–2011	5.7
Makwanpur	Mak	919	27.41620	85.15620	1050	1975–2015	4.0
Kakani	Kak	1007	27.81439	85.26978	2034	1972–2015	0.7
Thankot	Tha	1015	27.68820	85.22131	1457	1970–2015	0.1
Godavari	God	1022	27.59292	85.37883	1527	1970–2015	2.9
Khumaltar	Khu	1029	27.65175	85.32577	1334	1970–2015	1.9
Sundarijal*	Sun	1074	27.77270	85.42770	1669	1994–2015	3.9
Sindhuli Madi	Sin	1107	27.21829	85.92335	556	1986–2015	13.9
Pattharkot	Pat	1109	27.09985	85.65964	189	1970–2015	1.4
Nepalthok	Nep	1115	27.41967	85.84864	690	1970–2015	0.6
Hariharpur	Har	1116	27.29441	85.45642	250	1978–2015	0.0
Karmaiya	Kar	1121	27.13181	85.48380	139	1984–2015	3.0
Marsyangdi catchment							
Ranipauwa	Ran	608	28.81556	83.86222	3609	1970–2017	10.2
Jagat Setibas	Jag	801	28.35255	84.89732	1334	1970–2017	0.0
Khudi Bazar	Khu	802	28.28221	84.34542	838	1970–2017	1.0
Larke Samdo	Lar	806	28.66667	84.61667	3650	1979–2017	11.2
Kunchha	Kun	807	28.12678	84.34494	820	1970–2017	0.2
Bandipur	Ban	808	27.94183	84.40638	991	1970–2017	0.7
Gorkha	Gor	809	27.97139	84.58944	724	1970–2017	0.1
Chame	Cha	816	28.55090	84.23933	2680	1975–2012	5.4
Damauli	Dml	817	27.96667	84.28333	347	1974–2017	4.3
Manang Bhot	Man	820	28.66627	84.02257	3556	1976–2017	4.2
Gharedhunga	Gha	823	28.14751	84.58003	1088	1977–2017	7.5
Siklesh	Sik	824	28.35806	84.10449	1996	1978–2017	0.4
Phu Gaun*	Phu	834	28.76667	84.28333	4100	2003–2010	36.4

Table 2.2 Details of stations used for the study of surface air temperature. Note: Ktm* Airport denotes Tribhuvan International airport – Kathmandu, Pok* Airport denotes Pokhara domestic airport.

Station	**Short Name**	**Index No.**	**Latitude**	**Longitude**	**Elevation (m)**	**Data Used**	**Missing Data (%)**
Bagmati catchment							
Daman	Dam	905	27.60486	85.09417	2265	1971–2010	11.6
Kakani	Kak	1007	27.81439	85.26978	2035	1972–2017	2.7
Godavari	God	1022	27.59292	85.37883	1527	1971–2017	5.1
Khumaltar	Khu	1029	27.65175	85.32577	1334	1970–2017	1.0
Ktm* Airport	Ktm	1030	27.70382	85.35625	1337	1970–2017	0.1
Panipokhari	Pan	1039	27.72864	85.32415	1329	1972–2016	4.9
Nagarkot	Nag	1043	27.69335	85.52086	2147	1977–2017	1.1
Sindhuli Madi	Sin	1107	27.21829	85.92335	556	1989–2017	10.9
Karmaiya	Kar	1121	85.48380	27.13181	139	1984–2017	4.7
Marsyangdi catchment							
Jomsom	Jom	601	28.78401	83.72982	2744	1982–2017	5.7
Thakmarpha	Thk	604	28.73887	83.68183	2566	1970–2017	4.1
Khudi	Khd	802	28.28221	84.34542	838	1970–2016	2.9
Pok* Airport	Pok	804	28.20018	83.97952	827	1970–2017	0.1
Gorkha	Gor	809	27.97139	84.58944	724	1970–2017	5.2
Lumle	Lum	814	28.29654	83.81791	1740	1970–2017	0.5
Khairini Tar	Khr	815	28.02696	84.08660	515	1970–2017	1.6
Chame	Cha	816	28.55090	84.23933	2680	1978–2008	8.9

Daily average river discharge records from three river gauge locations within the study area were acquired for each of the catchments (Table 2.3, Figures 2.2 and 2.3). Selection of the river gauge stations was based on the availability of long-term data as well as their location for the purpose of separating sub-catchments representing different geographic settings. Since most of the hydro-climatic records are available from the early 1970s, this study focuses on variation in temperature, precipitation and river discharge between 1970 and 2017.

Table 2.3 Details of hydrometric stations used for the study of river discharge. Note: Pandheradovan and Bimalnagar are new locations replacing Karmaiya and Gophlinghat stations, respectively.

Station Name	**Index No.**	**Latitude**	**Longitude**	**Elevation (m)**	**Basin Area (km^2)**	**Data Used**	**Missing Data (%)**
Bagmati catchment							
Sundarijal	505	27.77500	85.42778	1600	15	1970–2017	1.5
Khokana	550.05	27.62889	85.29472	1250	620	1992–2017	0.0
Pandheradovan	589	27.15167	85.49167	180	2805	1978–2017	2.7
Karmaiya	590	27.13944	85.48944	152	2806	1965–1978	2.2
Marsyangdi catchment							
Garambesi	440	28.06139	84.48972	442	309	1970–2017	0.9
Bhakundebesi	439.35	28.20361	84.40306	610	3003	2000–2017	0.8
Bimalnagar	439	27.95073	84.43022	354	4052	1987–2017	4.9
Gophlingghat	439.8	27.92639	84.49500	320	4115	1974–1986	0.0

2.2.2 Remote sensing data

Remotely sensed images are widely used for mapping/estimation of LULC. Depending on the purpose of a study and resource availability, satellite images of various spatial resolutions can be used. However, despite availability of various image processing and classification techniques, it still requires substantial computational resources for processing and validation, especially if it has to be done for multiple periods. There is no complete availability of reliable LULC data that can be used for studying historical changes in the two river catchments. Various global coverage of pre-processed LULC products based on historical satellite images such as Moderate Resolution Imaging Spectroradiometer (MODIS) and Advanced Very High Resolution Radiometer (AVHRR) are also available, however there are some limitations in spatial and attribute accuracy of such datasets (Leroux et al 2017, Liang et al 2017). Hence, considering consistency required in LULC attribution as well as free availability, Landsat images between 1975 and 2016 are selected for the mapping of historical LULC in approximately 10-year intervals to reflect the LULC of five decades since the 1970s.

Most of the Landsat images available between May and August have high cloud cover. Moreover, separating shrubs and forest from agricultural areas is best done in dry season when there are less crops and grass, therefore the images between November and April (dry season) were chosen. Due to unavailability of the appropriate Landsat images around 1985, images from 1988 were used instead. A list of Landsat images used in the study for mapping LULC in the Bagmati and Marsyangdi catchments are presented in Table 2.4.

Table 2.4 Landsat images used for mapping LULC of the catchments. Note: images related to underlined dates are used as main image and cover greater than 90% of the study area. MSS, TM and OLI stand for Multi Spectral Scanner, Thematic Mapper and Operational Land Imager, respectively.

Satellite-Sensor	Acquisition Date	Image Path/Row
Bagmati Catchment:		
Landsat 2-MSS	12 Nov 1975	151/041
Landsat 5-TM	3 Apr 1988	141/041
Landsat 5-TM	7 Apr 1995	141/041
Landsat 5-TM	2 Apr 2005 & 31 Jan 2006	141/041
Landsat 8-OLI	24 Jan 2015 & 12 Feb 2016	141/041
Marsyangdi Catchment:		
Landsat 2-MSS	01 Apr 1975 & 04 Dec 1976	154/040 & 153/040
Landsat 5-TM	06 Feb 1988, 28 Nov 1988 & 29 Nov 1988	142/040, 142/041 &141/41
Landsat 5-TM	08 Nov 1994 & 05 Nov 1995	142/040 & 142/041
Landsat 5-TM	24 Dec 2006 & 19 Feb 2007	142/040 & 141/040
Landsat 8-OLI	05 Apr 2015 & 03 Feb 2016	142/040 & 142/040

The spatial resolution of Thematic Mapper (TM) and Operational Land Imager (OLI) images is 30 m, while the Multi Spectral Scanner (MSS) images used for 1975–1976 have a resolution of 60 m. The TM and OLI sensors have additional spectral bands and results of existing studies suggest that Landsat images taken from these sensors are comparable with MSS images (Royer et al., 1987; Saunier et al., 2017). Images from these sensors have been used successfully to map long-term LULC changes (Ross et al., 2017; Taft & Kühle, 2018; Vittek et al., 2014; Yang et al., 2019). These images are therefore considered suitable for the classification of LULC into the broad categories (e.g. built-up, agriculture, forest, unvegetated, snow) in this study.

2.2.3 Other data

MODIS 8-day maximum snow cover data (463 m spatial resolution) between September and November from 2000 to 2019 were also used to derive annual pre-winter minimum snow cover in Marsyangdi catchment. District level population data published by the Central Bureau of Statistics (CBS) Nepal, were acquired from the population monograph of Nepal (2014) and Open Data Nepal website. These were used to estimate the area-weighed population based on the population density and district area within the catchments. SRTM V4 elevation data available in 90 m resolution (Jarvis et al., 2008) were downloaded from the United States Geological Survey (USGS) website for topographical analysis and to delineate the river catchment boundaries. Digital soil data (FAO, 2003) were also used for the purpose of delineating hydrological soil groups.

2. 3 Data processing and analysis

Most of the data processing and analysis techniques used in this study are described in Tuladhar et al. (2019b) and Tuladhar et al. (2019a). Appropriate descriptions of the processing and analysis techniques are provided below with minor changes.

2.3.1 Processing of hydro-meteorological gauge records

While in-situ gauge records are best for examining hydro-climatic variability, data recorded over long historical periods require a qualitative check and validation before analysis. Apart from limitations related to missing records, climatic time series data can have non-natural variations introduced by gradual or abrupt changes in various components of the data collection, transformation methods and location of the gauging station (Costa & Soares, 2009; Wang et al., 2010). Therefore, RHtestsV4 package was used in R software (R-Core-Team, 2013) to test homogeneity of the daily temperature and river discharge time series data, while RHtests package for daily precipitation was used to process daily precipitation data. The software integrates a data adaptive Box-Cox transformation procedure to the penalized maximal F test and also takes the non-normal distribution of daily precipitation series into account (Wang et al., 2010). Information about historical changes in gauge location and any other settings that could be used to attribute potential changes in the records were largely unavailable. Therefore, inhomogeneous daily time-series data were homogenized by applying mean based adjustments with respect to the change points detected in the monthly series.

Out of the 47 hydro-climatic stations examined for long-term variability (Tables 2.1 to 2.3), 16 stations had less than 1% missing data, while 19 other stations had 1% to 5% missing records. Two temperature and three precipitation stations had 10% to 13.9% missing data, however these records are included in this study due to lack of appropriate alternatives. Considering the absence of strong correlation between monthly precipitation at nearby stations, data gaps in daily time series (up to a maximum of 2 years) were filled with 5-year daily averages (e.g. Shrestha, 2000) based on the daily records for two earlier and two latter years for the same station.

The gap-filled homogeneous daily T_{min} and T_{max} were used to create diurnal temperature range (DTR) series. Monthly and annual precipitation series were created based on total precipitation, whereas T_{min}, T_{max} and DTR at monthly and annual scales represent corresponding average of the daily series. Minimum, average and maximum river discharge at monthly and annual scale were created using minimum, average and maximum of the daily series, respectively.

2.3.2 Monthly distribution

Monthly distribution of precipitation, T_{min}, T_{max} and average river discharge were analysed using their long-term means (taken over the entire data periods). Standard z-scores were calculated for long-term mean of monthly precipitation and river discharge. The hydrological regime at each of the precipitation and river gauge stations was then classified based on the distribution of the standardized long-term monthly means (e.g. Hannah et al., 2005; Kansakar et al., 2004).

2.3.3 Long-term trend

Analysis of monotonic trend is an important tool to reveal the nature of long-term change in a hydro-climatic variable (Machiwal & Jha, 2012). The Mann-Kendall (MK) test is a widely used non-parametric technique to determine the existence of a significant monotonic trend in climatic variables. Such non-parametric methods use ranking of data rather than actual values, which reduces the impact of outliers in the time series (Hamed, 2008). Furthermore, the MK test is also suitable for data such as precipitation series, that are not normally distributed (Hamed, 2008). In this study, precipitation, T_{min}, T_{max}, DTR and river discharge time series at annual and monthly scale were tested for the presence of significant long-term (1970–2017) trends using the MK test. In the remainder of this study, monotonic trends statistically significant at 95% and 90% confidence intervals (CI) are described as significant and moderately significant, respectively.

2.3.4 Auto correlation and pre-whitening

The MK trend test result can be affected by the presence of autocorrelation in the series. Positive autocorrelation in the series can increase the probability of obtaining a significant trend (Hamed, 2008), while negative autocorrelation may decrease such probability (Yue et al. 2002). Therefore, the Ljung Box test statistic (Ljung & Box, 1978) was used in this study to determine, if the autocorrelation in the series is significant at 95% confidence interval.

The effect of autocorrelation can be eliminated either by removing it from the series before performing the trend test or by using a method that addresses the issue of autocorrelation such as a modified MK test (Hamed & Ramachandra Rao, 1998; Hirsch et al., 1982). In this study, pre-whitening option with Auto Regressive Integrated Moving Average (ARIMA) modelling (Box et al., 2008) was used on the hydro-climatic time series with significant autocorrelation. It also uses the differencing process to accommodate the potential non-stationarity of the series. Based on the ARIMA results, an optimal model fitting the time series with the smallest number of significant parameters and highest degree of freedom was then selected based on Bayesian information criterion (BIC) statistics (Machiwal & Jha, 2012) for trend tests.

2.3.5 Sen's slope

Sen's slope estimator is based on a linear model to estimate the rate of change and is a commonly used method in analyzing hydro-meteorological time-series data (e.g. Da Silva et al., 2015; Gocic & Trajkovic, 2013; Javari, 2017). In this study, Sen's slope value and its percentage in relation to the intercept are used to represent the magnitude of the change.

2.3.6 Departure from long-term mean

Temporal variation of precipitation was also analyzed in terms of departures (differences) of five-yearly average at annual and monthly scale in relation to the corresponding long-term (1970–2017) means. Similarly, decadal variation in annual and monthly river discharge were also analyzed. The departure values were standardized by calculating z-score value with respect to standard deviation of the corresponding time series. Positive (negative) departure from the long-term mean by greater than one standard deviation is referred in this study as 'substantially' higher (lower) departure.

2.3.7 Spatial interpolation

For the purpose of estimating surface runoff (Section 2.3.9) the basin average precipitation series was derived based on spatial interpolation of daily records. Furthermore, the basin average series of T_{min} and T_{max} were also derived to analyse association with precipitation and river discharge. In general, geostatistical interpolation methods such as kriging and co-kriging are expected to provide a better estimation of climatic variation (Goovaerts, 2000; Li & Heap, 2011; Ly et al., 2013) while deterministic methods such as inverse distance weighting (IDW), can also provide appropriate results (Hartkamp et al., 1999; Webster & Oliver, 2007). Based on preliminary comparison of kriging and IDW results, IDW of daily precipitation were used to represent basin average precipitation. Considering the high dependency of temperature distribution on elevation (e.g. Chalise et al., 1996; Nayava et al., 2017), co-kriging method incorporating digital elevation data was used to calculate basin average T_{min} and T_{max}. These interpolation techniques are successfully used in similar studies despite the inherent uncertainties associated with the lack of dense measurements stations (Gemmer et al., 2004; Li & Heap, 2011; Pingale et al., 2014; Webster & Oliver, 2007). Since the main aim was to derive the basin-average series to examine association between hydro-climatic variables generalized at sub-catchment level, the results interpolated using IDW and co-kriging were considered reasonable for this study.

2.3.8 Land use/land cover (LULC) mapping

LULC within both catchments were derived using selected Landsat images (cf. Table 2.4). The images were classified using maximum likelihood rule based supervised classification. Data collected during field visits in 2016 and 2017 as well as information available from higher resolution historical images such as on Google Earth Pro was also used to assist the classification process.

The LULC classifications for the study were kept to broad categories (Table 2.5) that were mappable consistently using historical Landsat images. Areas showing the characteristics of a forest, including tree cover and no other primary use (DFRS, 1999), were mapped as forest. Apart from obvious shrub lands, areas which were not evidently distinguishable as agriculture or forest and showing mixed characteristics are also classified as shrubs. The shrub area in the region can, in fact, be considered as depleted forest or mixed vegetated land adjacent to agricultural areas (DFRS, 1999) . Urban areas were classified as either built-up or a mix of settlements that included some vegetated area, such as agriculture or trees. Smaller towns and dispersed settlements that are generally a mixture of agriculture, sparse trees and scattered houses could not be distinguished consistently with Landsat images, therefore were not classified separately as urban areas. Since most of the water bodies in the two catchments were not mappable appropriately due to their small size in relation to the image resolution, coverage and change in water bodies are not analysed.

The image classification results derived from the 60 m resolution MSS (30 m resolution TM & OLI) image were filtered by merging areas that were smaller than three (five) image pixels with the surrounding LULC classes. The accuracy of each LULC results for Bagmati and Marsyangdi catchment were tested using 400 and 450 stratified random sites respectively, that were categorized based on Landsat and other higher resolution historical images available in Google Earth Pro. The accuracy statistics were calculated by comparing the actual LULC and the classified LULC results at the random sites. Descriptions of the LULC classes mapped in the two catchments and their average accuracy over the five mapping periods are presented in Table 2.5. The Kappa coefficients for the LULC classifications results in the Bagmati (Marsyangdi) catchments were between 0.89 and 0.91 (0.90 and 0.93) and the overall accuracy of the results for each mapping period was over 91% (92%).

Table 2.5 Description of LULC classes mapped in Bagmati and Marsyangdi catchment and their accuracy. Note: coverage and accuracy for water bodies are not analysed. User's accuracy for overall urban area (mixed urban + built-up area) in Bagmati catchment is 90.0%.

LULC Class	**Description**	**User's Accuracy (%)**
Bagmati catchment		
Forest	All types of forest with primary coverage by trees	98.6
Shrub/grass	Shrubs and grass areas including patchy vegetation and no other use	80.4
Agriculture	Land primarily used for agricultural activities	94.4
Mixed urban	Human settlements with partial coverage by open space and vegetation	84.8
Built-up	Densely built-up residential, commercial and industrial area including roads	87.6
Non-agricultural/ open field	Open land with or without vegetation and no other use (e.g. flood channel)	98.0
Water body	All water bodies including river and lakes	NA
Marsyangdi catchment		
Forest	All types of forest with primary coverage by trees	89.9
Shrub/grass	Shrubs and grass areas including patchy vegetation and no other use	93.7
Agriculture	Land primarily used for agricultural activities	91.7
Unvegetated	Barren land with no notable vegetation (e.g. on high mountain slopes)	94.2
Snow/glacier	Area coved with snow and glaciers	97.7
Water body	All water bodies including river and lakes	NA

Since the Landsat image captured in different months between November and April were used for the LULC mapping, changes in snow cover might have been affected by seasonal variation. Due to the higher temporal resolution, remote sensing products such as MODIS and AVHRR are also used to monitor dynamic land covers such as snow. For the purpose of supplementing results derived from Landsat images, annual pre-winter minimum snow cover derived from readily available MODIS 8-day maximum snow cover were used to examine annual snow cover change in the Marsyangdi catchment.

2.3.9 Surface runoff estimation

Direct surface runoff indicates the amount of precipitation that is available after surface retention and contributes to a significant portion of river discharge during rainy season. The Natural Resources Conservation Service's curve number (CN) method (Woodward et al., 2003) was used to estimate surface runoff from the sub-catchments, for the purpose of analyzing the impact of LULC and daily precipitation changes. This method calculates direct surface runoff based on precipitation, maximum soil retention and initial abstractions. Maximum soil retention can be estimated based on curve number that is determined by LULC and hydrological soil group (Woodward et al., 2003). Current LULC results and hydrological soil groups based on Food and Agricultural Organization (FAO) soil data (FAO, 2003) were used to identify soil curve numbers, as adopted by Mishra et al. (2009). Initial abstractions can be approximated in relation to maximum soil retention estimated as above. An initial abstraction ratio of 0.05 (i.e., initial abstraction = 0.05 × maximum soil retention), as suggested by Woodward et al. (2003) and Hawkins et al. (2019), was used in this study. The LULC results for five mapped years were used to estimate LULC proportion for other years during 1970–2017, assuming linear changes in LULC. Weighted runoff for sub-catchments were then estimated using percentages of the area with specific LULC-hydrologic soil groups. Apart from changes in precipitation and LULC, river discharge depends on many other factors, such as soil moisture, evaporation, evapotranspiration, etc. However, this study focused on the impact of precipitation and LULC changes only, since other data were not available and more comprehensive modelling was beyond the scope of the study.

2.3.10 Correlation and multiple regression analyses

Pearson's correlation coefficients were calculated to check associations between basin-average precipitation, T_{min}, T_{max}, estimated surface runoff and observed river discharge series at sub-catchment level. Cross correlations were also analysed to examine lagged association. Percentages of annual estimated surface runoff and observed river discharge series with respect to the total precipitation were also compared to analyse associations between them.

Multiple regression analysis was performed to quantify the influence of major LULC changes and precipitation, T_{min}, and T_{max} on river discharge. For the purpose of comparing the relative contributions of the predictor variables, the importance of the variables (predictors) was calculated as the ratio of change in the squared multiple correlation coefficient R^2 (when the variable of interest is not considered) to the overall R^2 (when all predictor variables are considered) (Judd et al., 2011; Tu et al., 2018). Correlation and influence results that are statistically significant at 95% and 90% confidence intervals are referred to as significant and moderately significant, respectively. Correlation coefficient results are interpreted as very weak (0.00–0.19), weak (0.20–0.39), moderate (0.40–0.59), strong (0.60–0.79) and very strong (0.80–1).

2. 4 Chapter summary

Considering the availability of hydro-meteorological data and common but contrasting geographical settings, the Bagmati and Marsyangdi catchments were selected for the study. Bagmati catchment covers low mountains below 1000 m (Siwalik) to mountains up to 2790 m, while topography of Marsyangdi catchment ranges from foothills (<500 m) to high Himalayan mountains up to 8090 m. Having over 28% of its area above 5000 m, most of the major tributaries in Marsyangdi catchment are snow fed, whereas Bagmati is a rainfed system. Total population within Marsyangdi catchment is estimated to be just over 0.2 million, whereas with an estimated population over 4 million in Kathmandu itself, Bagmati catchment has a notably higher level of human activities.

LULC within the two catchments are mapped using supervised classification of Landsat images in approximately 10-year interval. MODIS 8-day snow cover product between 2000 and 2019 is also used to examine annual pre-winter minimum snow cover in Marsyangdi catchment. SRTM elevation data is used to delineate sub-catchment boundaries and for topographical analysis. Daily precipitation records at 12 and 13 stations are used to examine precipitation variability in Bagmati and Marsyangdi catchments, respectively. Similarly daily T_{min}, T_{max} data at nine and eight stations are used to study temperature variability in Bagmati and Marsyangdi catchment, respectively. Daily river discharge records measured at three different locations in both catchments are used to analyse river discharge variability in the two catchments and their sub-catchments.

Daily hydro-meteorological data are checked for homogeneity and gap filled before creating monthly and annual series for further analysis. Distribution of monthly long-term (1970–2017) mean are used to examine monthly pattern of hydro-meteorological variables. Non-parametric Mann Kendall test statistics is used to examine long-term trend. Standardised departure from long-term mean are also examined for precipitation and river discharge.

Basin average precipitation, T_{min}, T_{max} are estimated using spatial interpolation methods, while direct surface runoff was estimated using the curve number method. Correlation analysis is used to examine associations between hydro-climatic variables, while multiple regression results are used to analyse influence of precipitation, T_{min}, T_{max} and major LULC changes on river discharge.

3 SPATIAL DISTRIBUTION AND CHANGES IN LAND USE/LAND COVER IN BAGMATI AND MARSYANGDI CATCHMENTS

3.1. Introduction

Globally, land use/land cover (LULC) has changed in relation to increasing population, largely to satisfy immediate needs for food and other natural resources (Meyer et al., 1994; Ramankutty et al., 2006; Vitousek et al., 1997). Agricultural and grazing areas have increased from 15% to over 35% of total land area in the last century, while urban land has also increased substantially in the latter half of the 20th century (Klein Goldewijk et al., 2010; Pielke Sr et al., 2011; Zhao et al., 2015). These changes, together with industrialisation and increased demand for forest products exert direct and indirect pressure on forest cover around the world.

Even though agricultural lands have increased on most continents, changes in LULC are not uniform and vary substantially on a regional level (Pielke Sr et al., 2011). Urbanisation generally occurs in locations with suitable infrastructure and accessibility to natural resources, but its scale and rate depends on various factors including population change and migration (UN-DESA, 2015). Globally, urban population has increased four-fold between 1950 and 2018 but the increase was more than ten-fold in less developed regions (UN-DESA, 2015). Forest cover has decreased in many parts of the world including Asia, South America and Africa, even though the rate of global average deforestation has slowed down to some extent (FAO, 2009; Pielke Sr et al., 2011). However, forest cover in Asia as a whole, increased during 2000–2010, while Europe has had a net gain in forest cover for the last two decades (FAO, 2009).

The type of land cover in any location depends heavily on climatic setting, but changes in LULC can also have multiple influences on local and regional hydro-climate (Ding & Shi, 2013; Dissanayake et al., 2017; Hale et al., 2008). For instance, increase in agricultural area and forest cover are linked with the cooling of local temperature, while urban landscape can contribute to further heating of the lower atmosphere (Alkama & Cescatti, 2016; Pielke Sr et al., 2011; Roy et al., 2011). Similarly, large scale increase in irrigated cropland is also linked to an increase in precipitation (Rodell et al., 2009; Roy et al., 2011), whereas a reduction in forest cover is seen to reduce precipitation (Suh & Lee, 2004; Werth & Avissar, 2005). Some studies have also found a direct relation between urbanisation and the intensity of rainfall events (e.g. Kishtawal et al., 2010; Pielke Sr et al., 2011). Furthermore, changes in LULC can also influence runoff within a river catchment by altering response of the land surface in a rainfall event.

In general, flat land and lower foothills of the South Asian region are used for urban and agricultural purposes, while some areas are covered with forest. Low to mid mountains of the Himalayan region feature reduced cover by urban areas, while agricultural activities and forest cover may be higher. Agricultural areas have increased substantially, whereas forest cover has decreased in most South Asian countries in the latter half of the 20th century (Kummer & Turner, 1994; Reddy, Saranya, et al., 2018; Zhao et al., 2006). Most urban developments in South Asia expand around existing town and cities, taking more of the surrounding arable or vegetated land. Industrialisation and government policy to maximise arable land for the purpose of securing food supply for large population-base can be related to large scale removal of forest in India and Nepal after the 1950s (Chaudhary et al., 2016; FAO, 2009; Reddy, Pasha, et al., 2018). Forest cover in Nepal decreased from 45% in 1966 to 29% in 1994 (Chaudhary et al., 2016; FAO, 2009), however the rate of decrease has slowed down in recent decades (Chaudhary et al., 2016). Forest covers were reported to be improving in some parts of Nepal especially from the 1990s, as a result of government regulations and management strategies including community-based forest management (Chaudhary et al., 2016; FAO, 2009; Gautam et al., 2002). Due to climate and soil conditions, high mountain regions (e.g. above 4000 m elevation) have little or no vegetation cover, while snow and glaciated areas are common in high altitude areas (e.g. above 5000 m elevation).

With a population of nearly 1.8 billion (Vadrevu et al., 2017), South Asian countries are facing huge challenges in sustainable development of agricultural and urban areas. Furthermore, crop productivity is seen to have decreased due to many factors including climate change (Dissanayake et al., 2017). This, together with low rates of economic growth in the region may lead to heavy reliance and exploitation of natural resources which can cause concern over future availability of the valuable resources (Dissanayake et al., 2017; Zhao et al., 2006). Increase in agricultural activities and urbanisation in South Asia is also affecting regional climate, biodiversity and hydrology (Madsen, 2013; Vadrevu et al., 2017). Water quality of many rivers in Nepal, India and Bangladesh is reported to have degraded as a result of waste discharge from urban areas (Babel et al., 2011; Karn & Harada, 2001). Therefore, detailed understanding of LULC changes and their association with hydro-climatic changes is significant for sustainable management of natural resources.

LULC within and between the Bagmati and Marsyangdi catchments tends to vary significantly as the result of vast diversity in topography and climate (cf. Section 2.1). Being a typically mountainous part of the South Asian Himalayan region, agricultural activities and forest covers can be expected to be common between lower foothills and mid mountains of both catchments, while the higher elevations of Marsyangdi catchment are mostly unvegetated or glaciated (Paudel et al., 2016). Due to the high concentration of population in the Kathmandu valley, urban land use can be expected to be higher in the Bagmati catchment, relative to the Marsyangdi catchment.

LULC of Nepal has been mapped for 1978, 1986, 1994 and 2010 based on aerial photographs and satellite images (DFRS, 1999; Gautam et al., 2004; LRMP, 1986; Uddin et al., 2015), while mapping of some specific land cover (e.g. forest, snow covered/glaciated areas) has been conducted for a few periods (e.g. Shrestha & Joshi, 2009). Other studies have focused on LULC over smaller parts of the country (Gao et al., 2013; Gautam et al., 2002). Existing studies suggest that in general, forest cover and grass land have decreased, while agricultural and urban areas increased during recent decades. However, there is a considerable spatio-temporal variation in LULC changes in different parts of Nepal (Paudel et al., 2016). Detailed comparisons of LULC, based on existing data are difficult due to the use of different methods and lack of availability in comparable intervals.

The aim of this chapter is to assess historical LULC within the Bagmati and Marsyangdi river catchments between 1975 and 2015. The next section provides a brief description of methods while the results of LULC changes within the Bagmati and Marsyangdi River catchments, are presented in Section 3.3. An analysis is presented to demonstrate spatial and temporal variations within these catchments. Section 3.4 provides a discussion on the results of the two river catchments and their sub-catchments. A chapter summary is provided in Section 3.5.

3.2. Data and methods

As discussed in Chapter 2, considering image availability and resource limitations, LULC of the two river catchments have been mapped approximately in 10-year intervals using Landsat images to represent the mid-decade LULC. Details of Landsat images used to classify LULC in the two catchments are listed in Table 2.4. LULC were mapped using supervised classification and details of processing and accuracy check are provided in Section 2.3.8.

Considering the user accuracy of 90% to 98%, part of the changes reported for forest, agricultural and overall urban area in Bagmati catchment (Table 2.5) could be affected by the accuracy of the LULC results. Similarly, considering the user accuracy of 94% to 98%, part of the changes reported in snow cover and shrub/grass of Marsyangdi catchment can also be related to accuracy of the results. However, small changes in overall coverage by forest, shrub and agriculture (e.g. <2%) in Marsyangdi catchment may be within the error range of the LULC mapping, therefore such changes are not emphasised in the analysis.

MODIS 8-day maximum snow cover data between September and November were also used to examine changes in annual and 5-yearly pre-winter minimum snow cover in Marsyangdi catchment during 2000–2017.

3.3. Results

3.3.1. LULC change in the Bagmati catchment

The results of LULC changes within the Bagmati catchment between 1975 and 2015 is reported in Tuladhar et al (2020) (Appendix A - Article 2). This paper analyses changes in basin average rainfall, LULC and the influence of rainfall and LULC changes on surface runoff and river discharge in sub-catchments of the Bagmati River. A brief summary of the key findings on LULC coverage and changes is provided here.

LULC maps for five years viz. 1975, 1988, 1995, 2005 and 2015 were derived from supervised classification of historical Landsat images. It was classified into broad categories viz. forest, agriculture, shrub, non-agricultural, built-up and mixed urban land (Table 2.5).

Variation in LULC within the Bagmati catchment was analysed for headwater, upper and middle sub-catchments defined in Section 2.1.1. According to the latest LULC map of 2015, 69% of the middle Bagmati catchment is covered by forest, while 28% of land is used for agriculture. The headwater catchment has the highest forest coverage (86%) with only 11% of the catchment area being used for agriculture. However, only 36% of the upper catchment is covered by forest, while agricultural and urban areas cover 38% and 24%, respectively. Due to the limitation in spatial detail of Landsat images in consistently mapping scattered settlements and small towns, especially in mountain regions, they were not mapped separately as urban areas.

Forest coverage is the lowest in flat land (slope <10˚) of Kathmandu valley in the upper catchment and river valleys in the lower catchment. In fact, 85% of the flat land in the elevation between 1000 m and 1500 m is covered by agricultural and urban area, whereas forest cover is over 60% at any other elevation. Except in the Kathmandu valley, agricultural activities generally decrease with increase in elevation and slope.

Analysis of LULC changes showed that forest area in the entire catchment increased by 4.1% between 1975 and 2015 with a slightly higher rate (4.4%) in the middle catchment. The main LULC change within the Bagmati catchment was an increase in urban and built-up areas, in the upper catchment. Mixed urban and built-up areas which only covered 2.3% of the upper catchment in 1975, increased to 23.8% in 2015. The loss of agricultural area in the upper catchment was 37%, most of which is associated with the increase in urban land use, while the 1975–2015 change in agricultural area was negligible in the middle catchment. There was no substantial (e.g. less than 2%) LULC changes in the headwater catchment. Spatial extent and changes in shrub and non-agricultural areas are also nominal (e.g. less than 1%).

3.3.2. LULC change in the Marsyangdi catchment

Historical Landsat imagery for five years viz. 1976, 1988, 1995, 2006 and 2015 were used to derive the approximately 10-year LULC within the Marsyangdi River catchment. The LULC was classified into six broad categories viz. forest, shrub/grass, agriculture, unvegetated land, snow covered/glaciated and water body.

Figures 3.1 to 3.5 show the LULC within the Marsyangdi catchment for the five study years. According to the latest LULC of 2015 (Table 3.1), forest and agriculture areas cover slightly over 30% and 10% of the catchment, respectively. These figures show that lower to middle mountainous regions of the catchment are generally either used for agriculture or covered by forest. Upper parts of the catchment (>3000 m) mostly consist of snow covered/glaciated areas, unvegetated and shrub/grass areas with a very limited coverage by forest. Close to 20% of the total catchment is covered by shrub/grass areas, while approximately 40% is either barren or covered with snow and glaciers. Water bodies covered only 0.2–0.3% of the catchment. However, due to the small size of most river networks, not all water bodies in the catchment are mappable accurately and consistently with Landsat images, therefore no further analysis is done on changes in water bodies.

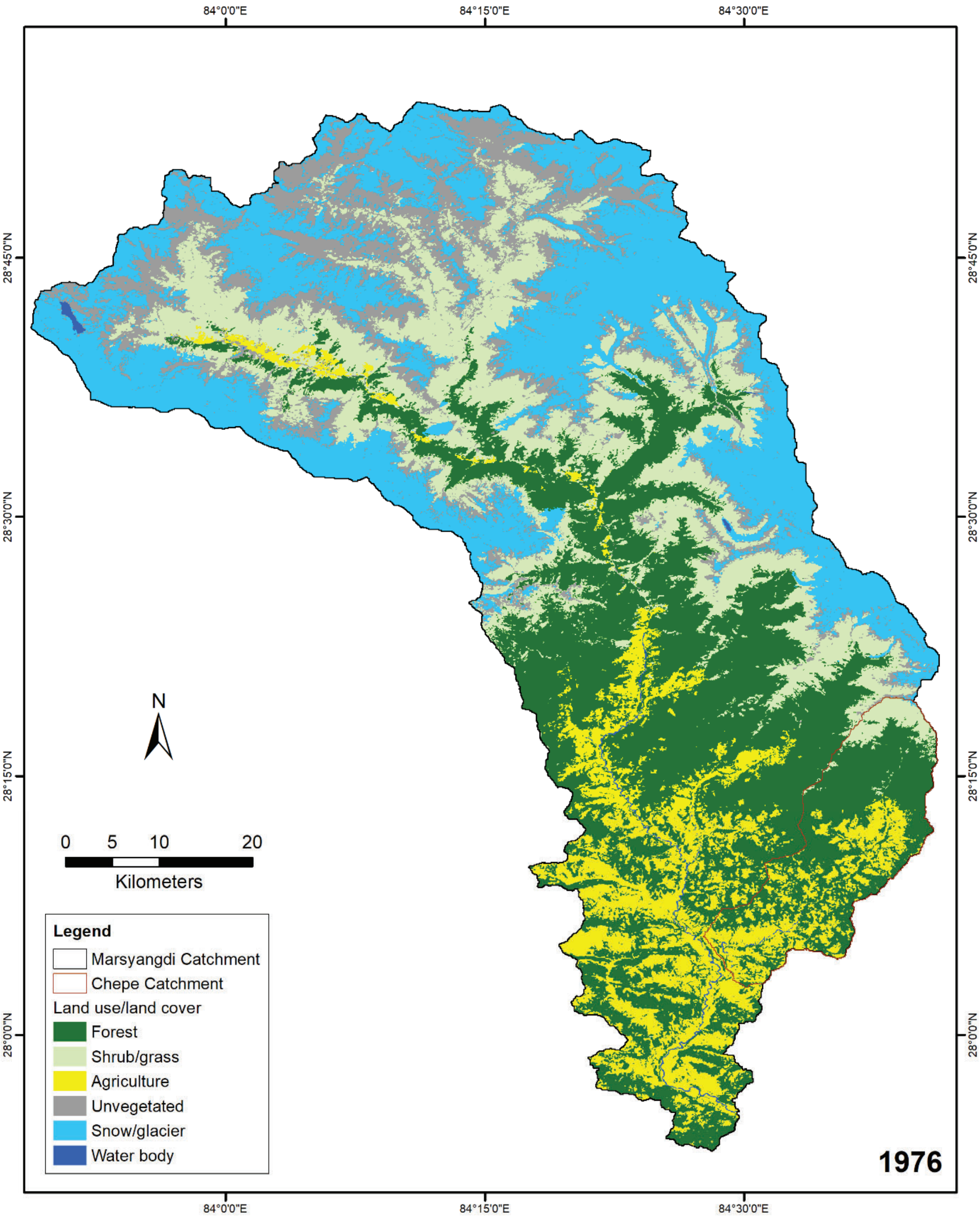


Figure 3.1 Land use/land cover in the Marsyangdi catchment - 1976

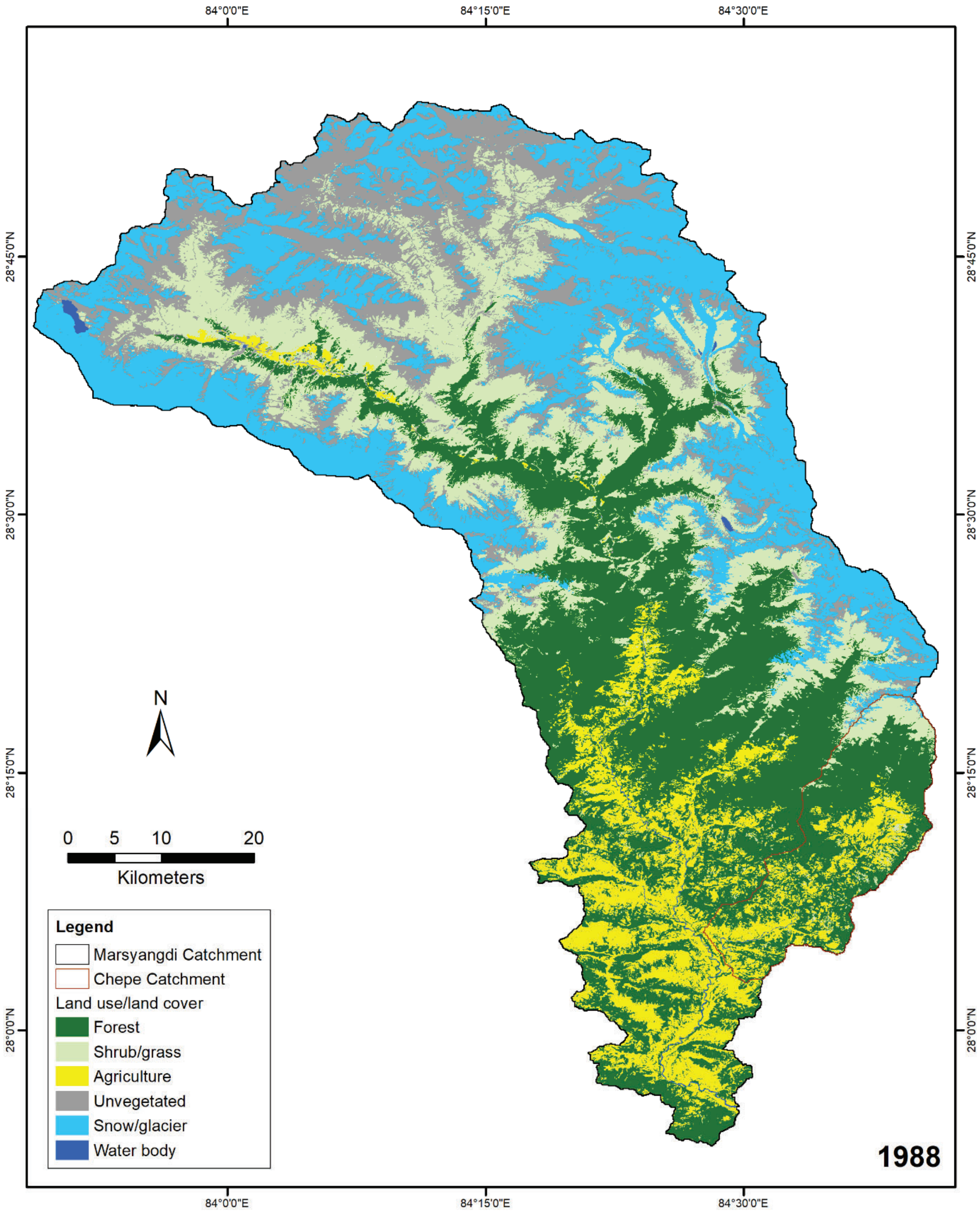


Figure 3.2 Land use/land cover in the Marsyangdi catchment -1988

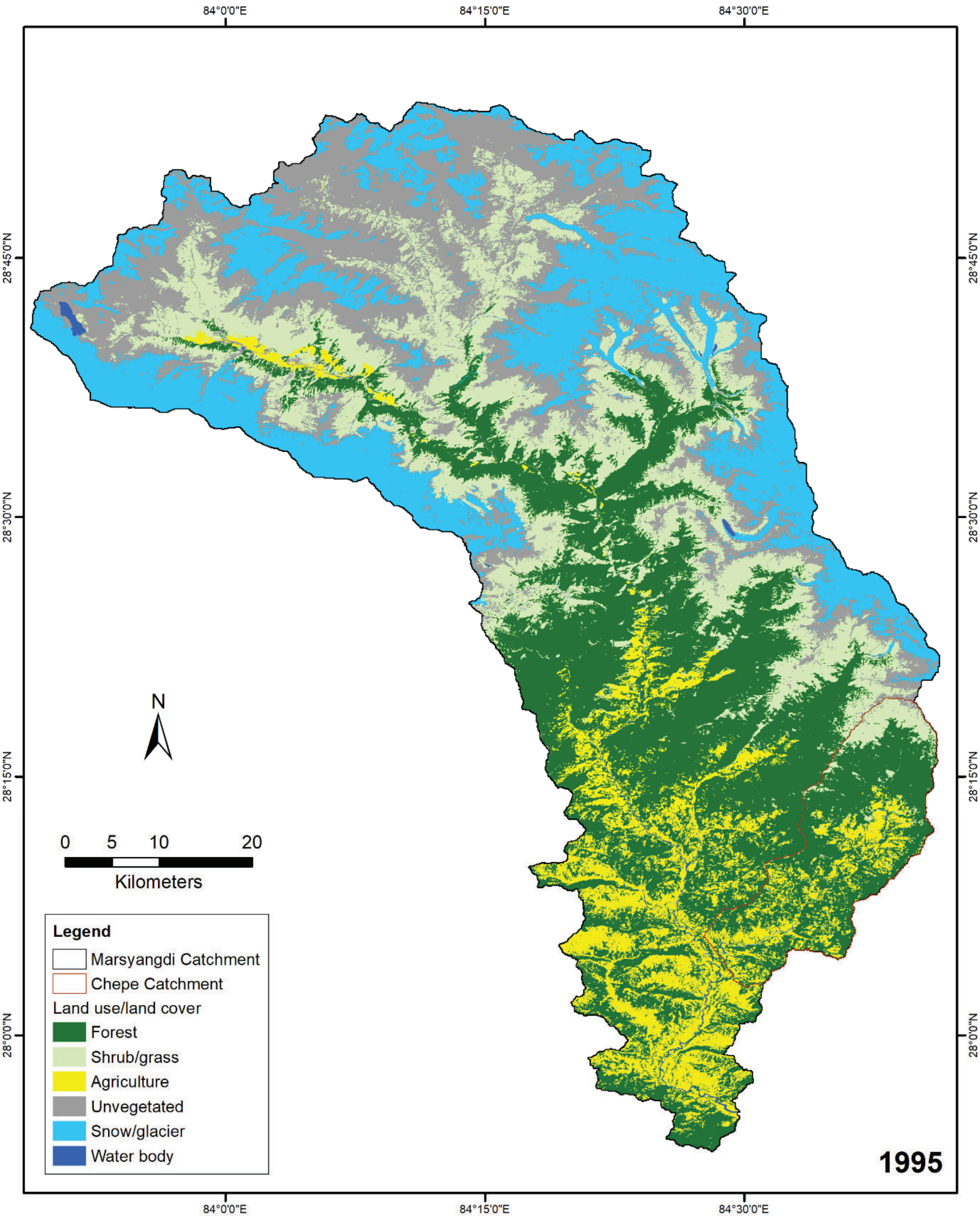


Figure 3.3 Land use/land cover in the Marsyangdi catchment - 1995

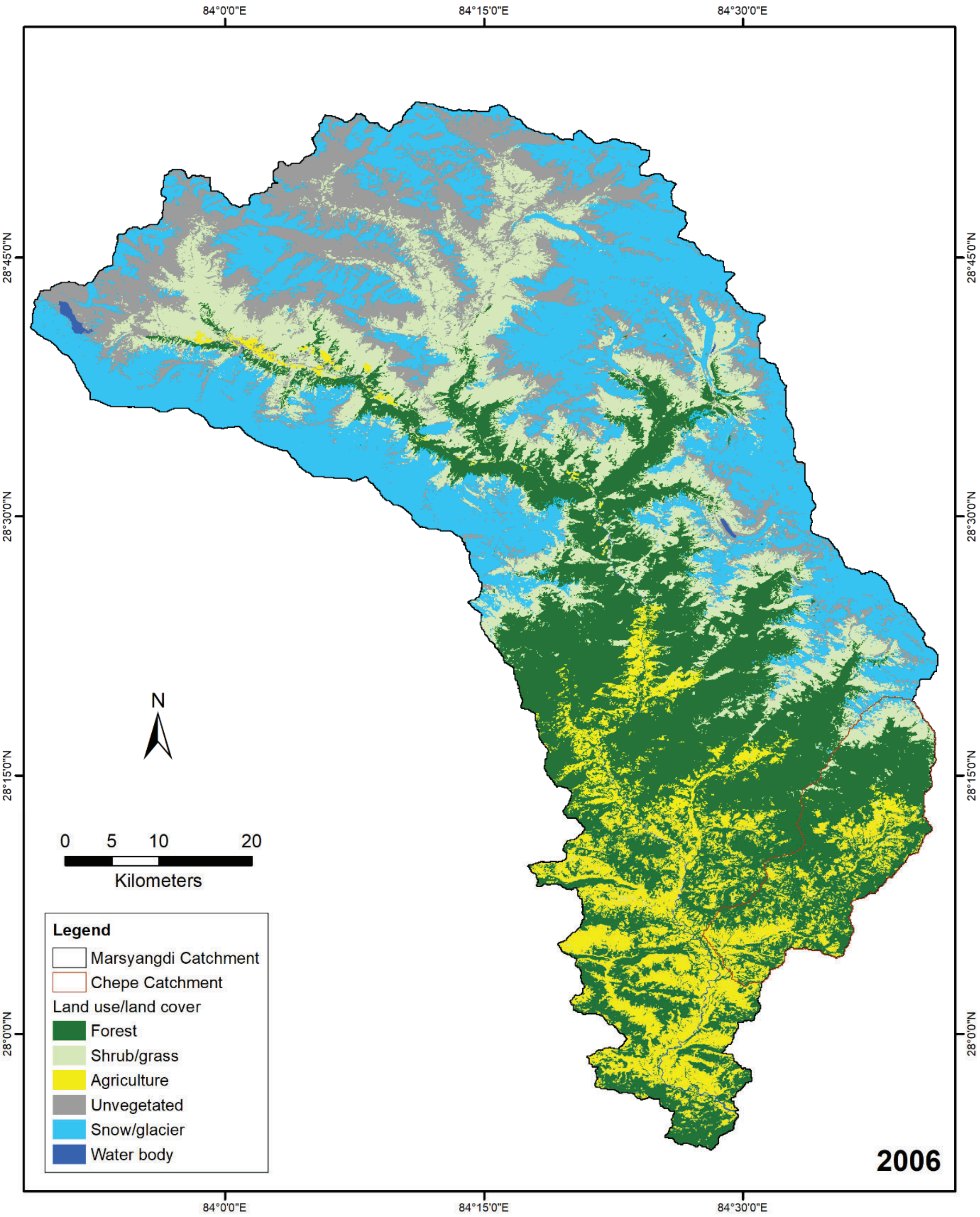


Figure 3.4 Land use/land cover in the Marsyangdi catchment - 2006

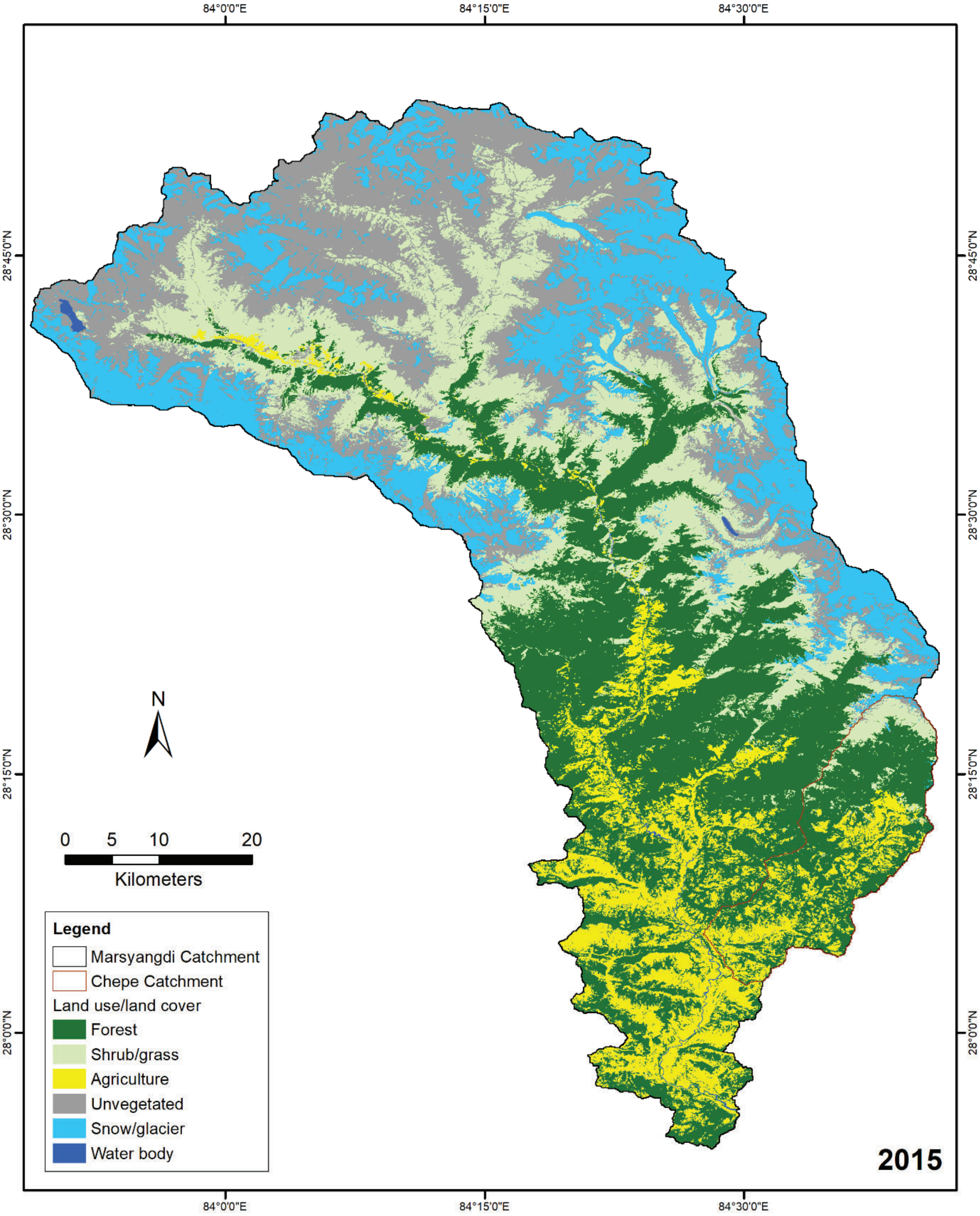


Figure 3.5 Land use/land cover in the Marsyangdi catchment - 2015

Table 3.1 LULC in the Marsyangdi catchment between 1976 and 2015. Note: areas are in km^2 and values within parenthesis represent percentage of the LULC area in relation to the catchment area.

LULC	1976	1988	1995	2006	2015	Average
Forest	1262.5 (30.7%)	1255.0 (30.5%)	1277.2 (31.0%)	1244.8 (30.3%)	1254.5 (30.5%)	1258.8 (30.6%)
Shrub/Grass	784.5 (19.1%)	794.8 (19.3%)	791.6 (19.2%)	709.0 (17.2%)	796.8 (19.4%)	775.3 (18.8%)
Agriculture	452.5 (11.0%)	421.3 (10.2%)	404.5 (9.8%)	406.7 (9.9%)	433.8 (10.5%)	423.8 (10.3%)
Unvegetated	569.0 (13.8%)	693.0 (16.8%)	850.6 (20.7%)	667.8 (16.2%)	955.1 (23.2%)	747.1 (18.2%)
Snow/glacier	1033.2 (25.1%)	938.0 (22.8%)	778.1 (18.9%)	1076.4 (26.2%)	664.2 (16.1%)	898 (21.8%)
Water	12.8 (0.3%)	12.3 (0.3%)	12.4 (0.3%)	9.8 (0.2%)	10.1 (0.2%)	11.5 (0.3%)

Comparison of LULC coverage between 1976 and 2015 (Table 3.1) suggests that overall change in forest cover during 1976–2015 was less than 1%, while the shrub/grass increased by less than 2%. Agricultural area in the catchment shows a decrease of 4%. Even though total land area covered with snow/glaciers indicate a decrease, the changes are variable with highest coverage in 2006 followed by that in 1976. It is notable that, since the LULC were mapped using images from different months, part of these differences is related to seasonal variation of snow cover.

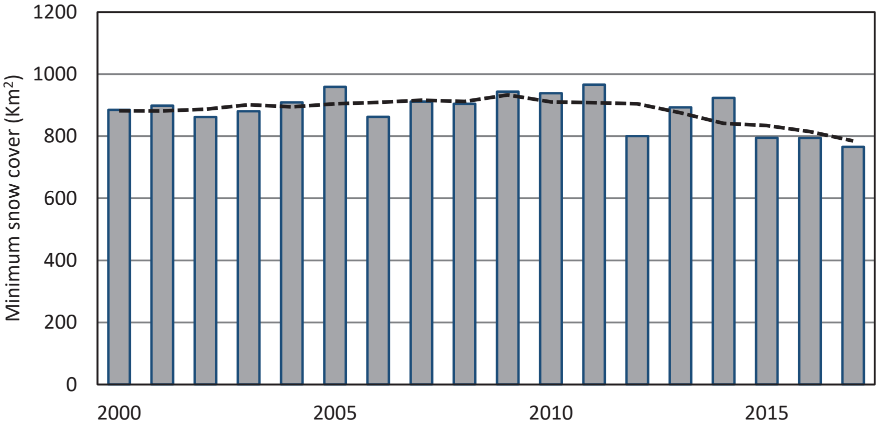


Figure 3.6 Change in pre-winter minimum snow cover in Marsyangdi catchment between 2000 and 2017. Note: dotted line represents the 5-year running average based on 2000–2019 coverage.

Figure 3.6 shows the change in annual pre-winter minimum snow cover in Marsyangdi catchment, derived from MODIS 8-day maximum snow cover data. Annual pre-winter minimum snow cover decreased by over 11% between 2000 and 2017. Changes in 5-yearly minimum between 2000 and 2019 also suggest a similar decrease in the snow cover.

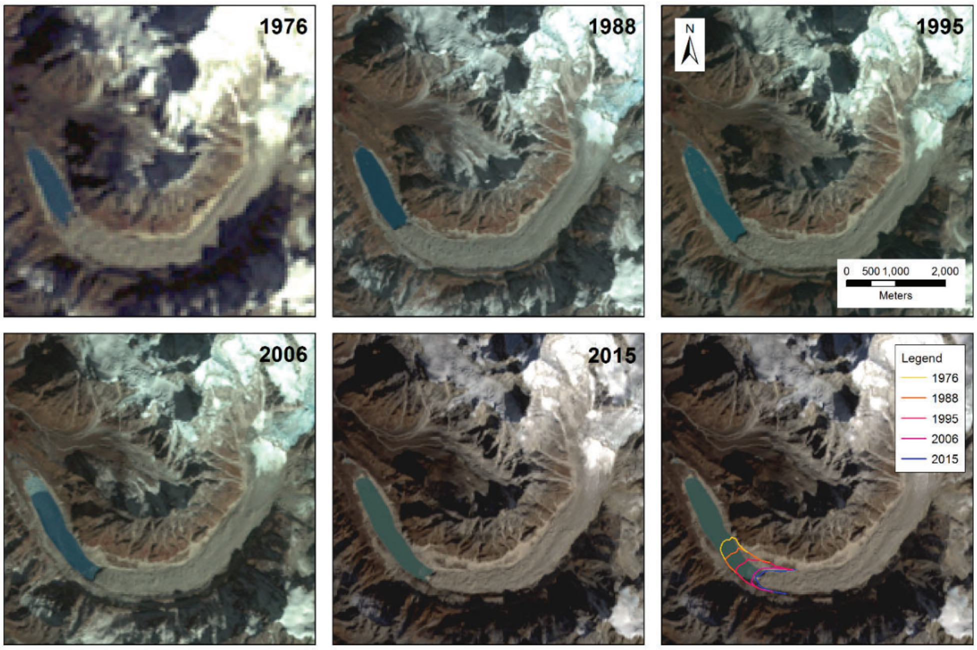


Figure 3.7 Thulagi glacier retreat between 1976 and 2015. Note: lines represent end of the terminus between 1976 and 2015.

Considering limitations in consistently classifying debris covered glaciers (Paul et al., 2009), a case study of glacier melt highlighted by expansion of a glacier lake is presented here. Figure 3.7 shows the retreat of Thulagi glacier at Dona Lake which is classified as one of the critical glacier lakes in Nepal (Haritashya et al., 2018; Khanal et al., 2015). It reveals that the rate of terminus retreat was >300 m per decade during 1976–2006 even though the retreat was just over 100 m between 2006 and 2015.

LULC within the catchment of the Chepe River, a tributary of the Marsyangdi River is analysed separately (cf. Table 3.2) to examine if results are comparable with the entire catchment. Overall change in forest cover within Chepe sub-catchment between 1976 and 2015 is negligible (0.2%). Agricultural area in the sub-catchment declined by approximately 2% (7 km^2), while shrub/grass area increased by a small amount (1.5%). In total, unvegetated and snow covered/glaciated area cover approximately 1% of the land.

Table 3.2 LULC in Chepe sub-catchment between 1976 and 2015. Note: areas are in km^2 and values within parenthesis represent percentage of the LULC area in relation to the sub-catchment area.

LULC	1976	1988	1995	2006	2015	Average
Forest	192.7 (62.4%)	191.7 (62.1%)	201.0 (65.1%)	200.7 (65.0%)	192.1 (62.2%)	195.6 (63.3%)
Shrub/Grass	25.0 (8.1%)	33.3 (10.8%)	31.6 (10.2%)	24.0 (7.8%)	29.8 (9.6%)	28.7 (9.3%)
Agriculture	89.6 (29.0%)	79.4 (25.7%)	72.3 (23.4%)	79.1 (25.6%)	82.7 (26.8%)	80.6 (26.1%)
Unvegetated	0.4 (0.1%)	1.0 (0.3%)	2.3 (0.7%)	1.2 (0.4%)	2.6 (0.8%)	1.5 (0.5%)
Snow/glacier	0.3 (0.1%)	2.2 (0.7%)	0.4 (0.1%)	3.6 (1.2%)	1.4 (0.4%)	1.6 (0.5%)
Water	0.9 (0.3%)	1.2 (0.4%)	1.2 (0.4%)	0.2 (0.1%)	0.3 (0.1%)	0.8 (0.2%)

Considering such spatially variable results within the catchment, changes in LULC have also been analysed in relation to elevation and slope. Left panels of Figure 3.8 show the distribution of major LULC in relation to elevation, while right panels show LULC distribution in relation to slope. They show that forest covers more than half of the land in the elevation between 1000 m and 3500 m, but becomes negligible above 4000 m. Agricultural areas are mostly concentrated at elevations below 2000 m with the highest cover (~80%) in areas below 500 m and approximately half of the land between the elevation of 500 m and 1500 m is used for agriculture.

With the reduced amount of forest above the elevation of 2500 m, the coverage by shrub/grass increases with elevation, which has the highest coverage (>50%) between 3500 m and 4500 m. At the same time, unvegetated area increases with elevation above 3500 m and most land between 4500 m and 6000 m is unvegetated. Coverage by snow/glacier increases in relation to the elevation above 4000 m and it covers 80–100% land above 6000 m.

Generally, area of forest increases with slope up to 30–35°, then starts to reduce steadily for all elevations except between 500 m and 1000 m, where percentage of forest cover remains high for slopes up to 70°. Percentage of shrub and grass areas also increase with slope in the elevation between 1500 m and 5000 m, whereas agricultural area decrease with slope at any elevation. Percentage of unvegetated area also increases with slope, especially between 3500 m and 5500 m elevation, however snow covered/glaciated area increases with slope above 25˚ for all elevation above 3500 m.

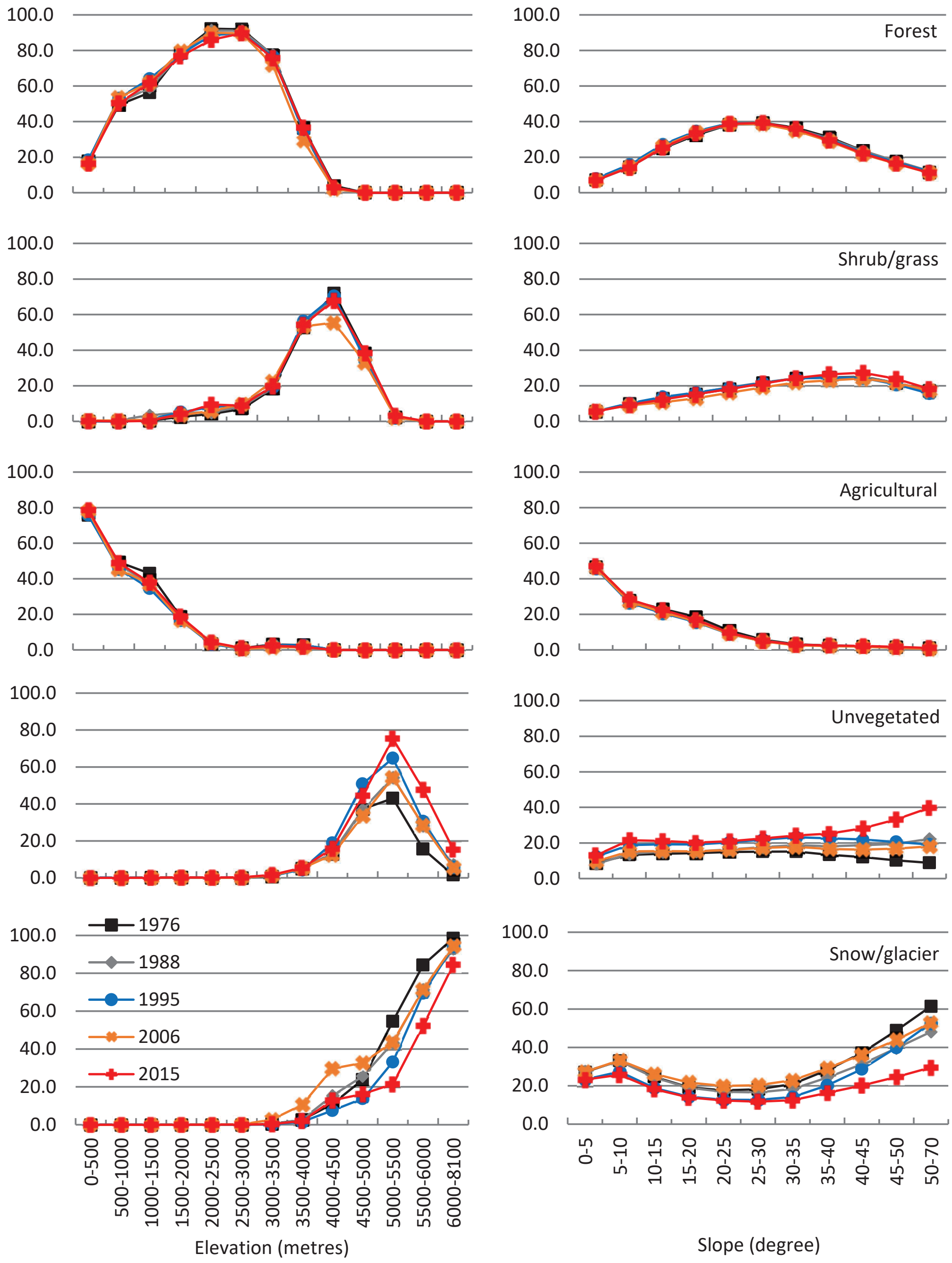


Figure 3.8 Percentage of major LULC within the Marsyangdi catchment in relation to elevation (left) and slope (right). Note: elevation is divided into 500 m intervals except the single category above 6000 m.

During 1976–2015, forest area increased by 3% between the elevation of 500 m and 1500 m with greatest increase (5.3%) between 1000 m and 1500 m, where agriculture area decreased by 5%. Forest area however, decreased by 3% between the elevation of 1500 m and 3500 m with greatest decrease of over 6% between 2000 m and 2500 m. Shrub/grass area increased by 5.3% between 2000 m and 2500 m, however it decreased by 4% in the elevation between 4000 m and 4500 m. During 1976–2015, snow covered/glaciated areas above 4500 m decreased by more than 20% with the highest reduction of 32% in elevation between 5000 m and 6000 m. Consequently, unvegetated area increased by over 20% above 4500 m elevation with greatest increase of 32% between 5000 m and 6000 m.

3.4. Discussion

Based on the LULC results, the lower to mid mountainous regions of the Bagmati and Marsyangdi catchments below 2000 m elevation can mostly be characterised by agricultural activities with some forest cover. Forest coverage is highest in the elevation between 2000 m and 3000 m for both catchments. Decreasing agricultural area in relation to increasing elevation above 2000 m within the Marsyangdi catchment is comparable with results of the Bagmati catchment. Upper parts of the Marsyangdi catchment between the elevation of 4000 m and 5000 m are mostly covered with shrub/grass, while snow covered/glaciated areas and unvegetated land are common above 5000 m. Such relationship between LULC and elevation are generally true in the mountain regions of Nepal (Shrestha & Zinck, 2001; Uddin et al., 2015) supporting the results of this study.

Overall, compared to the Bagmati catchment, forest coverage at any slope of the Marsyangdi catchment is lower and decreases sharply at slopes higher than 30˚. Part of this can be associated to the sharply decreasing forest area above 3000 m elevation which comprises 65% of the Marsyangdi catchment, whereas maximum elevation in Bagmati is less than 2800 m. However, forest cover at slopes higher than 35˚ in the Marsyangdi catchment is lower than that in the Bagmati catchment even below 3000 m, as area of shrub/grass in such terrain increases with slope.

In the Bagmati catchment, 85% of flat land (slope <10˚) in the elevation between 1000 m and 1500 m is covered by agriculture and urban use, while less than 60% of such land is used for agriculture in the Marsyangdi catchment. This can partly be related to the large population and fertile land of the Kathmandu valley, while not all the flat land at this elevation of other mountainous regions may have suitable condition for agriculture.

Forest cover reduces with elevation between 2500 m and 4500 m, whereas areas of shrub/grass continue to increase with slope and elevation up to 4500 m. These results are reasonable considering the general geographical condition of mountainous regions which are not very suitable for agriculture or forest, especially with increasing slope. The increase in unvegetated area in relation to slope, particularly above 3500 m elevation, generally holds true for the Central Himalayan mountain region.

Forest area in the middle and entire Bagmati catchment increased by over 4%, between 1975 and 2015, however the change in forest cover in the Marsyangdi catchment was less than 1%. The increase in forest cover within the Bagmati catchment between 1988 and 2005 is consistent with FAO (2009) findings suggesting a 4% increase in forest cover of central Nepal during 1986–1994. However, Neupane and Dhakal (2017) suggested that forest cover within the Kamala watershed, adjacent to the Bagmati catchment decreased by 2.3% between 1995 and 2015. Reddy, Pasha, et al. (2018) also suggested that overall forest coverage in Nepal decreased by 3.1% during 1975–2005. Other than the changes in the Kathmandu valley of upper Bagmati catchment, overall changes in agricultural areas in the Bagmati catchment were less than 2%, while it decreased by 4% in Marsyangdi catchment. Neupane and Dhakal (2017) found a 2.5% increase in agricultural land in the Kamala watershed during 1995–2015, whereas Rimal et al. (2019) found less than 2% change in agricultural areas in hill and mountain regions of the Koshi river catchment (1996–2016). These dissimilarities in results highlight the spatial variability in LULC changes in different parts of the region. At the same time, protection and regulations associated with the Annapurna conservation area, which covers more than half of the Marsyangdi catchment especially in upper parts, can also be attributed to the lack of substantial LULC changes in the catchment.

Changes in area of unvegetated land with barren soil or rocky area in higher elevation were seen to be complementary to changes in snow covered/glaciated area. Decreasing snow covered/glaciated area above 4500 m and increasing unvegetated area especially in the elevation between 5000 m and 6000 m could also be related to climatic changes. Furthermore, slightly lower coverage of shrub/grass in 2006 can partly be related to larger area of snow cover. Fluctuations in snow cover and barren land in the mountainous region of the Koshi catchment between 1996 and 2016 (Rimal et al 2019) also support the results of this study.

Increase in urban area over the agricultural land in the Kathmandu valley was the most significant LULC change in Bagmati catchment. Coverage by built-up area within 2 km of Kathmandu metropolitan area estimated by Kumar (2017) is comparable with the 2015 estimate of this study. This study showed a remarkable (513%) increase in combined area of mixed urban and built-up land together with a 38% decrease in agricultural area of upper Bagmati catchment between 1988 and 2015. This is comparable with the estimate of Ishtiaque et al. (2017) showing a 412% increase in built-up area and 32% decrease in agricultural area within the Kathmandu valley. Similarly, the 1978–2000 urban expansion of 450% estimated by Haack and Rafter (2006) is comparable with the 375% increase for the period estimated from linear extrapolation of results of this study. However, apparent differences could be related to the difference in land use classification scheme and methods employed. The results of upper Bagmati catchment further suggested that due to the increase in human settlements, mixed urban land use takes place in agricultural areas which eventually develops into built-up areas. This can be attributed to substantial increase in population as the result of internal migration to Kathmandu valley in relation to several reasons including economic opportunities, access to public services and armed political insurgency (Pradhan, 2004; Thapa & Murayama, 2010). Furthermore, urban population in Kathmandu valley, one of the fastest growing urban agglomerations in South Asia (Muzzini & Aparicio, 2013) has increased annually by 4% to 5.8% between 1970 and 2010 (UN-DESA, 2015). As pointed out by Pradhan (2004), conversion of agricultural area to urban land in the upper Bagmati catchment is consistent with the rapid population growth in the Kathmandu valley.

Results of Rimal et al. (2019) showing a significant increase in urban areas in major municipalities in the lower hill and Terai region between 1996 and 2016 also support the urban expansion in relation to population growth. Most of the existing and emerging urban areas in Nepal are located on flat land (<10° slope), while scattered rural settlements are also common on mountain slopes and in small river valleys. However, as mentioned in Section 3.2, smaller towns and dispersed settlement in both catchments were not mapped as urban land, due to the spatial limitation of Landsat images in deriving comparable results. The total population of any municipality other than those in the upper Bagmati catchment (e.g. BesiSahar, Sundarbajar, Bhanu in Marsyangdi and Thaha in Bagmati catchment) is less than 50,000 (CBS 2018). Furthermore, assessment of high-resolution images e.g. DigitalGlobe in Google Earth and ArcMap base layers showed that coverage by urban area in any of these municipalities is smaller than 1 km^2. Therefore, spatial extent of such urban land in the Marsyangdi catchment and mountainous parts of the Bagmati catchment and their changes can still be considered minimal in relation to the total catchment area.

Use of historical Landsat data for LULC change studies at the catchment level is common (e.g. Githui et al., 2009; Weng, 2001), however image classification in rugged mountainous terrain is associated with some limitations such as sun angle and shade (Shrestha & Zinck, 2001). Results on shrub and grass land should be interpreted with care considering the limitations in separating them accurately from sparse forest and agricultural area on mountain slopes. At the same time, coverage and changes of water bodies were also not analysed due to the limitation of the Landsat images and size of the majority of river network (Tuladhar et al., 2019a).

Overall, forest cover change between 1976 and 2015 in the Chepe sub-catchment was similar to that in the entire Marsyangdi catchment, however the decrease in agricultural areas and the increase in shrub/grass area was higher in the Chepe sub-catchment. This suggest that LULC changes may vary locally, even when overall findings may not be substantial as the result of offsetting results within.

An assessment of 1976–2017 LULC changes in relation to elevation showed reasonable results. For instance, increasing forest area in the elevation between 500 m and 1500 m and especially between 1000 m and 1500 m can be related to a decrease in agricultural activities. Results showed that apart from the decrease related to urban expansion in Kathmandu valley, agricultural area decreased by more than 10% in the elevation between 500 m and 2000 m of Bagmati catchment while it also decreased between the elevation of 1000 m and 1500 m as well as above 3000 m of Marsyangdi catchment. As suggested by Khanal and Watanabe (2006), part of the loss in agricultural area can also be related to abandonment of some of the agricultural activities on the mountain slopes, due to various factors such as decline of productivity and lack of appropriate human resource resulting from internal and external migration. This might also have resulted in some of the increase in shrub/grass area. On the other hand, loss of forest in the elevation between 2000 m and 3500 m elevation can be related to depletion of forest and conversion to shrub/grass area. However, loss of shrub/grass area in higher elevations between 4000 m and 4500 m has resulted in an increase in unvegetated areas. Poor soil, rocky condition and erosion as well as changes in climatic conditions can be associated with lack or loss of vegetation on high elevation mountains (Bajracharya & Sherchan, 2009; Dorji et al., 2014).

The majority of increase in unvegetated area above the elevation of 5000 m as well as those over 4500 m can be related to a reduction in snow covered/glaciated areas. Changes in snow covered/glaciated area of Marsyangdi catchment showed a decrease, but since the Landsat images used for mapping were captured in different months, part of the changes could be related to seasonal variations. However, results derived from MODIS products between September and November also suggested that the pre-winter minimum snow cover was decreasing at an alarming rate between 2000 and 2017. Furthermore, the assessment of Thulagi glacier showed that the glacier has retreated by >1000 m between 1976 and 2015. Considering similar geographic and climatic conditions over the high mountain region of the Marsyangdi catchment, other glaciers in the Marsyangdi catchment could also be melting at high rate. Other studies (Bolch et al., 2012; King et al., 2020; Kulkarni & Karyakarte, 2014; Wang et al., 2015) have also suggested that glaciers are melting at alarming rates in the Himalayas due to recent climate change. Loss in snow covered areas and glacier melt can alter the mountain ecosystem of the region as well as influence the seasonal and overall water availability over a longer term (Stres et al., 2013; Vorobyeva et al., 2015).

3.5. Chapter summary

LULC of a location can change as a result of human activities as well as due to the changes in geographic conditions including climate (Klein Goldewijk et al., 2010; Pielke Sr et al., 2011). LULC in South Asia and the Himalayan mountainous region have changed significantly in the latter half of the 20th century (Vadrevu et al., 2017; Zhao et al., 2006). Agricultural area has increased substantially due to mounting pressure from increasing population, while forest area has decreased as a result of industrialisation and increasing demand of agricultural land. More than one third of forest cover in Nepal was lost between 1966 and 1994, however the rate of changes is reported to have slowed down or improved recently (Chaudhary et al., 2016; FAO, 2009; Gautam et al., 2004). Considering challenges associated with the large and growing population, as well as climatic changes that can put further pressure on natural resources, fine scale assessments of historical changes are crucial for sustainable management of natural resources in the region.

Historical changes in the two sub-catchments of the Ganges River basin viz. Bagmati and Marsyangdi River catchment have been examined in this chapter. The LULC were mapped in approximately 10-year intervals between 1975 and 2015 using Landsat images. LULC were classified into broad categories viz. forest, shrub/grass, agriculture, unvegetated land, snow covered/glaciated, built-up and mixed urban area.

Results showed that approximately 60% area of the Bagmati catchment was covered by forest, while over 30% area was used for agricultural purpose. Overall forest coverage in the Marsyangdi catchment was only 30%, while agricultural area constitutes about 10% of total catchment. However, when considering only the area below 3000 m elevation (which represents the overall elevation range of Bagmati catchment), coverage by agricultural land in the Marsyangdi catchment is also about 30% and forest cover is 67%. Forest cover in the Bagmati catchment is smallest over the flat land (< 10° slope) of the Kathmandu valley, while 85% of the flat land in the elevation between 1000 m and 1500 m is used for agriculture or urban purpose. Agricultural area, which generally reduces with increasing elevation, is a major land use below 2000 m in both catchments. On the other hand, forest cover is highest in the elevation between 2000 m and 3000 m in Bagmati and up to 3500 m in Marsyangdi catchment.

Shrub/grass land covered less than 3% of the Bagmati catchment, while such land comprises 19% of total land in the Marsyangdi catchment with the highest coverage between 3000 m and 5000 m elevation. These lands are generally associated with reducing forest cover in relation to increasing elevation. Unvegetated land, mostly characterised by barren soil/rocky area and the land covered with snow/glaciers, especially in the upper parts of the catchment constitute close to 40% of the Marsyangdi catchment. Unvegetated area has the highest coverage between elevations of 4500 m and 6000 m, while snow covered/glaciated areas increase in relation to elevation above 4000 m. Coverage by unvegetated land was negligible in the Bagmati catchment and there is no area with permanent snow cover.

Forest cover in the Bagmati catchment increased by 4% between 1975 and 2015, while overall change in forest and shrub/grass area in the Marsyangdi catchment was less than 1% and 2%, respectively. With an increase from 2.3% of upper catchment in 1975 to 23.8% in 2015, urban land expansion resulting in a 37% decrease in agricultural area of the upper catchment was the main change in Bagmati catchment. There was greater than 10% decrease in agricultural land in the elevation between 500 m and 2000 m of Bagmati catchment. Agricultural area decreased by 4% in Marsyangdi catchment with a higher percentage (>10%) in the elevation between 1000 m and 1500 m as well as above 3000 m. Changes in shrub/grass and agricultural area were also less than 1% in the Marsyangdi catchment, while agricultural area decreased by 2% in the Bagmati catchment. Most of the decreases in agricultural area in the Bagmati catchment are associated with increase in urban land in the upper catchment.

Within Bagmati catchment, forest cover increased relatively high (4.4%) in the middle catchment than in other parts of the catchment. Compared to entire Marsyangdi catchment, decrease in agricultural areas and increase in shrub/grass areas were higher in Chepe sub-catchment, even though changes in forest cover were similar. Urban land increased from 2.3% of upper Bagmati catchment in 1975 to 23.8% in 2015, during which agricultural area decreased by 37%. The urban expansion is directly related to the population growth in Kathmandu valley. On the other hand, the lack of substantial LULC changes in the Marsyangdi catchment can be attributed to relatively low population growth as well as protection and regulation associated with Annapurna conservation area which covers half of the Marsyangdi catchment.

LULC changes in relation to elevation and slope also support the finding that changes in LULC within the catchments vary from one place to another and may offset some of the changes within. For instance, forest area in the Marsyangdi catchment increased by 3% at elevations below 1500 m, however it decreased by 3% between 1500 m and 3000 m. On the other hand, agricultural area decreased by 5% in the elevation between 1000 m and 1500 m, while it increased by 3% below 500 m. Shrub/grass area increased by 5.3% in the elevation between 2000 m and 2500 m, while it decreased by 4% between 4000 m and 4500 m.

Snow covered/glaciated area above 4500 m decreased by over 20% during 1976–2015, whereas unvegetated area increased by a similar percentage in Marsyangdi catchment. The changes in area of these two land covers are complementary to each other, but the decrease in snow/glacier area, especially in the elevation between 5000 m and 6000 m was substantial. Further examination of MODIS 8-day maximum snow cover data suggested that pre-winter minimum snow cover in Marsyangdi catchment decreased by over 11% between 2000 and 2017. In addition, the case study of Thulagi glacier, related to one of the critical glacier lakes of Nepal, showed that the glacier retreated by more than 1000 m during the 1976–2015 period. These findings combined with existing results showing higher rate of snow and glacier melt from Himalayan mountains, suggest that other glaciers in the Marsyangdi catchment could also be retreating at higher rates.

4 SPATIAL AND LONG-TERM VARIABILITY OF PRECIPITATION AND TEMPERATURE IN BAGMATI AND MARSYANGDI CATCHMENTS

4.1. Introduction

Surface air temperature is generally increasing in most parts of the world with an accelerated rate of change since the 1970s (Hansen et al., 2006; Pachauri et al., 2014). As outlined in Chapter 1, increases in regional and/or global surface air temperature can have multiple effects on precipitation, including changes in its distribution and intensity. Furthermore, any changes in temperature can also influence the extent of snow cover, rate of glacial melting, evapotranspiration and soil moisture, all of which can affect water retention and runoff. Since precipitation in various forms such as rainfall and snow are major components of the hydrological cycle, even a subtle change in precipitation and surface air temperature can significantly influence the hydrological budget of a given region (e.g. Flato, 2011).

Even though daily average temperature is increasing in general, daily minimum and maximum temperatures (T_{min} and T_{max}) might not be changing in the same way. In fact, while both T_{min} and T_{max} around most parts of the world have increased in the second half of the 20th century , many studies have shown that T_{min} is increasing faster than T_{max} (Fallah-Ghalhari et al., 2019; Lobell et al., 2007; Vose et al., 2005). This asymmetric change in temperature has resulted in a significant decrease in diurnal temperature range (DTR) in many parts of the world (Gil-Alana, 2018; Lobell et al., 2007; Sun et al., 2017; Vose et al., 2005). Moreover, hydrological processes of a region can have differing responses to the changes in T_{min}, T_{max} and DTR (e.g. Lobell et al., 2007). Therefore, a study of T_{min} and T_{max} together with daily average is important to obtain complete information regarding temperature changes.

Global average land precipitation has increased by about 2% during the 20th century (Dai et al., 1997; Jones & Hulme, 1996), while rainfall in the sub-tropical region of the northern hemisphere decreased by 10% (Jones & Hulme, 1996). Furthermore, precipitation in various regions such as the eastern parts of North and South America, northern Europe and central and northern Asia is increasing significantly but is decreasing in other areas such as the Mediterranean, Africa and parts of South Asia (IPCC, 2007; Liuzzo et al., 2016; Oguntunde et al., 2011; Pachauri et al., 2014; Partal & Kahya, 2006; Tabari & Talaee, 2011; Xu et al., 2018). Changes in seasonal and monthly precipitation may be significant even when change in annual precipitation is not, and monthly trends within a season may also vary significantly (Fukushima et al., 2019; Yue & Hashino, 2003; Zhao et al., 2018).

Changes in regional mean precipitation and temperature may not fully represent variations in a topographically diverse area such as the Himalayan mountainous region (Gadgil, 1977; Kadel et al., 2018). Changing climate and higher rates of snow/glacier melt can have critical implication on the biodiversity of the high mountain region (Huss et al., 2017) while the impacts on flora and fauna may be different in lower elevation. Moreover, long-term changes in temperature and precipitation may also vary significantly from month-to-month (Degirmendžić et al., 2004; Fischer et al., 2010; Jiang et al., 2007) which can have differing implications. For instance, warming in winter months may be beneficial for farming activities and vegetation growth at higher elevations (e.g. >2000 m) of the Himalayan region but an increase in pre-monsoon temperature, especially combined with less precipitation, may have negative impacts on agriculture, where irrigation facilities are restricted. On the other hand, decrease in snow to precipitation ratio due to increasing temperature and an increase in July/August rainfall may increase the risk of water induced disasters such as landslides and flooding. Therefore, understanding local distribution and long-term variability in precipitation and surface air temperature at monthly and annual scales is important for the sustainable management of water resources of a region.

As described in Chapter 2, the typical climate in the Himalayan region ranges from sub-tropical in the southern plain to alpine in the northern Himalayas, changing rapidly in relation to elevation over short horizontal distances. Summer monsoon rainfall which dominates the annual total, decreases from east to west, whereas winter precipitation caused by westerly disturbances is higher in the west compared to the east (Kansakar et al., 2004; Nayava et al., 2017). Several studies have suggested that T_{min} and T_{max} in the Himalayan region are increasing (Bhutiyani et al., 2007; Kattel & Yao, 2013; Nayava et al., 2017; Shekhar et al., 2010; Yang et al., 2013). The T_{min} and T_{max} in the Indian sub-continent increased by 1.04 ˚C and 0.25 ˚C, respectively during 1901–2016 (Pattnaik & Dimri, 2020). Historical records indicate a decline in monsoon precipitation in South Asian region, especially in the second half of the 20th century (Chatterjee et al., 2016; Ramanathan et al., 2005; Turner & Annamalai, 2012). Pattnaik and Dimri (2020) reported no significant trend in monsoon rainfall over the Indian subcontinent during 1901–2016. Furthermore, Kumar and Jain (2011) noted mixed changes (e.g. increasing and decreasing) and mostly non-significant trends of annual rainfall (1951–2004) in river catchments of India including no change in the Ganges basin within Indian territory.

Extreme rainfall events have become more frequent in many parts of South Asia including the Himalayan region (Dore, 2005; Pattnaik & Dimri, 2020). Large-scale climatic phenomena, such as ENSO and IOD are also seen to have influence on inter-annual climatic variability, including the distribution of rainfall and extreme events in the region (Kumar et al., 1999; Shrestha & Kostaschuk, 2005; Zhang et al., 2014). However, the relationship varies both spatially and temporally (Bohlinger & Sorteberg, 2018; Ichiyanagi et al., 2007; Shrestha, 2000).

It is believed that the rate of recent changes in climatic variables around the globe will continue into the near future (Lobell et al., 2007; Pachauri et al., 2014). Dimri et al. (2018) have predicted that both T_{min} and T_{max} will increase significantly between 0.23 ˚C and 0.52 ˚C per decade towards the end of 21st century in the Indian part of the Himalayan region, in all seasons, under Representative Concentration Pathway (RCP) scenarios 4.5 and 8.5. Predictions of future precipitation are inconclusive within the Ganges catchment and have significant spatial variability (Jeuland et al., 2013; Sadoff et al., 2013). However, in general, Indian summer monsoon precipitation is projected to increase in the future (Annamalai et al., 2007; Kripalani et al., 2007; Sperber et al., 2013; Whitehead et al., 2015) together with an increase in frequency and intensity of extreme events (Mittal et al., 2014; Whitehead et al., 2015).

Kansakar et al. (2004) analysed spatial variation in the precipitation regime in Nepal based on 1965–1995 records at 222 stations, while some other studies have analysed precipitation variation over the past few decades using 41 to 82 stations (Bohlinger & Sorteberg, 2018; Karki et al., 2017; Shrestha, 2000). In general, these studies have reported an increase in extreme precipitation events but decreasing overall precipitation, at most of the stations, even though the majority of trends were statistically non-significant. Based on APHRODITE gridded data, Pokharel et al. (2020) also found that extreme precipitation events in Nepal are increasing significantly, leading to the risk of flash floods. Some other studies have examined temperature changes in Nepal using observations at differing numbers of gauging stations (between 13 and 58) and indicated generally increasing trends (Kattel & Yao, 2013; Nayava et al., 2017; Poudel et al., 2020; Shrestha et al., 1999; Thakuri et al., 2019). Some studies have examined climate variabilities specific to one or two river catchments (Dahal et al., 2020; Dhital et al., 2013; Neupane & Dhakal, 2017; Panthi et al., 2015; Shrestha & Sthapit, 2015). A few studies have also attempted to predict changes in climatic variables in different parts of Nepal for the near future (Pokharel et al., 2020; Sigdel & Ikeda, 2012).

Despite existing studies on climatic variabilities in the Himalayan region, comprehensive studies on temperature and precipitation changes with specific focus on local variations within the Himalayan mountain catchments are limited. This chapter examines spatial and long-term (1970–2017) variabilities in T_{min}, T_{max}, DTR and precipitation using observed data available at stations within and nearby the Bagmati and Marsyangdi River catchments. As noted in Chapter 2, these two catchments have contrasting variation in topography, LULC as well as distribution of population and represent two very common cases of the Himalayan mountain sub-catchments. Therefore, understanding climatic variation at annual and monthly scales, in relation to geographic characteristics within and between the two catchments, is expected to be of significant value.

Next section provides a brief description of data and methods used. Section 4.3.1 and 4.3.2 present results of spatial and long-term precipitation variabilities in the Bagmati and Marsyangdi catchments, respectively. Similarly, Sections 4.3.3 and 4.3.4 describe spatiotemporal variabilities in temperature in the two catchments, respectively. A discussion of the variations in precipitation and temperature is presented in Sections 4.4.1 and 4.4.2, respectively. A major focus of the discussion section is to assess similarities and differences in the spatial distribution and long-term changes in the precipitation and temperature with respect to geographic conditions. A summary is provided in Section 4.5.

4.2. Data and methods

Details of meteorological stations in and around the Bagmati and Marsyangdi River catchments used in this study are presented in chapter 2 (cf. Figures 2.2 and 2.3, Tables 2.1 and 2.2). Since most of the stations have records available from the early 1970s, the analysis focuses on the 1970–2017 period. The daily records on precipitation, T_{min} and T_{max} were checked for homogeneity and gaps were filled as detailed in Section 2.3.1. The DTR series were created based on the processed T_{min} and T_{max} records. Monthly and annual series of total precipitation as well as average daily T_{min}, T_{max} and DTR were created from the daily series. Long-term trend in precipitation, T_{min}, T_{max} and DTR associated with individual stations were analysed at monthly and annual scales using the non-parametric Mann-Kendall test including a pre-whitening process and Sen's slope estimate (see Section 2.3.3 to2.3.4). In addition, departures of 5-yearly monthly and annual precipitation from corresponding long-term means were derived to identify the behaviour of long-term changes (see Section 2.3.6).

Based on common physiographic divisions of Nepal (Kansakar et al., 2004; Nayava et al., 2017; Thakuri et al., 2019) and other geographic settings, meteorological stations used in this study can be classified into five broad elevation zones. They are lower foothill zone (<500 m), lower mountain zone (500–1000 m), mid mountain zone (1000–2000 m), mountain zone (2000–2500 m) and high mountain zone (>2500 m). Apart from analysis of local variability for individual stations, dependency of the spatial distribution and long-term changes in temperature and precipitation are also analysed in relation to these elevation zones, where applicable.

4.3. Results

4.3.1. Precipitation variability in the Bagmati catchment

While assessment of the spatial distribution and long-term changes in precipitation in the Bagmati catchment is published in (Tuladhar et al., 2019b) (Appendix A), this section provides a brief summary of the study and its major outcomes. Daily precipitation records between 1970 and 2015 at 12 meteorological stations in and around the Bagmati catchment were used to examine monthly and annual rainfall variabilities in terms of long-trend trend and 5-yearly departures from long-term mean.

Annual precipitation ranges from 900 mm to over 2930 mm among the stations examined in this study. All the stations receive peak precipitation in July, while August precipitation is also high at two of stations. The distributions of monthly and annual precipitation exhibit considerable spatial variations over short distances of 10–25 km as well. The orographic effect of mountain ranges over 1500 m extending from east to west in the middle catchment and mountains (e.g. >2000 m) surrounding the Kathmandu valley, appears to play a major role affecting spatial distribution of rainfall in the catchment.

Long-term trend results show decreasing annual rainfall at most of the stations including a statistically significant decrease of 0.5% to 1% per year at four stations (viz. Thankot, Godavari, Sindhuli Madi and Pattharkot), located in the various elevation zones. Two stations show a positive change, however only the increase at Makawanpur Gadhi station, located in the mid mountain zone is statistically significant. The analysis of 5-yearly departure from long-term mean suggests that lower than long-term mean precipitation has become more common after 2000. The monthly breakdown of departure from the long-term mean shows that departure of annual precipitation is mostly determined by departure of precipitation between June and August with the highest dominance of July departure. However, results of monthly precipitation trends show no consistent pattern of significant trends in any months associated with a significant annual trend. Unlike other months, in which few stations show at least a non-significant increase, precipitation between November and January does not have any positive change.

A subsequent study (Tuladhar et al., 2019a) has analysed precipitation variation within the Bagmati catchment and its sub-catchments which included additional data for 2016 and 2017. The results suggest that long-term rainfall trend in the catchment does not differ significantly even with the inclusion of two additional years.

4.3.2. Precipitation variability in the Marsyangdi catchment

Variability of precipitation at 13 meteorological stations, in and around the Marsyangdi River catchment, is analysed following the same methodology, described above as used for the Bagmati catchment. The details of the stations used in the study can be found in Table 2.2 and their geographic classification in terms of the elevation zone and type of location is shown in Figure 4.1 (left). Monthly and annual total precipitation series were used to examine spatial variation as well as temporal changes in terms of long-term trend and 5-yearly departure from long-term mean.

4.3.2.1. Spatial distribution of precipitation

Figure 4.1 (right) shows the distribution of long-term (1970-2017) mean annual precipitation around the Marsyangdi catchment, highlighting marked spatial variations. Three of the high mountain zone stations viz. Manang, Phu and Ranipauwa, located above 3500 m elevation, receive very little annual precipitation (<500 mm), while the other two high mountain zone stations receive 500–1000 mm precipitation annually. On the other hand, Siklesh and Khudi stations located south of high mountain ranges (e.g. >4000 m), receive the highest precipitation of more than 3000 mm, while two other lower to mid mountain zone stations located further south receive 2500–3000 mm precipitation.

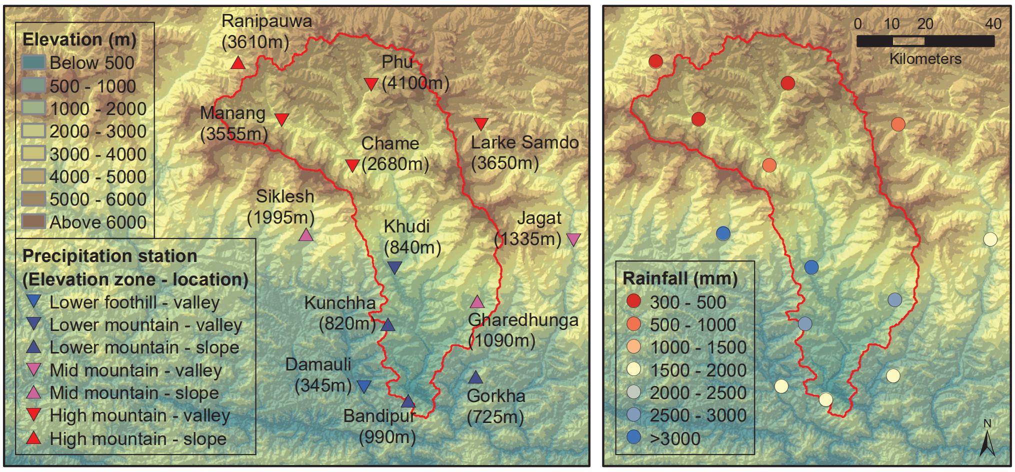


Figure 4.1 Geographical setting of precipitation stations in and around the Marsyangdi catchment (left) and annual precipitation distribution (right). Note: elevation of the stations is rounded to the nearest 5 m.

Figure 4.2 shows monthly precipitation regimes in and around the Marsyangdi catchment. In general, stations below 2000 m (Panel a and b) show gradually increasing precipitation from April/May, with a peak in July. Among these stations however, lower foothill zone station Damauli and three other lower mountain zone stations located in southern parts of the catchment have a sharp increase starting from April and sharp decrease after July (Panel a). At the same time, lower mountain zone station Khudi and three other mid mountain zone stations in the middle parts of the catchment have a delayed increase in precipitation starting from May (Panel b). Apart from the highest peak during monsoon season, high mountain zone stations (>2500 m, Panel c and d) receive relatively high precipitation in March. Nevertheless, July and August precipitation at Manang and Phu stations is not much higher than that in September.

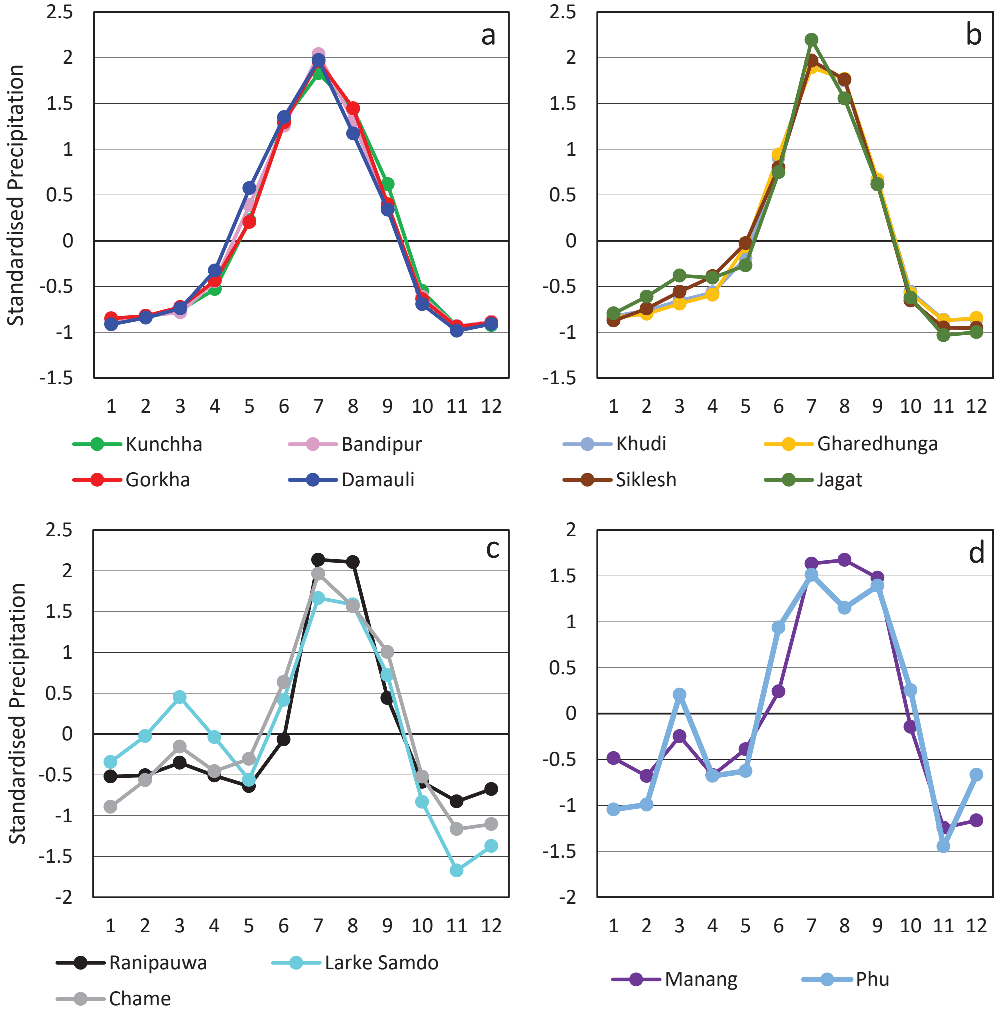


Figure 4.2 Monthly precipitation regime of stations in and around the Marsyangdi catchment

Figure 4.3 shows the relative distribution of monthly precipitation at the individual stations in relation to the corresponding average among all stations (hereafter referred to as all-station average). The four stations that receive the highest annual precipitation have higher than all-station average precipitation in the months between June and October, while all five of the high mountain zone stations with lowest annual precipitation receive the lowest precipitation in the months between May and September. However, November to March precipitation at Larke Samdo and Chame stations is higher than all-station average, even though they receive very low precipitation during monsoon months.

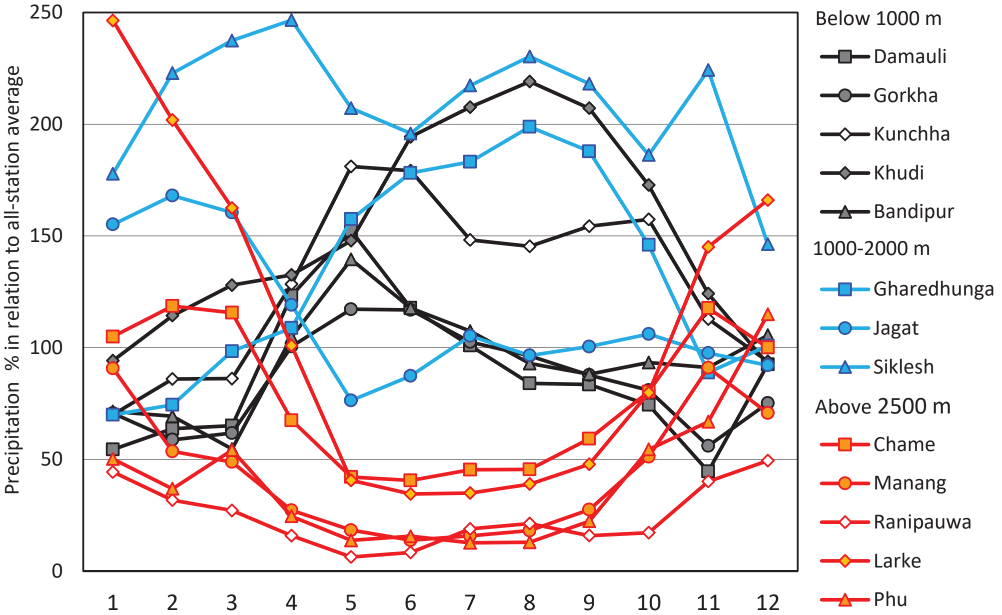


Figure 4.3 Monthly precipitation distribution in and around the Marsyangdi catchment in relation to all-station average. Note: stations are listed in order of lowest to highest elevation.

4.3.2.2. Long-term trend in precipitation

Long-term trends in annual precipitation in and around the Marsyangdi catchment are shown in Figure 4.4. Monotonic trends that are statistically significant at 90% but not at 95% CI are categorised as moderately significant. Since the records at Phu station are only available for a short period (2003–2010), it is only used to analyse spatial distribution and precipitation regimes, but not included here in the assessment of long-term trends. Most of the stations show decreasing precipitation including significant trend at four stations (viz. Bandipur, Jagat, Larkesamdo and Manang) and a moderately significant trend at Gorkha station. Among these stations, the rate of decrease at two of the high mountain zone stations is highest (>1% per year).

Figure 4.5 shows the spatial distribution of long-term trends in monthly precipitation. Even though there is a notable spatial variation in the distribution of significant monthly trends, most of the stations show decreasing precipitation in the majority of months, including those in the monsoon period. Chame station shows a moderately significant increase in May and August precipitation, while the other two moderately significant increasing trends are related to the low rainfall months of January and March each. Except Siklesh and Gharedhunga located in mid mountain zone and Chame station, all other stations show decreasing precipitation in four or more months between May and September.

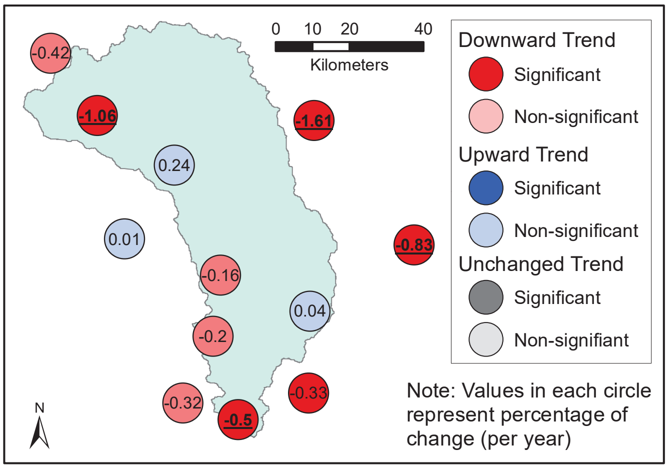


Figure 4.4 Trend in annual precipitation in and around the Marsyangdi catchment. Note: significance of trend relates to 90% CI and trends significant at 95% CI are shown with bold and underlined labels.

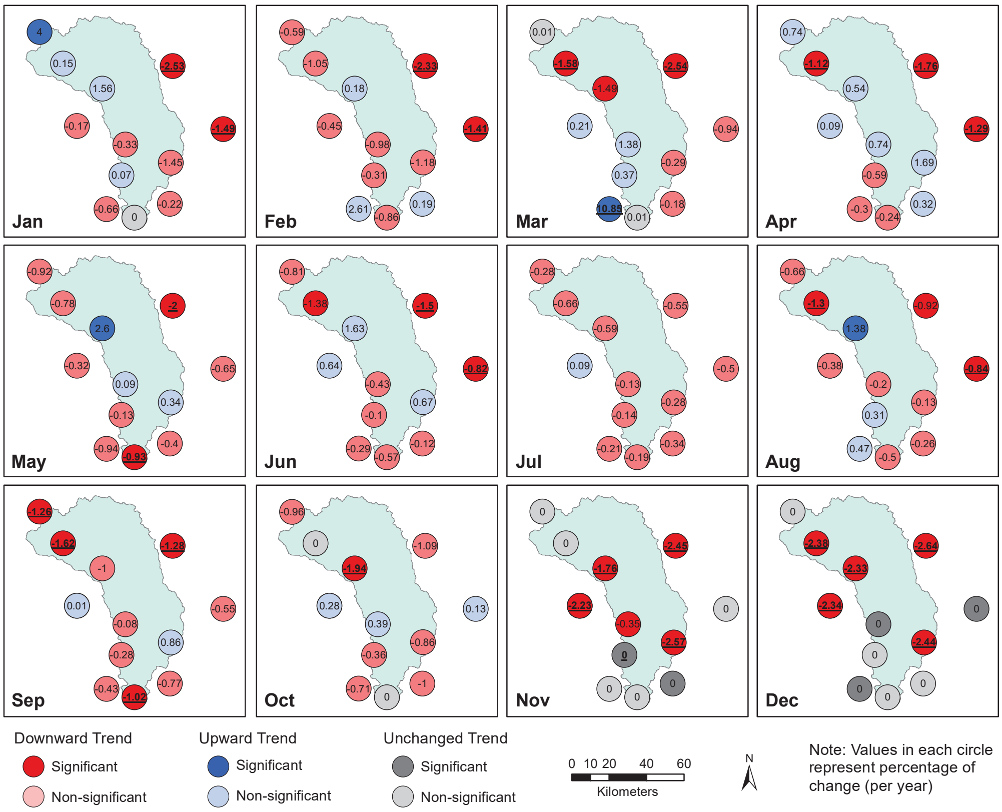


Figure 4.5 Trend in monthly precipitation in and around the Marsyangdi catchment. Note: significance of trend relates to 90% CI and trends significant at 95% CI are shown with bold and underlined labels.

Table 4.1 shows a summary of statistical significance and direction of trend (e.g. increase/decrease) of the monthly precipitation trends. There is no specific pattern of significant decrease in monthly precipitation including that in monsoon months in relation to a significantly decreasing annual trend. Larke Samdo is the only station that indicates negative trend in all months, including significant or moderately significant trend in ten months. On the other hand, despite non-significantly increasing precipitation in February and April, a non-significant decrease in eight other months has also resulted in a moderately significant decreasing trend at Gorkha. Two other stations (Manang and Jagat) with significantly decreasing annual precipitation show significant monthly trends in varying combinations of five months. It is notable that, decrease in July precipitation is not significant at any station though a decrease in June and August are significant at two stations each. No station has any positive trend in November and December precipitation. In fact, precipitation in these dry months is decreasing significantly at several stations located in the middle to upper catchment, whereas most of the stations in lower parts of the catchment show no change, a few of which are significant at 90% CI.

Table 4.1 Summary of significant and non-significant monthly and annual precipitation trend in and around the Marsyangdi catchment. Note: '+' represents increasing trend, '-' represents decreasing trend and 'o' represents no change. The changes within round and square brackets represent statistically significant trend at 95% and 90% CI, respectively. Stations are listed in order of highest to lowest elevation. Stations are referred by short name as listed in Table 2.1.

Elevation (m)	**Station**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**Annual**
>2500	Lar	(-)	(-)	(-)	(-)	(-)	(-)	-	[-]	(-)	-	(-)	(-)	(-)
	Ran	[+]	-	+	o	-	-	-	-	(-)	-	o	o	-
	Man	+	-	(-)	(-)	-	[-]	-	(-)	(-)	o	o	(-)	(-)
	Cha	+	+	[-]	+	[+]	+	-	[+]	-	(-)	(-)	(-)	+
1000–2000	Sik	-	-	+	+	-	+	+	-	+	+	(-)	(-)	+
	Jag	(-)	(-)	-	(-)	-	(-)	-	(-)	-	+	o	[o]	(-)
	Gha	-	-	-	+	+	+	-	-	+	-	(-)	(-)	+
500–1000	Ban	o	-	o	-	(-)	-	-	-	(-)	o	o	o	(-)
	Khd	-	-	+	+	+	-	-	-	-	+	[-]	[o]	-
	Kun	+	-	+	-	-	-	-	+	-	-	(o)	o	-
	Gor	-	+	-	+	-	-	-	-	-	-	[o]	o	[-]
<500	Dml	-	+	(+)	-	-	-	-	+	-	-	o	[o]	-

4.3.2.3. Departure from long-term mean

Figure 4.6 shows 5-yearly departures of annual and monthly precipitation from corresponding long-term means over the period of 1970 to 2017. Positive (negative) standardized departure from the long-term mean that is larger than one standard deviation is referred to as substantially higher (lower).

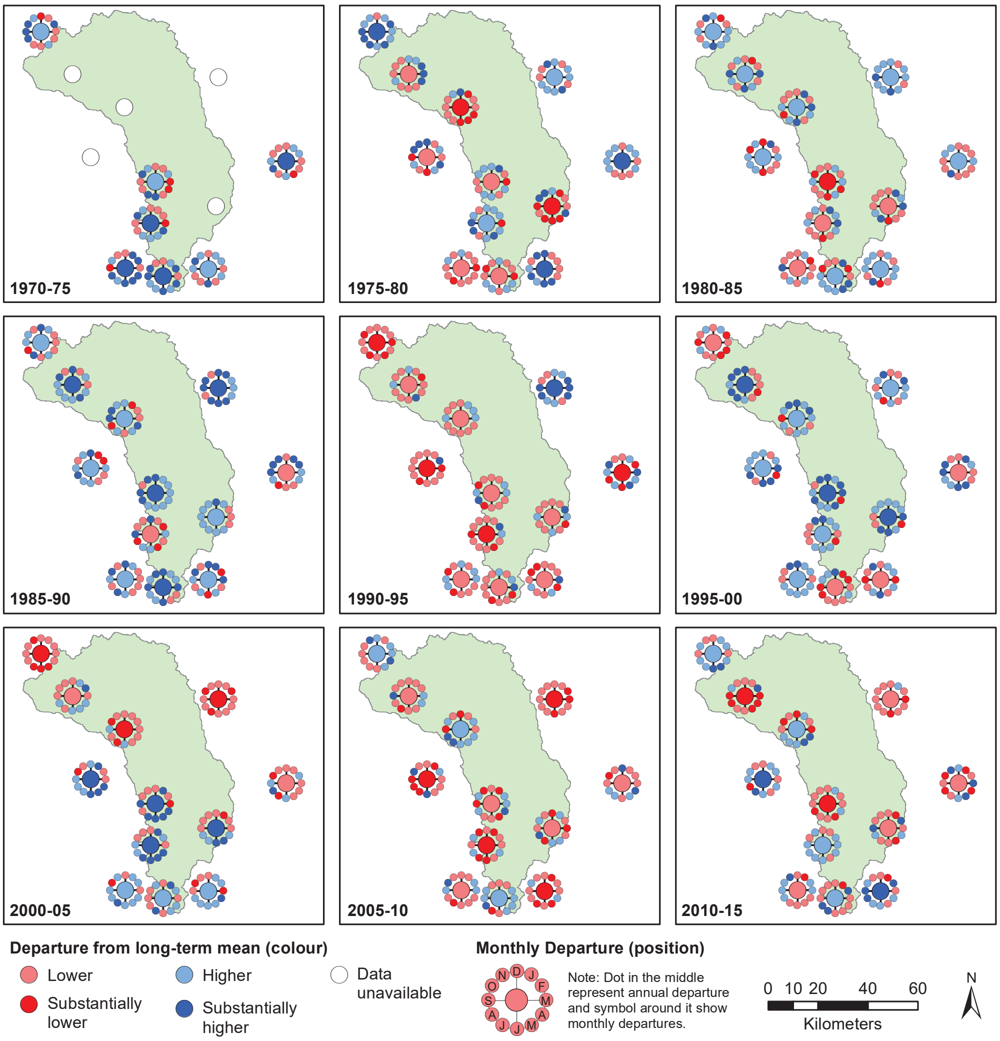


Figure 4.6 Annual and monthly departure of 5-yearly precipitation from long-term mean in and around the Marsyangdi catchment. Note: the larger circle in the centre represents annual departure, while smaller circles around it represent monthly departures in clockwise direction with December departure shown in North. Positive (negative) standardized departure larger than one standard deviation, is referred to as a substantially higher (lower) departure.

Precipitation in the first half of the 1970s and later halves of the1980s and 1990s was generally higher than the long-term mean, including substantially higher precipitation at three to four locations in each period. On the other hand, precipitation during 1990–1995 and 2005–2010 was generally lower than the long-term mean with four stations receiving substantially lower precipitation in both periods. The departure in other periods exhibits a mix of higher and lower precipitation, however during 2000–2005, five stations located in the upper parts of the study area received higher than average precipitation, whereas stations in the lower parts received lower precipitation compared to long-term mean. Comparison of 5-yearly departure for individual stations shows longer-term fluctuation in precipitation with periods of 10–15 years. However, a few stations have more frequent occurrence of lower than long-term mean precipitation in recent times. For instance, Larke Samdo and Jagat have higher or substantially higher precipitation before 2000 and 1985 respectively, while the precipitation at the same stations after 2000 and 1885 respectively, are lower or substantially lower.

The departure of monthly precipitation from long-term means shows that a substantially higher or lower annual departure is generally related to the majority of monthly departures being in same direction. However, there is no specific combination of substantial monthly departures resulting in any substantial annual departure. In many instances, a mix of higher and lower departures with one or two substantial monthly departure have also resulted in a substantial departure in annual precipitation. For example, a substantially higher precipitation at Jagat station for 1970–1975 (1975–1980) were related to higher precipitation compared to long-term mean in five (seven) months with substantially higher departure in one (none) of the months. However, substantially lower annual precipitation at Ranipauwa station during 1990–1995, 2000–2005 and Larke Samdo station during 2000–2010 were related to uniform changes across all months.

A month-wise summary of the overall agreement between monthly and annual departures for all stations considering all 5-yearly cases is presented in Table 4.2. It shows that at least 73% of the 5-yearly monthly departure between May and July have the same direction (SDSM and SDDM) as the annual departure including the highest match (81%) in July. On the other hand, the direction of monthly departure in other months differs from that of annual departure in 35–50% of the cases.

Table 4.2 Summary of relationship between annual and monthly precipitation departures from long-term mean in and around the Marsyangdi catchment. Note: Values represent percentage of the relationship (e.g. agreement/difference) for each category with respect to total number of 5-yearly monthly departure cases among all stations. Abbreviation: departure in the same direction with the same magnitude (SDSM), departure in same direction with a different magnitude (SDDM), departure in opposite direction with the same (non-substantial) magnitude (ODSM-NS), departure in opposite direction with a different magnitude (ODDM) and departure in the opposite direction but both with substantial magnitude (ODSM-S).

Month	SDSM %	SDDM %	ODDM %	ODSM-NS %	ODSM-S %
January	34	28	17	19	2
February	32	28	15	23	2
March	28	23	24	24	2
April	35	27	13	21	4
May	50	23	9	17	2
June	50	28	7	14	1
July	47	34	6	13	0
August	35	30	10	25	1
September	36	28	14	21	1
October	34	26	18	18	4
November	42	24	16	17	1
December	31	24	19	25	1

4.3.3. Temperature variability in the Bagmati catchment

Spatial and long-term (1970–2017) variations in temperature in the Bagmati catchment is analysed using records at nine climate stations, including six that were used for the precipitation study (Figure 4.7). These climate stations are located at elevations ranging from 139 m to 2265 m. Daman, Kakani and Nagarkot stations are located on higher mountain slopes, while others are located on valley bottoms and flat land. The middle part of the Bagmati catchment does not have a very good coverage of climate stations, however all available data are considered here.

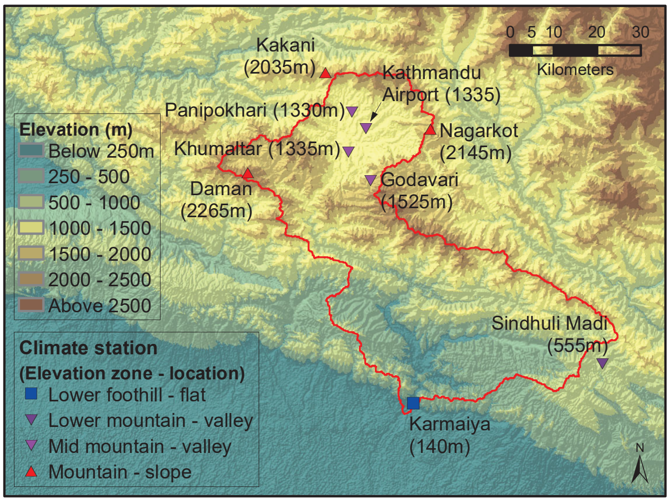


Figure 4.7 Geographical setting of temperature stations in and around the Bagmati catchment. Note: elevation of stations is rounded to the nearest 5 m.

4.3.3.1. Spatial variability in temperature

Distribution of long-term means of monthly average T_{min} and T_{max} at the stations in and around the Bagmati catchment are presented in Figure 4.8. Both T_{min} and T_{max} at all the stations are lowest in January. For all stations, T_{min} is generally high from June to September and highest in July. However, T_{max} is generally high from April to September and reaches its peak in June at the majority of stations. T_{max} at Karmaiya and Sindhuli Madi stations, located in lower foothill and lower mountain zones, is highest from April to May, while T_{max} at Daman station, located on a mountain slope above 2200 m, is highest in August.

Figure 4.8 also highlights the fact that T_{min} and T_{max} vary considerably according to elevation. T_{min} at all the stations located above 1000 m, is less than 10 °C between November and March, which is markedly lower than other stations examined, even though the T_{max} distribution does not show such pattern. In general, monthly T_{max} is lowest at mountain zone stations (>2000 m) followed by stations within the Kathmandu valley, while lower foothill and lower mountain zone stations in southern parts of the catchment exhibit the highest monthly T_{max}. In general, monthly T_{min} is lowest at Daman, while it is highest at Karmaiya, followed by Sindhuli station throughout the year. It is worthwhile to note that the pattern of T_{min} during the summer months at Godavari station, located at an elevation of 1527 m in the Kathmandu valley, is similar to that of mountain zone stations above 2000 m.

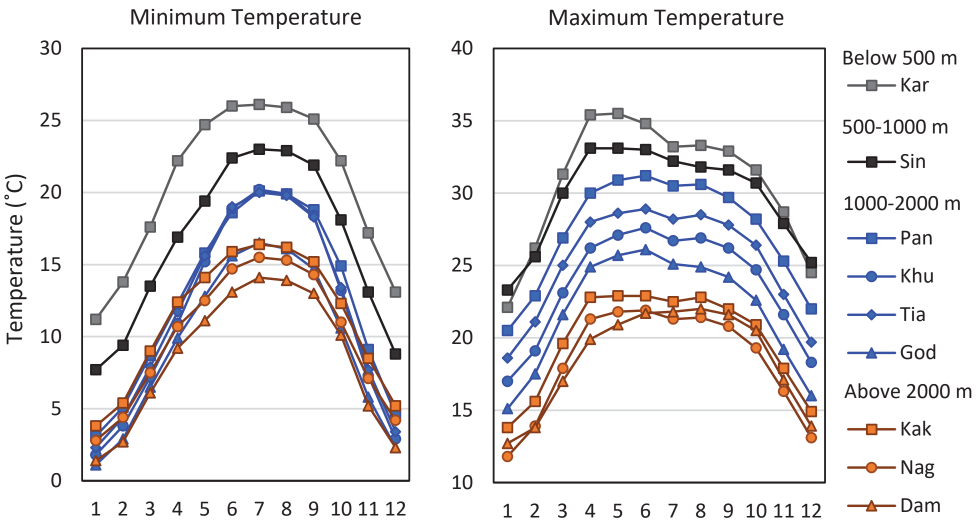
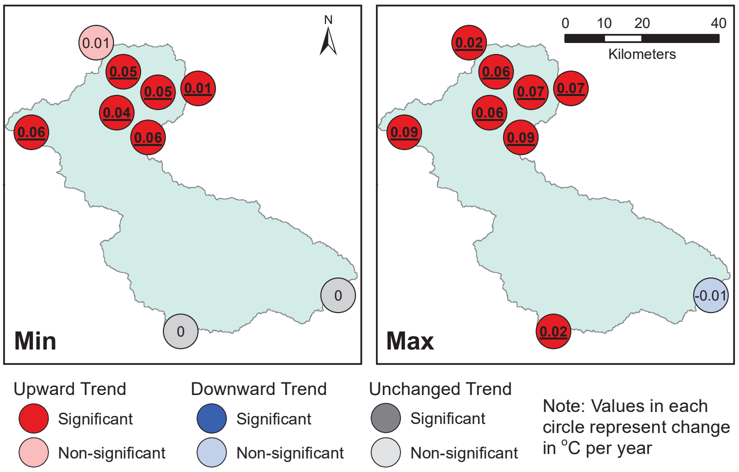


Figure 4.8 Monthly distribution of T_{min} and T_{max} in and around the Bagmati catchment. Note: stations are listed in order of lowest to highest elevation. Stations are referred by short name as listed in Table 2.2.

4.3.3.2. Trends in minimum and maximum temperature



Note: Values in each circle represent change in °C per year

Figure 4.9 Trend in annual mean minimum and annual mean maximum temperature in and around the Bagmati catchment. Note: significance of trend relates to 90% CI and trends significant at 95% CI are shown with bold and underlined labels. Some of the stations are shifted from the true geographic location for clarity.

Figure 4.9 shows the spatial distribution of long-term trends in annual average T_{min} and T_{max}. T_{min} is increasing at all stations, except for two stations (Karmaiya and Sindhuli Madi) located in lower foothill and lower mountain zones (<1000 m). Of the increasing trends, all but that of the Kakani stations are statistically significant. Annual average T_{max} is rising significantly at all stations, except Sindhuli Madi station. Apart from the significant positive change in T_{max} at Karmaiya station, other changes in T_{min} and T_{max} at both stations below 1000 m are non-significant. The rate of increase is generally higher at stations in the Kathmandu valley and Daman where both T_{min} and T_{max} are increasing between 0.04 ˚C and 0.06 ˚C per year.

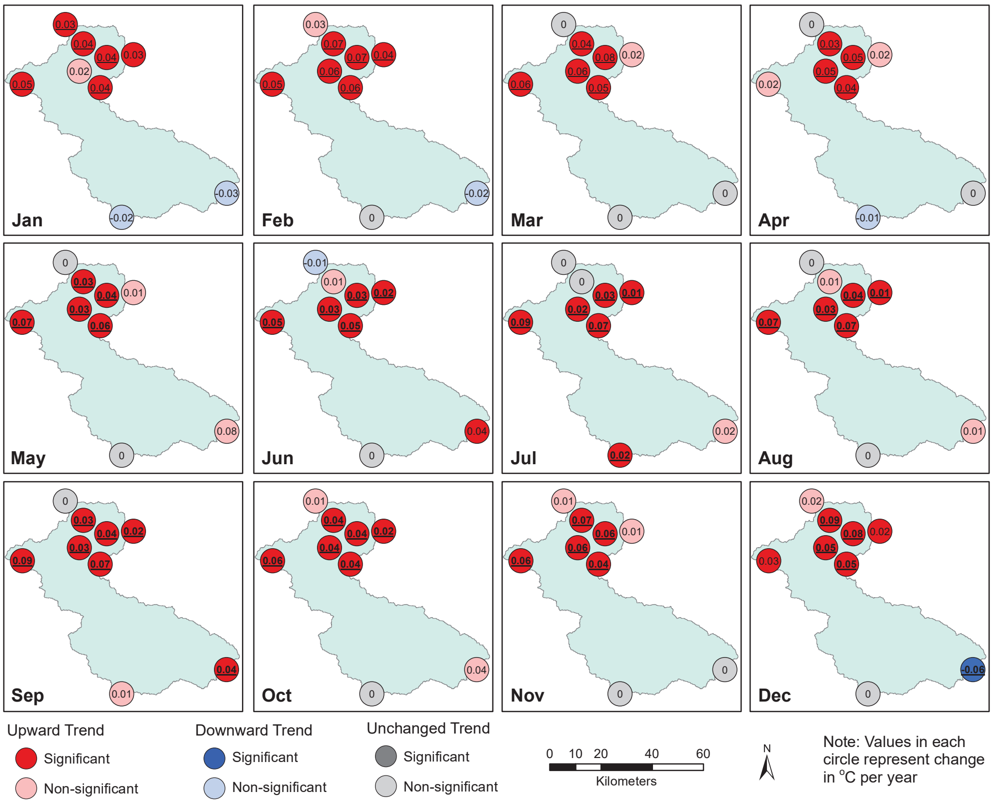


Figure 4.10 Trend in monthly mean minimum temperature in and around the Bagmati catchment. Note: significance of trend relates to 90% CI and trends significant at 95% CI are shown with bold and underlined labels. Some of the stations are shifted from the true geographic location for clarity.

Figures 4.10 and 4.11 show the spatial distribution of trend of monthly average of daily minimum and maximum temperature, respectively. In general, T_{min} is increasing at all stations except the two stations (Sindhuli Madi and Karmaiya) located below 1000 m elevation where the changes are mostly non-significant with inconclusive (e.g. increasing and decreasing) directions. Monthly T_{max} is generally increasing significantly at all stations in mid mountain and mountain zones, except at Kakani station. Monthly T_{max} is also increasing at Karmaiya station, including a significant increase in May and from July to November. The rate of significant increase in T_{min} ranges from 0.01 ˚C to 0.09 ˚C per year, while the rates of significant increase in T_{max} are between 0.02 ˚C and 0.11 ˚C per year. Additionally, more stations show a significant increase in T_{max}

compared to significant increase in T_{min} in all months. The highest rates of increase are generally associated with Daman and Godavari stations.

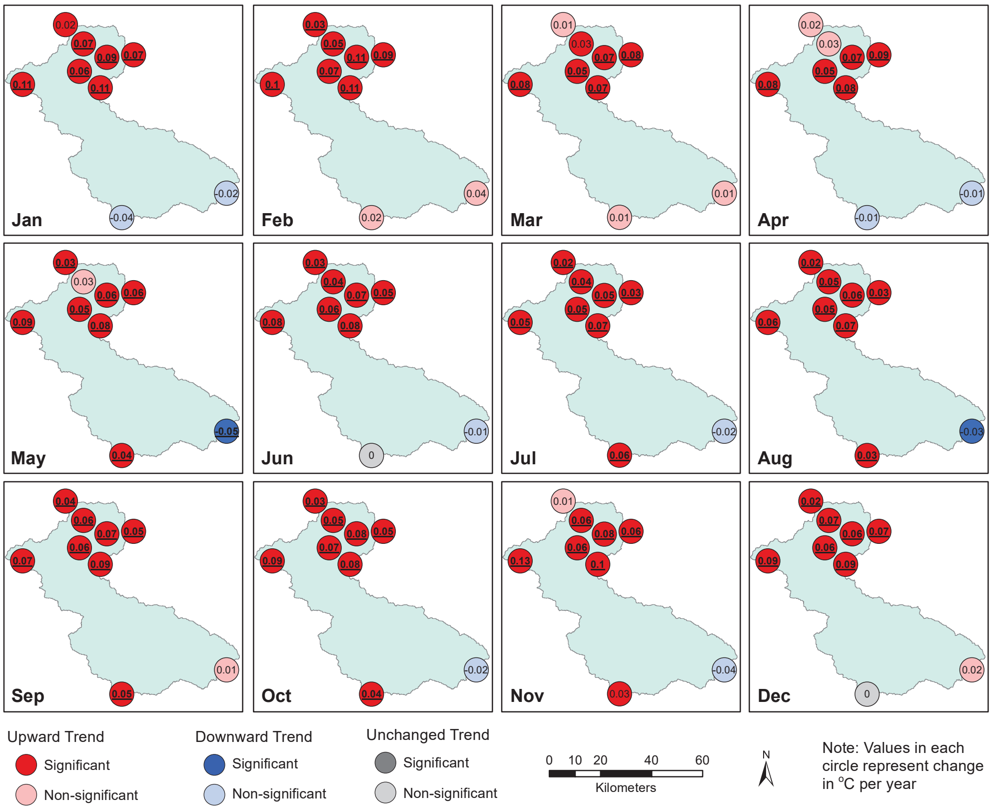


Figure 4.11 Trend in monthly mean maximum temperature in and around the Bagmati catchment. Note: significance of trend relates to 90% CI and trends significant at 95% CI are shown with bold and underlined labels. Some of the stations are shifted from the true geographic location for clarity.

Table 4.3 and 4.4 summarise the direction of trend (e.g. increasing/decreasing) and significance of monthly and annual trends in T_{min} and T_{max}. In general, significantly increasing trend in annual T_{min} and T_{max} are associated with significant trend in most of the months, whereas statistically non-significant annual trends reflect non-significant changes in most months. Monthly T_{max} at Karmaiya and Kakani stations is increasing significantly at 90% CI in six to nine months resulting in a significant increase in annual T_{max}, even though changes in T_{min} are negligible. Sindhuli Madi, the only station with no increase in T_{max} show downward changes in the majority of months.

Table 4.3 Summary of significant and non-significant monthly trends in mean minimum temperature in and around the Bagmati catchment. Note: '+' represents increasing trend, '-' represents decreasing trend and 'o' represents no change. The changes inside round and square parentheses represent statistically significant trend at 95% and 90% CI, respectively. Stations are referred by short name as listed in Table 2.2.

Elevation (m)	Station	J	F	M	A	M	J	J	A	S	O	N	D	Annual
>2000	Nag	[+]	(+)	+	+	+	(+)	(+)	(+)	(+)	(+)	+	[+]	(+)
	Dam	(+)	(+)	(+)	+	(+)	(+)	(+)	(+)	(+)	(+)	(+)	[+]	(+)
	Kak	(+)	+	o	o	o	-	o	o	o	+	+	+	+
1000–2000	God	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)
	Tia	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)
	Khu	+	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)
	Pan	(+)	(+)	(+)	(+)	(+)	+	o	+	(+)	(+)	(+)	(+)	(+)
500–1000	Sin	-	-	o	o	+	[+]	+	+	(+)	+	o	(-)	o
<500	Kar	-	o	o	-	o	o	(+)	o	+	o	o	o	o

Table 4.4 Summary of significant and non-significant monthly trends in mean maximum temperature in and around the Bagmati catchment. Note: '+' represents upward trend, '-' represents downward trend and 'o' represents no change. The changes inside round and square parentheses represent statistically significant trend at 95% and 90% CI, respectively. Stations are referred by short name as listed in Table 2.2.

Elevation (m)	Station	J	F	M	A	M	J	J	A	S	O	N	D	Annual
>2000	Nag	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)
	Dam	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)
	Kak	[+]	(+)	+	+	(+)	(+)	(+)	(+)	(+)	(+)	+	(+)	(+)
1000–2000	God	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)
	Tia	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)
	Khu	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)
	Pan	(+)	(+)	[+]	+	+	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)
500–1000	Sin	-	+	+	-	(-)	-	-	[-]	+	-	-	+	-
<500	Kar	-	+	+	-	(+)	o	(+)	(+)	(+)	(+)	(+)	o	(+)

4.3.3.3. Long-term change in DTR

Long-term trends in annual and monthly average DTR were analysed and the results are presented in Table 4.5. Even though there is no clear consistency in pattern of significant trends, generally the monthly DTR is increasing. The DTR is increasing significantly at Nagarkot station in all months. Godavari and Daman stations which showed highest increase in T_{max}, had a significant DTR increase in most of the months between September and April. For other stations, most of the significant increases in DTR are seen between May and September. In general, significantly increasing DTR is a result of a higher rate of increase in T_{max} compared to the change in T_{min}. A significantly decreasing DTR trend, noticed in one or two months at Daman and Panipokhari stations are the result of higher increase in T_{min}, while negative changes at Sindhuli Madi station are generally related to decrease in T_{max}.

Table 4.5 Trend in monthly and annual average DTR in and around the Bagmati catchment. Note: bold and underlined values indicate statistically significant trend at 95% and 90% CI, respectively. Stations are referred by short name as listed in Table 2.2.

Elevation (m)	Station	J	F	M	A	M	J	J	A	S	O	N	D	Annual
>2000	Nag	**0.06**	**0.06**	**0.06**	**0.07**	**0.05**	**0.04**	**0.03**	**0.02**	**0.03**	**0.04**	**0.06**	**0.06**	**0.05**
	Dam	**0.09**	**0.05**	0.02	**0.05**	0.00	0.02	**-0.04**	-0.01	**-0.03**	0.03	**0.06**	**0.08**	**0.02**
	Kak	0.00	0.02	0.01	0.02	**0.03**	**0.04**	**0.03**	0.02	**0.03**	0.01	-0.01	-0.01	**0.02**
1000–2000	God	**0.07**	**0.03**	**0.03**	**0.04**	0.01	0.02	0.00	-0.01	0.02	**0.04**	**0.07**	**0.06**	**0.02**
	Tia	0.03	0.03	-0.01	0.01	0.02	**0.02**	**0.02**	**0.02**	**0.03**	0.02	-0.01	**-0.03**	0.01
	Khu	**0.06**	0.02	-0.02	0.00	0.02	**0.04**	**0.03**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.03**
	Pan	0.01	-0.04	**-0.07**	-0.03	0.00	**0.04**	**0.04**	**0.05**	**0.03**	-0.01	0.00	-0.01	0.00
500–1000	Sin	0.00	0.05	0.02	-0.01	**-0.13**	-0.03	-0.04	**-0.04**	-0.04	-0.06	-0.01	0.07	-0.01
<500	Kar	**0.02**	0.03	0.01	-0.01	0.02	-0.01	**0.05**	**0.03**	**0.05**	0.03	0.02	-0.01	**0.02**

4.3.4. Temperature variability in the Marsyangdi catchment

Temperature variability in the Marsyangdi catchment is analysed based on T_{min} and T_{max} records at eight climate stations, located at elevation between 515 m and 2741 m, in and around the catchment (Figure 4.12). Only Chame, Khudi and Gorkha stations are common to those used in the study of precipitation, since temperature data were not available at all the stations. Gorkha and Lumle stations are located on mountain slopes. Pokhara airport and Khairini stations are located in flat valleys, while others are located in lower parts of narrow river valleys.

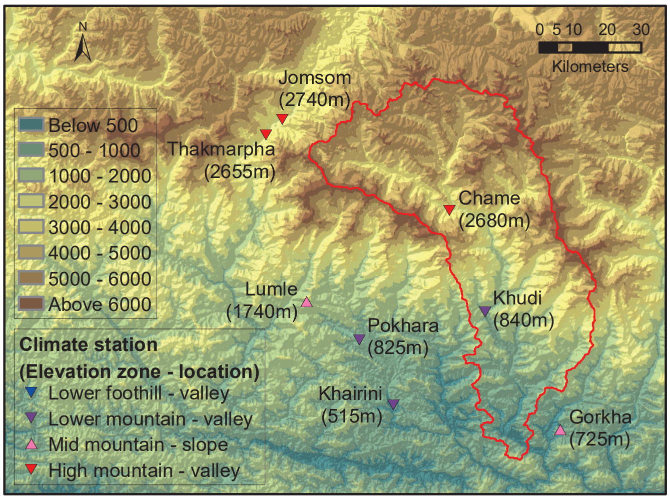


Figure 4.12 Geographical setting of temperature stations in and around the Marsyangdi catchment. Note: elevation of the stations is rounded to nearest 5 m.

4.3.4.1. Spatial variability in monthly temperature

Figure 4.13 shows the distribution of long-term (1970-2017) mean monthly T_{min} and T_{max}. All stations show lowest T_{min} in January, while T_{min} is highest in June. T_{max} is also lowest in January at all stations, while it is highest in June except at two of the high mountain zone stations (Jomsom and Thakmarpha), where it is highest in July.

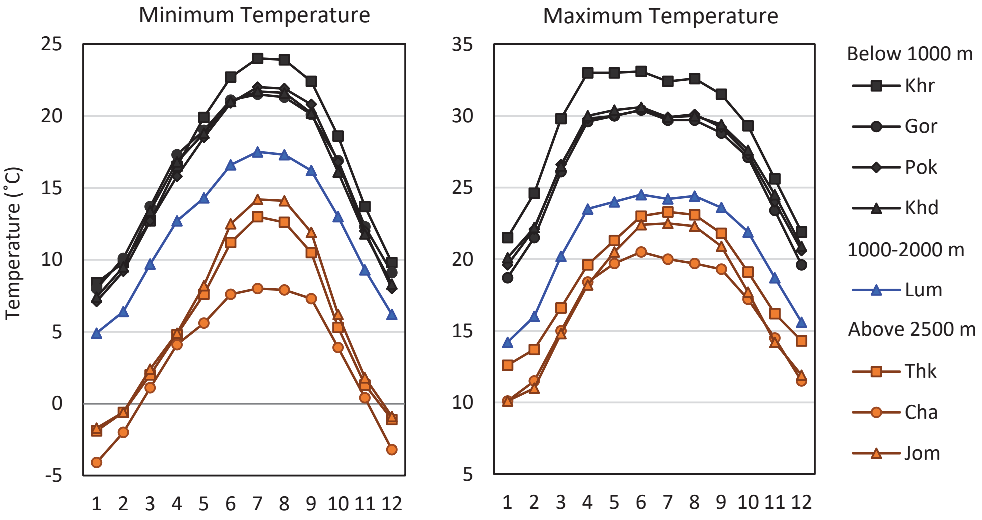


Figure 4.13 Monthly distribution of T_{min} and T_{max} in and around the Marsyangdi catchment. Note: stations are listed in order of lowest to highest elevation. Stations are referred by short name as listed in Table 2.2.

Figure 4.13 also highlights that in general, the spatial distribution of monthly T_{min}/T_{max}, is closely associated with change in elevation. Both T_{min} and T_{max} are lowest at high mountain zone stations (Jomsom, Chame and Thakmarpha), followed by that at Lumle station in the middle mountain zone (1740 m). T_{min} at stations above 2500 m are below 0 ˚C during the winter months of December to February. T_{min} (T_{max}) at rest of the stations located below 1000 m are at least 8 ˚C (5 ˚C) higher compared to stations located above 2500 m. Among these stations, Khairini station located at 515 m, has evidently a high T_{max} in all months as well as high T_{min} in summer months.

4.3.4.2. Trend in minimum and maximum temperature

Figure 4.14 shows long-term trends in annual T_{min} and T_{max} at stations in and around the Marsyangdi catchment. Annual T_{max} is increasing significantly at all stations with the highest increase (0.08 ˚C to 0.09 ˚C per year) at Chame and Gorkha. The positive changes in T_{min} (0.02 ˚C to 0.04 ˚C per year) noticed at three of the low mountain zone stations (Pokhara airport, Khairini and Gorkha) are significant, while two of the high mountain zone stations (Jomsom and Thakmarpha) located in the north-west part of the study area show a decreasing T_{min}.

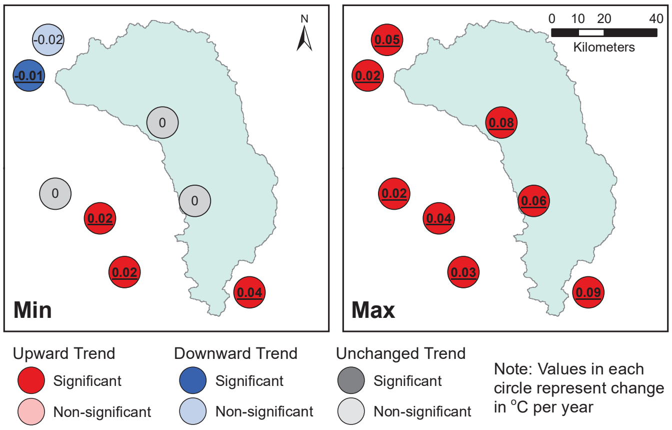


Figure 4.14 Trend in annual T_{min} and T_{max} in and around the Marsyangdi catchment. Note: significance of trend relates to 90% CI and trends significant at 95% CI are shown with bold and underlined labels. Some of the stations are shifted from the true geographic location for clarity.

Figure 4.15 and 4.16 show distribution of long-term trends in monthly T_{min} and T_{max}, respectively. The T_{max} is generally increasing including a significant trend that can be seen at four or more stations in all months. Except for a non-significant decrease in March at Khairini station, T_{max} at all stations, located in the lower mountain zone is increasing in all months and most of the changes are statistically significant. All stations below 1000 m, except Khudi, also show generally increasing T_{min} with a significant or moderately significant trend in eight to ten months. Monthly T_{max} at Jomsom and Chame stations in the high mountain zone is increasing in all months including a significant increase in the majority of months, while Thakmarpha, the lowest station of this elevation zone, exhibits a significant or moderately significant increase in four months only. However, stations in the high mountain zone have a decreasing T_{min} for varying group of five to nine months including a significant or moderately significant trend in three to four months. Statistically significant increases in monthly T_{min} ranges between 0.02 ˚C and 0.11 ˚C per year with an average rate of 0.04 ˚C per year. Monthly T_{max} is increasing between 0.02 ˚C and 0.16 ˚C per year with an average rate of 0.06 ˚C per year, and it is highest in March (0.16 ˚C per year) at the Chame station.

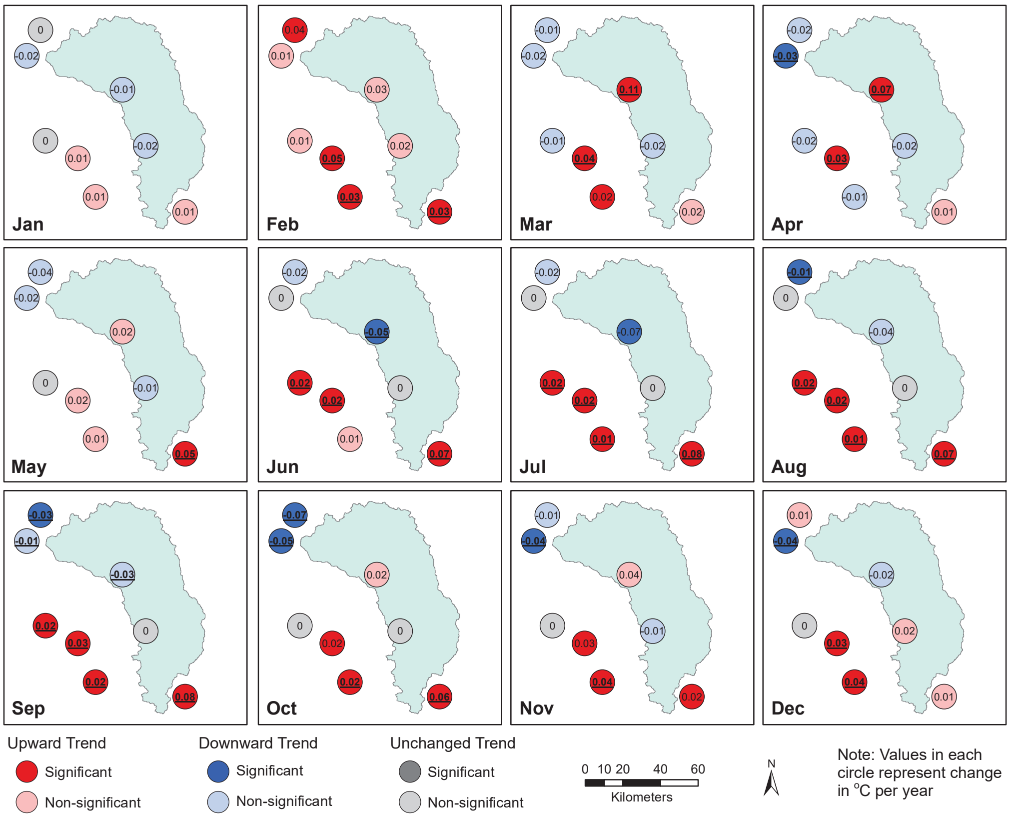


Figure 4.15 Trend in monthly T_{min} in and around the Marsyangdi catchment. Note: significance of trend relates to 90% CI and trends significant at 95% CI are shown with bold and underlined labels. Some of the stations are shifted from the true geographic location for clarity.

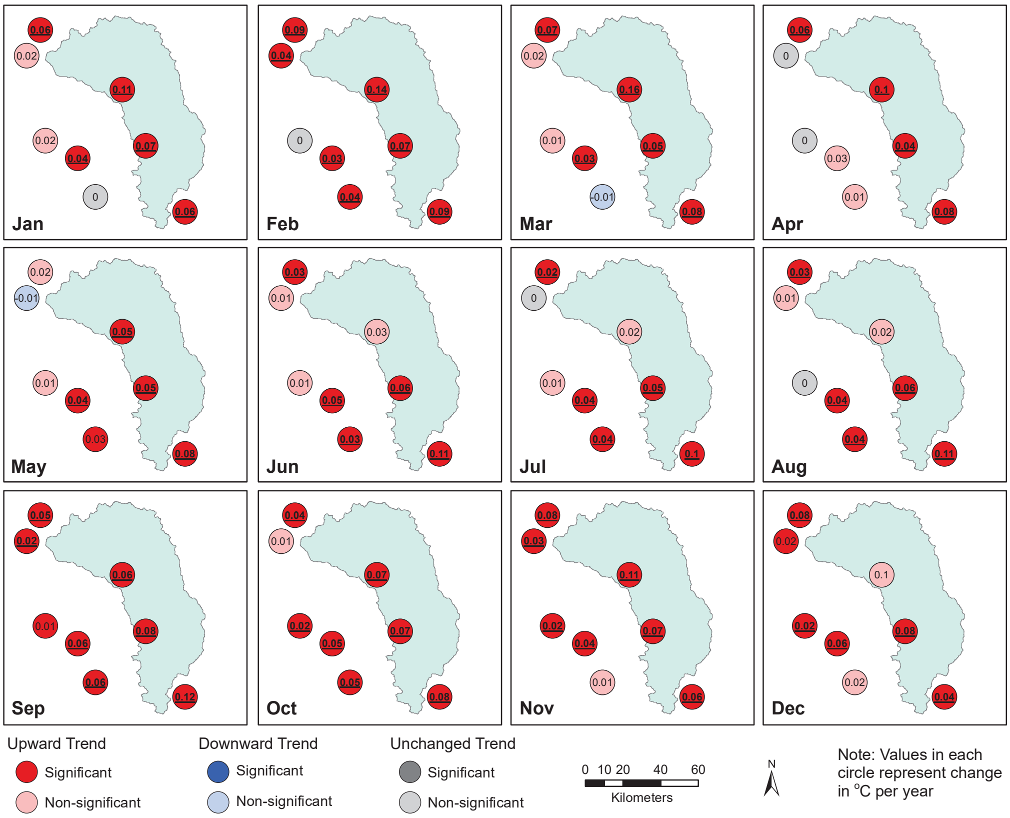


Figure 4.16 Trend in monthly T_{max} in and around the Marsyangdi catchment. Note: significance of trend relates to 90% CI and trends significant at 95% CI are shown with bold and underlined labels. Some of the stations are shifted from the true geographic location for clarity.

Table 4.6 Summary of significant and non-significant monthly trends in mean minimum temperature in and around the Marsyangdi catchment. Note: '+' represents increasing trend, '-' represents decreasing trend and 'o' represents no change. The changes inside round and square parentheses represent statistically significant trend at 95% and 90% CI, respectively. Stations are referred by short name as listed in Table 2.2.

Elevation (m)	Station	J	F	M	A	M	J	J	A	S	O	N	D	Annual
>2500	Jom	o	[+]	-	-	-	-	-	(-)	(-)	(-)	-	+	-
	Cha	o	+	(+)	(+)	o	(-)	(-)	-	-	+	+	-	o
	Thk	-	+	-	(-)	-	o	o	o	-	(-)	(-)	(-)	(-)
1500–2000	Lum	o	+	-	-	o	(+)	(+)	(+)	(+)	o	o	o	o
500–1000	Khd	-	+	-	-	-	o	o	o	o	o	-	+	o
	Pok	+	(+)	(+)	(+)	+	(+)	(+)	(+)	(+)	[+]	[+]	(+)	(+)
	Gor	+	(+)	+	+	(+)	(+)	(+)	(+)	(+)	(+)	[+]	+	(+)
	Khr	+	(+)	[+]	-	+	+	(+)	(+)	(+)	(+)	(+)	(+)	(+)

Tables 4.6 and 4.7 provide a summary of direction of change (e.g. increase/decrease) and significance of monthly and annual trends in T_{min} and T_{max}, respectively. Even though T_{max} is increasing in general, monthly T_{min} is increasing consistently at only three stations (Pokhara airport, Kharini and Gorkha) located below 1000 m. T_{min} at the mid mountain zone station Lumle is increasing significantly between June and September even though there is no change in the annual average. None of the stations show a significant change in T_{min} in January, despite the majority of stations showing a significant or moderately significant increase in T_{max} in this month.

Table 4.7 Summary of significant and non-significant monthly trends in mean maximum temperature in and around the Marsyangdi catchment. Note: '+' represents increasing trend, '-' represents decreasing trend and 'o' represents no change. The changes inside round and square parentheses represent statistically significant trend at 95% and 90% CI respectively. Stations are referred by short name as listed in Table 2.2.

Elevation (m)	**Station**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**Annual**
>2500	Jom	(+)	(+)	(+)	(+)	+	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)
	Cha	[+]	(+)	(+)	(+)	(+)	+	+	+	(+)	(+)	(+)	+	(+)
	Thk	+	(+)	+	o	-	+	o	+	(+)	+	(+)	[+]	(+)
1500–2000	Lum	+	o	+	o	+	+	+	o	[+]	(+)	(+)	(+)	(+)
500–1000	Khd	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)
	Pok	(+)	(+)	(+)	+	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)
	Gor	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)	(+)
	Khr	o	(+)	-	+	[+]	(+)	(+)	(+)	(+)	(+)	+	+	(+)

4.3.4.3. Long-term change in diurnal temperature range

Results of long-term trends in DTR are presented in Table 4.8. In general, most of the monthly DTR are increasing and only positive trends are statistically significant. Apart from Khairini station located at the lowest elevation of 515 m, the DTR increase at all stations is statistically significant in six or more months. Moreover, the DTR is increasing significantly in 10–11 months at Gorkha, Khudi and Jomsom stations.

Table 4.8 Trend in monthly and annual average DTR in and around the Marsyangdi catchment. Note: bold and underlined values indicate statistically significant trend at 95% and 90% CI, respectively. Stations are referred by short name as listed in Table 2.2.

Elevation (m)	Station	J	F	M	A	M	J	J	A	S	O	N	D	Annual
>2500	Jom	0.05	**0.07**	**0.11**	**0.08**	**0.06**	**0.05**	**0.03**	**0.04**	**0.08**	**0.09**	**0.09**	**0.09**	**0.06**
	Cha	**0.09**	**0.09**	0.05	0.03	0.03	**0.07**	**0.08**	**0.07**	**0.09**	**0.08**	**0.08**	0.04	**0.08**
	Thk	**0.05**	**0.04**	**0.03**	**0.03**	0.01	0.02	0.01	0.01	**0.03**	**0.05**	**0.07**	**0.05**	**0.02**
1000–2000	Lum	**0.03**	0.02	**0.02**	0.01	0.00	-0.01	-0.01	-0.02	-0.01	**0.02**	**0.03**	**0.02**	0.02
500–1000	Khd	**0.11**	**0.07**	**0.06**	**0.07**	**0.07**	**0.07**	**0.06**	**0.06**	**0.09**	**0.08**	**0.07**	**0.06**	**0.07**
	Pok	**0.04**	0.02	-0.01	-0.01	0.02	**0.02**	**0.03**	**0.02**	**0.05**	**0.04**	0.01	0.02	**0.02**
	Gor	**0.07**	**0.06**	**0.08**	**0.07**	**0.05**	**0.03**	0.02	0.03	**0.04**	**0.05**	**0.05**	**0.05**	**0.06**
	Khr	0.01	0.00	-0.04	0.01	0.00	**0.03**	**0.02**	**0.02**	**0.02**	0.02	-0.03	-0.02	0.01

4.4. Discussion

4.4.1. Spatio-temporal variability in precipitation

Results showed that the distribution of precipitation in the two catchments is highly dependent on orographic effects and elevation. In the Marsyangdi catchment, annual precipitation is highest at Siklesh station, followed by Khudi, Gharedhunga and Kunchha stations, located south of the high mountain ranges (e.g. 4000 m). This is related to monsoon circulation delivering the bulk of precipitation on the windward side of the high mountain ranges (Chalise et al., 1996; Nayava, 1980). Very low monsoon precipitation of less than 250 mm at the high mountain zone stations (>2500 m) namely Phu, Manang and Ranipauwa, compared to 1300–2800 mm at stations below 2000 m is consistent with the spatial distribution found by Panthi et al. (2015) and Chalise et al. (1996). However, monsoon circulation moving north through the valleys of Marsyangdi and Burhi Gandaki rivers (cf. Figure 2.3), seems to deliver slightly higher precipitation at two other high mountain zone stations (>2500 m) located at north-eastern part of the upper catchment. In the Bagmati catchment also, Makwanpur and Hariharpur stations, located on the windward side of the mountain ranges above 1500 m, receive higher precipitation compared to stations in the inner foothills of the Kathmandu valley, with precipitation in the middle of the valley being even lower (Singh & Kumar, 1997; Tuladhar et al., 2019b).

The highly variable distribution of precipitation in the Marsyangdi catchment discussed above can mostly be attributed to the orographic effects of higher mountains above 3000–4000 m as seen in other parts of Himalayan region (e.g. Bookhagen & Burbank, 2010; Diodato et al., 2010; Houze, 2012; Panthi et al., 2015; Singh & Kumar, 1997). Furthermore, as suggested by Tawde and Singh (2015) and Panthi et al. (2015), the influence of smaller mountains (e.g. ~1500 m) in triggering convections is also responsible for high spatial variability in both catchments. Even though precipitation at the stations located above 2500 m elevation in the Marsyangdi catchment is lowest, precipitation distribution in these two catchments seems to depend more on the combined effect of orography and elevation rather than on elevation alone. Extension of the mountain ridge and slope on the windward side also determine the amount of precipitation, depending on the mountain breeze and prevailing atmospheric circulation (Bhatt & Nakamura, 2005; Diodato et al., 2010; Tawde & Singh, 2015), resulting in substantial local variability in the region.

The study of monthly precipitation distribution in relation to all-station averages revealed that stations which receive higher (lower) precipitation during the monsoon months had the highest (lowest) annual precipitation in both catchments. This can be related to the dominance of monsoon precipitation in the region (Nayava, 1974; Nayava, 1980). All stations in the Bagmati catchment showed a steady increase in precipitation from May, peaking in July. Monthly precipitation at four stations below 2000 m in the Marsyangdi catchment also showed a similar pattern peaking in July.

Although they receive relatively low monsoon precipitation, stations in high mountain zone of the Marsyangdi catchment have a secondary peak in March. The spatial distribution of precipitation shown by Chalise et al. (1996) also shows the slightly higher precipitation in March at most of these stations. Even though results of Kansakar et al (2004) were not available for all stations examined in this study, the precipitation regime at most of the common stations were generally comparable with their classification, including a secondary peak in March at high mountain zone stations. However, considering their results were based on 1965–1995 data, slightly different peaking pattern at some of the stations (e.g., Kakani, Sankhu, Siklesh, Khudi, Gharedhunga) indicates that monsoon precipitation patterns could have changed in some parts of the Himalayan region in the recent decades. Compared to monsoon months, the percentage of winter and pre-monsoon precipitation in relation to all-station averages, is generally higher at stations located in north and north-western parts of the two catchments. On the other hand, low elevation stations below 300 m and 1000 m of Bagmati and Marsyangdi catchments, respectively, had lower precipitation in February and March. This is consistent to the behaviour of the Westerly systems that deliver higher rainfall in northern and western mountainous parts of Nepal (e.g. Nayava, 1980).

In the Himalayan mountain region, snowfall to annual precipitation ratio increases with elevation, especially above 2000 m. Singh and Kumar (1997) estimated that all precipitation above 5000 m falls as snow, however the elevation of the permanent snowline in Himalayan mountains may extend up to 6000 m, depending on topographical settings, including slope and aspect (Jain et al., 2009; Nayava et al., 2017; Thakuri et al., 2016). Nevertheless, any precipitation in the high elevation zone above 5000 m is important for snow and glacier mass accumulation (Bolch et al., 2012) compared to higher percentage of direct surface runoff in lower altitude.

This study has shown that annual precipitation was decreasing at most of the stations examined, including a significant decrease at four stations each in the both catchments and a moderately significant decrease at one more station in Marsyangdi catchment. However, one station in the Bagmati catchment did show a significantly increasing trend, though none of the three increasing annual trends in Marsyangdi catchment were statistically significant. These results are consistent with other findings showing generally decreasing rainfall in Nepal (Bohlinger & Sorteberg, 2018; Karki et al., 2017). The trend analysis at Sindhuli Madi and Karmaiya stations should be interpreted with care when comparing with long-term trends of other stations, since data for these two stations were available from 1984 and 1986 only. Among 42 stations analysed nation-wide, Bohlinger and Sorteberg (2018) found that one station in the Kathmandu valley and one in the lower parts of the Marsyangdi catchment had significant negative trends in monsoon precipitation. However, due to the lack of detailed information for the stations tested by Bohlinger and Sorteberg (2018), corresponding results for common stations could not be compared individually.

Annual precipitation at three of the four high mountain zone stations (>2500 m) was decreasing including significant trend at two of them. This is comparable with results of Panthi et al. (2015) that also showed decreasing annual precipitation in the mountain zone of Gandaki catchment above 2500 m during 1980–2012. Even though the distribution of significant trends did not have a clear relationship with elevation, there was a generally higher rate of decrease at the high mountain zone stations of Marsyangdi catchment. Mostly decreasing seasonal precipitation at Thankot, Godavari and Bandipur stations during 1981–2010 identified by Karki et al. (2017) supports the results obtained in this study showing significantly decreasing annual precipitation at these stations. Significantly decreasing monsoon precipitation at Godavari during 1980–2009 (Dhital et al., 2013) and significantly decreasing annual precipitation at Pattharkot during 1985–2014 (Neupane & Dhakal, 2017) also confirm the results in this study showing significantly decreasing annual precipitation at Godavari, Sindhuli Madi and Pattharkot stations in the Bagmati catchment.

Looking at the wider scale, Prokop and Walanus (2015) found no significant change in annual and seasonal rainfall at three stations located at various elevation of the Meghalaya hills which are in close proximity from Bay of Bengal in terms of the summer monsoon path. Other studies have found both increasing and decreasing trends in annual and monsoon rainfall in different parts of India including neighbouring locations of Nepal, though some of them found a higher occurrence of negative changes (Chatterjee et al., 2016; Ghosh et al., 2009; Guhathakurta & Rajeevan, 2008; Kumar & Jain, 2011). The lack of uniform changes in precipitation in the South Asian/Himalayan region but decreasing precipitation in both catchments examined suggest that other regional factors such as aerosols also have contributed to the changes in precipitation. For instance, increased level of aerosols in the South Asian region seems to have complicated the hydrological cycle including suppression of monsoon rainfall (Huntington, 2006; Ramanathan et al., 2005; Trenberth, 2008). As suggested by Shrestha (2000), decreasing monsoon precipitation in the region, despite predictions for increasing rainfall in relation to climate change (Babel et al., 2014; Khadka & Pathak, 2016; Lal et al., 2001), could be related to an offsetting effect of higher concentration of aerosols in the atmosphere.

Despite the lack of a specific pattern in significant monthly trends relating to a significant annual trend, the results of monthly trends also suggested that precipitation in the two catchments was mostly decreasing with only a few increasing trends. Furthermore, the decrease in precipitation was more consistent in the Marsyangdi catchment compared to that in the Bagmati catchment. Three of the stations in Marsyangdi catchment, which had significantly decreasing annual trends, showed significant or moderately significant trends in five to ten months. However, significantly decreasing annual trends in Bagmati catchment were related to significantly decreasing monthly trends in a maximum of four months, but with non-significantly decreasing precipitation in most of the other months. Apart from significant or moderately significant increase in precipitation in six months at Makwanpur station, few other increasing monthly trends were significant or moderately significant in Bagmati catchment including those in July at Kakani and Nepalthok stations. In Marsyangdi catchment, monthly precipitation was seen to be increasing significantly or moderately significantly in four instances including May and August increase at Chame station. Among these, the rate of change at Ranipauwa station in

January and Damauli station in March looked unusually high as 4% and 10% per year, respectively. However, further examination showed that the annual changes were 0.18 mm and 1.19 mm in relation to the long-term mean precipitation of 4.5 mm and 11.0 mm, respectively.

None of the stations in the Bagmati and Marsyangdi catchment showed any increase in the months of November to January and November to December precipitation, respectively. However, in contrast to mostly unchanged monthly trends in the Bagmati catchment, precipitation in the months between November and February was decreasing significantly or moderately significantly at varying groups of five stations in the Marsyangdi catchment. This is supported by the results of Panthi et al. (2015) showing generally decreasing precipitation in post-monsoon, winter and pre-monsoon seasons in hills, mid mountains (500–2500 m) and trans-Himalayan zones (above 2500 m) of the Gandaki River basin (of which the Marsyangdi catchment is part). Further analysis of trend in basin-wide aerial monthly average (not included here) showed that overall precipitation in November was decreasing significantly in all parts of Marsyangdi catchment. Such changes in these months, together with any decrease in other dry months, may have critical impacts on vegetation, water availability for general purposes as well as snow accumulation in the region (Barnett et al., 2005).

Results of departure from long-term mean showed that, precipitation during 1970–1975 and 1985–1990 was higher than the long-term mean at most of the stations in both catchments. On the other hand, 2005–2010 precipitation was lower than the long-term mean at most of the stations in these catchments. Despite the spatial variation within the catchments, results that showed lower than long-term mean precipitation becoming more common after 2000 compared to before 1990 support the generally decreasing long-term trend in the region. The fluctuation of 5-yearly annual precipitation aligns with generally decreasing decadal oscillation identified by Shrestha (2000) for western and eastern mid-mountain regions as well as the western Himalayan region of Nepal.

Even though long-term trends in monsoon months were not always consistent with the annual trend, the direction of precipitation departure in July was the same as that of annual departure in over 80% of the overall monthly cases. This can again be related to the dominance of monsoon precipitation. However, the departure of monthly precipitation between June and August seemed to have a strong influence in the Bagmati catchment, while precipitation between May and July is dominant in Marsyangdi catchment.

Some of the temporal fluctuations in precipitation in the South Asian region are found to be associated with ENSO and IOD, but the influence is not spatially uniform (Bohlinger & Sorteberg, 2018; Ichiyanagi et al., 2007; Shrestha, 2000). The results by Khandu et al. (2016) showed relatively high impact of ENSO in western Nepal and surrounding region compared to other parts of the Ganges-Brahmaputra-Meghna system. Based on 1901–2003 data over India, Guhathakurta and Rajeevan (2008) also suggested that the negative influence of ENSO on the Indian monsoon was weakening since the 1980s. Analysing association of such phenomenon with precipitation and temperature variability is however, beyond the scope of this study. Regardless of the influence of ENSO/IOD, the long-term decrease in precipitation in the two catchments is important considering the potential issues associated with future availability of water resource for various purpose including agriculture and hydropower.

4.4.2. Spatio-temporal variability in temperature

Monthly distributions of T_{min} and T_{max} are similar in the two catchments. For example, T_{min} and T_{max} are lowest in January, while T_{min} is highest in July and T_{max} is highest in June at most of the stations in both catchments. Furthermore, spatial variation in T_{min} and T_{max} showed high consistency in relation to elevation, most clearly in the Marsyangdi catchment. T_{min} at stations above 2500 m in the Marsyangdi catchment is markedly lower than others in all months, while stations below 1000 m showed considerably higher T_{max} in all months. It is notable that two climate stations (Sindhuli Madi and Khairinitar), located in the elevation between 500 m and 550 m of the two river catchments have a similar monthly temperature distribution. The elevation dependency was also confirmed by Nayava et al. (2017) who suggested that an inverse relation between average surface temperature and elevation is present in Nepal regardless of location. However, the Godavari station, located in the Kathmandu valley (mid mountain zone), showed a T_{min} distribution similar to mountain stations above 2000 m for all months. In fact, as indicated by Regmi et al. (2003) and Panday and Prinn (2009), the winter T_{min} at three stations located in the mountain zone (>2000 m) of the Bagmati catchment, are not markedly lower than those in the Kathmandu valley at an elevation between 1300 m and 1550 m . Nevertheless, T_{max} for the same months varied notably with approximately 5 °C difference between stations located in the Kathmandu valley and higher elevations above 2000 m. This can be attributed to stagnation of cold air in the valley during winter (December–February) nights and the temperature inversion, resulting in further cooling at the lower parts of the valley (Aryal et al., 2009; Panday & Prinn, 2009; Panday et al., 2009). Even though T_{min} is highest from June to

August, monsoon precipitation seems to reduce monthly average T_{max} at both catchments during these months. Additionally, the cooling effect seems to be higher at stations below 1000 m and in the Kathmandu valley compared to those located on higher mountains. At the same time, despite being located at a similar elevation as Thakmarpha and Jomsom stations, temperature at Chame station is seen to be the lowest, including notably lower T_{min} and T_{max} between May and September. This can be related to its geographic settings including the location in a narrow valley between snow covered mountains.

Annual average T_{max} showed increasing trends at all stations in both catchments, except the Sindhuli Madi station in the Bagmati catchment. However, since the temperature records at this station were only available from 1989, the trend result is not directly comparable with results of other stations. The results of this work are consistent with findings from other studies (Kattel & Yao, 2013; Nayava et al., 2017; Shrestha et al., 2019; Thakuri et al., 2019), suggesting an increasing trend of surface air temperature in the region.

T_{min} was also increasing significantly at most stations in the upper parts of the Bagmati catchment. Two of the stations in the high mountain zone (>2500 m) of the Marsyangdi catchment showed decreasing T_{min} including statistically significant trend at one of them, even though T_{min} was increasing below 1000 m. These results suggest that, even though the spatial distribution of T_{min} and T_{max} is seen to be closely related to elevation, the trend results do not have a clear relationship with elevation. This is in contrast to the findings of Liu et al. (2009) and Palazzi et al. (2017) suggesting a direct influence of elevation on T_{min} increase in the Hindu Kush Himalayan region. Thakuri et al. (2019) suggested that T_{max} and DTR increase had a significant positive correlation with elevation in Nepal even though there was no significant correlation between change in T_{min} and elevation.

Unlike in the case of precipitation, monthly trends in T_{min} and T_{max} were consistent with annual trends in both catchments. Except at Thakmarpha and Lumle stations of the Marsyangdi catchment, where only four of the monthly trends were significant or moderately significant, annual trends were significant when the majority of monthly trends (e.g. six to twelve months) were significant. Moreover, T_{min} at the high mountain zone stations of the Marsyangdi catchment that showed no significant trend in annual average, were also decreasing significantly in two to three months. Mostly unchanged and decreasing T_{min} at high mountain zone stations of Marsyangdi catchment suggest that the snow to precipitation ratio and the accumulation of snow might not have decreased in the higher mountainous parts of the Himalayan region (Dimri et al., 2018). However, significantly increasing T_{max} indicates that the rate of snow/glacier melt might have accelerated. The number of significant monthly trends in T_{min} and T_{max} for 1986–2015 period identified by Poudel et al. (2020) at six of the common stations (viz. Thakmarpha, Lumle, Pokhara airport, Khairini, Khumaltar and Kathmandu airport) also supports the monthly trend results of this study in general.

The rate of T_{max} increase was 0.05 ˚C per year or higher at most of the stations above 1000 m in the Bagmati catchment including the stations in the Kathmandu valley. In Marsyangdi catchment, the average rate of increase in T_{max} was 0.05 ˚C per year including a relatively high rate at stations within and closer to the catchment. The rate of statistically significant increase in T_{min} at stations around the Marsyangdi catchment (0.02 ˚C to 0.03 ˚C per year) was also lower compared to the rate in the Bagmati catchment (0.02 ˚C to 0.06 ˚C per year). Contrary to changes in T_{min} and T_{max} obtained in this study, Shrestha et al (1999) found that rate of change in surface mean temperature was higher in mid and high mountain regions of Nepal compared to the Siwalik (<1000 m) and Terai (<200 m) region. Some of these differences in the results can also be related to the different sets of stations used and the different time span of the data. This again highlights that changes in T_{min}, T_{max} and average temperature vary notably in the region. However, findings of Nayava et al. (2017) suggesting generally higher temperature change in hills compared to the Terai and higher mountains, aligns with the results of this study.

The T_{max} increase of between 0.5 ˚C and 0.09 ˚C per year seen at stations around the two catchments are higher compared to increase in regional average noticed around the world. However, similarly high rates of increase in average temperature have been reported in South Asia (Khandu et al., 2016; Pachauri et al., 2014; Thodsen, 2007; Yang et al., 2019). The rate of change obtained in this study is comparable with the results of Shrestha et al. (2019) and Nayava et al. (2017). Similar rate of changes in middle mountain region identified by Shrestha (2000) and Dhital et al. (2013) along with their conclusion that changes in T_{max} were greater compared to that in T_{min} supports the results of this study.

The rates of T_{min} and T_{max} increase at Kathmandu airport, Khumaltar and Pokhara airport are comparable with the rate identified by Nayava et al. (2017), Thakuri et al. (2019) and Poudel et al. (2020) over the last three to four decades. Kattel and Yao (2013) identified a negative but statistically non-significant trends in T_{max} and T_{min} at Thakmarpha for 1980–2009, however, the rate of increase in T_{max} at Lumle were slightly higher compared to results obtained in this study. The rate of temperature change at the Nagarkot station was considerably smaller than the rate identified by Nayava et al. (2017) for 1981–2010. Some of these differences in the rate of changes can also be related to the temporal span of data.

Temperature in the region is predicted to increase significantly in the near future (Dhaubanjar et al., 2020; Dimri et al., 2018; Khadka & Pathak, 2016; Liu et al., 2009). Babel et al. (2014) estimated the highest increase at Tribhuvan International airport in Kathmandu (2.1 ˚C to 2.7 ˚C) by 2080 under A2 and B2 emission scenarios, while Daman is predicted to have a smaller increase (1.5 ˚C to 1.7 ˚C). A linear extrapolation of the average rate identified in this study for stations around Kathmandu valley suggest that the increase in T_{max} (by 2080) would be approximately 3.5 ˚C. This indicate that, even though the recent high rates of temperature increase may not continue over a long period, the rate of temperature change in the catchments may remain high in the near future.

Long-term trends in DTR support the T_{min} and T_{max} results in both catchments. The difference in the rates of change between T_{min} and T_{max} were closely relatable with the DTR, and generally varied within ±0.03 ˚C per year. Most of the stations in the Marsyangdi catchment had significantly increasing DTR in six or more months, and none of the significant or moderately significant change in DTR was negative. Relatively fewer changes in DTR were significant in the Bagmati catchment compared to the Marsyangdi catchment. However, most of them were positive, except at the Sindhuli Madi station, where the decrease in DTR was significant or moderately significant in four months (May and August to October). The DTR seemed to be increasing as a result of a higher rate of increase in T_{max} compared to T_{min} in the Bagmati catchment. Likewise, a higher rate of change in T_{max} change in relation to T_{min} was generally related to significantly increasing DTR at stations below 1000 m in the Marsyangdi catchment. However, most of the monthly DTR at stations above 2500 m seem to have increased as the result of decreasing T_{min} and increasing T_{max}. These results are contrary to findings of other studies mostly showing decreasing DTR as the result of higher rate of T_{min} increase compared to T_{max} (Fallah-Ghalhari et al., 2019; Gil-Alana, 2018; Lobell et al., 2007; Vose et al., 2005). However, Poudel et al. (2020) and Thakuri et al. (2019) found that the rate of T_{max} change was higher compared to T_{min} in Nepal. Pattnaik and Dimri (2020) also suggested that compared to T_{min}, the increase in T_{max} was higher in the Indian subcontinent during 1901–2016 and future change in T_{max} is also estimated to be higher, causing an increase of DTR. Cloud cover can also reduce

DTR significantly by reducing the solar radiation (Dai et al., 1998). Therefore, generally increasing DTR can also be related to the reduction of cloud cover in the region (Thakuri et al., 2019) which is also consistent to decreasing precipitation seen in both catchments.

4.5. Chapter summary

Even though average temperature is shown to be increasing around the world, the rate of change varies considerably. Furthermore, changes in T_{min} and T_{max} may not be similar and can result in the changes in DTR (Sun et al., 2017; Vose et al., 2005). Historical changes in precipitation also showed substantial spatial variability including increasing trend in some regions, while decreasing or not changing significantly in others (IPCC, 2007; Xu et al., 2018). While spatial variability in temperature in the Himalayan region is predominantly related to the change in elevation, variabilities in precipitation and temporal changes in temperature also depend on other factors including regional climate, air circulations and overall topography (Kumar & Jain, 2011; Liu et al., 2009; Palazzi et al., 2017). This chapter examined spatio-temporal variability in precipitation and temperature in Bagmati and Marsyangdi catchment in the Himalayan mountain region in relation to their contrasting geographic settings.

Historical precipitation data (1970–2017) available at 13 and 12 meteorological stations within and around the Bagmati and Marsyangdi catchments, respectively were used to study the spatial and temporal variability in precipitation. Similarly, daily minimum and maximum temperature data available at nine and eight stations were used to analyse temperature in Bagmati and Marsyangdi catchments, respectively. Spatial variability in monthly patterns of T_{min}, T_{max} and precipitation were analysed in relation to geographic settings. Long-term change in T_{min}, T_{max}, DTR and precipitation were analysed at annual and monthly scales using non-parametric MK test and Sen's slope estimator on homogenised data. Spatial variability at the meteorological stations were also analysed in relation to elevation zones.

4.5.1. Precipitation variability in Bagmati and Marsyangdi catchments

The spatial distribution of precipitation highlighted a very important influence of local orography in both catchments. Annual precipitation at Nepalthok station located north of mountain ranges (>1500 m) in Bagmati catchment is as low as 900 mm, while three stations south of the mountain range receive more than 2000 mm precipitation. Furthermore, annual precipitation in the middle of Kathmandu valley is also lower compared to areas located in foothills of the surrounding mountains. Three of the high mountain zone stations of Marsyangdi catchment viz. Manang, Phu and Ranipauwa stations (>3500 m) located north of Annapurna Himalayan range receive less than 500 mm precipitation annually, while Siklesh and Khudi stations located south of the high mountains (>4000 m) receive more than 2500 mm precipitation.

In Bagmati catchment, other than Kakani and Sankhu stations, where August precipitation is almost as high as in July, precipitation at all stations peaks in July with a steady decline from August. Precipitation at stations located in low mountain zone in the southern part of Marsyangdi catchment generally peak in July, whereas the high mountain zone stations mostly located north of high Himalayan range have July/August peak as well as a secondary peak in March. Daman and Thankot stations located in the north-western part of the Bagmati catchment receive relatively high precipitation in March compared to other stations. Similarly, Larkesamdo and Chame station of Marsyangdi catchment also receive higher than all-station average precipitation in February and March, although they receive very low precipitation during monsoon months.

Results of long-term trends suggested that precipitation at most of the stations was decreasing in Marsyangdi catchment, including statistically significant trend in four stations (Bandipur, Jagat, Larkesamdo and Manang) and a moderately significant decrease at Gorkha station. Annual precipitation was also decreasing in Bagmati catchment with significant trend at four stations (Pattharkot, Sindhuli Madi, Thankot and Godavari) even though Makawanpur station had a statistically significant increase. Apart from significant or moderately significant decreasing trends at Godavari and Thankot in three months between June and September, there were no consistency in significance of monthly trend in relation to any significant annual trend. Godavari, Nepalthok, Thankot stations of Bagmati catchment and Larkesamdo, Manang and Jagat of Marsyangdi catchment had significantly decreasing trend in two to three months between June and September. However, significantly decreasing trend in one or two months and non-significant but negative changes in most of the months have also resulted in a significant decrease in annual precipitation at Sindhuli Madi station of Bagmati catchment as well as Bandipur and Gorkha stations of Marsyangdi catchment. The rate of significant decrease at stations in Bagmati catchment was between 0.5% and 1% per year, while it ranges between 0.5% and 1.6% per year in the Marsyangdi catchment with rates of over 1% at two high mountain zone stations.

Departure of 5-yearly precipitation from long-term mean was also examined to see if long-term variability exists. Decadal average precipitation was higher than long-term mean during 1970–1975 and 1985–1990, whereas 2005–2010 precipitation were lower than long-term mean at most of the stations in both catchments. Results of departure from long-term mean at monthly scales showed that departure of July precipitation is in the same direction as annual departure in over 80% of the cases in the two catchments. However, departure in May and June also showed a very high agreement (around 70%) with annual departure in Marsyangdi catchment compared to that in June and August in Bagmati catchment. Departure in February and March were different from annual departure for over half of the cases in Bagmati catchment, while December and March departure were different for over 45% of the cases in Marsyangdi catchment. Considering the dominance of monsoon precipitation, the higher alignment of the departure between the months of May and August is reasonable, however there is no specific combination of substantial monthly departures resulting in a certain annual departure in the two catchments.

4.5.2. Temperature variability in Bagmati and Marsyangdi catchments

T_{min} and T_{max} at all of the stations analysed in both catchments reach their lowest in January. T_{min} at stations in Bagmati catchment is highest in July, whereas stations in Marsyangdi catchment have highest T_{min} in June. T_{max} in both catchments were generally high in June. However, it peaks earlier (April to May) at Karmaiya and Sindhuli Madi stations located in lower mountains of Bagmati catchment, while the Daman station (2265 m) of Bagmati catchment and two of the high mountain stations (Jomsom and Thakmarpha) of Marsyangdi catchment have their T_{max} peak later in July. Temperature distribution at climate stations in both catchments show a consistent relationship with the elevation zone. For instance, T_{min} and T_{max} at stations below 1000 m are highest, followed by those located in Kathmandu valley in Bagmati catchment and mid mountain station Lumle throughout the year. Temperature at mountain stations located above 2500 m elevation are consistently lower by at least 9–10 ˚C compared to those located below 1000 m throughout the year. However, as the results of colder winter nights in Kathmandu valley due to the stagnation of cool air and temperature inversion (Aryal et al., 2009; Panday & Prinn, 2009), T_{min} at stations in Kathmandu valley (1300–1530 m) are not remarkably different from those at stations above 2000 m between November and April.

Results of long-term trend showed that annual T_{max} is increasing significantly at all stations of the two catchments except for Sindhuli Madi of Bagmati catchment. Annual T_{min} were also increasing significantly at all stations of Bagmati catchment above 1000 m except Kakani. However only three stations located below 1000 m showed significantly positive change in Marsyangdi catchment, while two of the high mountain stations showed negative changes including significant trend at Thakmarpha. Results of trend in monthly T_{min} and T_{max} showed that most of the significantly increasing annual trends were related to statistically significant increasing trends in most of the months. A significantly decreasing trend in annual T_{min} at Thakmarpha can also be related to negative changes in most of the months except between June and August. On the other hand, as generally expected, stations with non-significant annual trends had no consistent pattern of monthly trends in terms of direction and significance. Average rate of significant changes in T_{min} and T_{max} in Bagmati catchment were 0.05 ˚C and 0.06 ˚C per year respectively, while the rate of change at stations in Marsyangdi catchment were 0.04 ˚C and 0.06 ˚C per year, respectively.

Results of long-term trend suggested that DTR is generally increasing in both catchments. Most of the significant changes in the two catchments were related to higher rates of increase in T_{max} compared to those in T_{min}, while decreasing T_{min} and increasing T_{max} contributed towards the DTR increase in upper Marsyangdi catchment. DTR at Nagarkot (2147 m) of Bagmati catchment and Jomsom (2744 m) of Marsyangdi catchment was increasing significantly in all months. Furthermore, Kathmandu airport, Khumaltar and Panipokhari located between the elevation of 1300 m and 1400 m in Bagmati catchment as well as Pokhara airport, Gorkha and Khairini located in the elevation between 500 m and 1000 m of Marsyangdi had significantly increasing DTR in most of the months between June and October.

5 SPATIAL AND LONG-TERM VARIABILITY OF RIVER DISCHARGE IN BAGMATI AND MARSYANGDI RIVER CATCHMENTS

5.1. Introduction

River discharge represents hydrological output from a catchment that not only indicates water availability within it but is also very important for downstream regions. Rivers have always served as a basis for human civilization, providing water for various purposes including domestic use, irrigation and recreation. Furthermore, hydropower generation as well as other industrial and commercial uses can be vital for the economy of a country. Rivers also play an important role in the environment by providing habitat and nutrient for aquatic lives as well as supporting other biotic community (Leppi et al., 2012; Woodward et al., 2010). Therefore, any alteration in flow distribution and quality of water can affect the ecosystem and long-term changes in river discharge in a catchment can have cascading effects on population and development of the region.

Over a long temporal scale, river discharge from a catchment may change in response to the variability of climatic factors such as precipitation, temperature and evaporation (Zhang et al., 2014). Additionally, changes in land use/land cover (LULC) may alter land surface characteristics in terms of water retention, runoff and evapotranspiration, resulting changes in river discharge. Decrease in snow/glacier cover as reported in many parts of the world is also linked with changes in river discharge (Sorg et al., 2012; Stewart, 2009).

Studies show that long-term changes in river discharge are spatially variable, however a decrease in river discharge has been reported for more than half of major rivers around the world, especially from latter half of the 20th century (Shi et al., 2011; Villar et al., 2009). In general, discharge from the majority of rivers in North America, South America, Africa, Australia, and Asia has decreased since the 1960s, whereas an increasing trend has been reported in discharge from rivers in Europe (Naik & Jay, 2011; Shi et al., 2011; Van Vliet et al., 2013). Within these regions, however changes in discharge from some rivers might be contrasting to generally observed pattern. For instance, the Mississippi and Colorado rivers in North America, the Orinoco and Parana rivers of South America, the Yangtze River in Asia are reported to have had an increase in discharge between 1960 and 2010, whereas the Danube and Rhine rivers of Europe experienced a decline in water flow (Frans et al., 2013; Shi et al., 2011; Zhang & Schilling, 2006). At the same time, some studies have found no significant change in river discharge in relation to changes in temperature, precipitation and LULC (Kong & Pang, 2014; Pizarro et al., 2006; Wilk et al., 2001).

Monthly discharge patterns are also seen to have altered in the past as a result of changes in climatic variables and human activities (Hodgkins et al., 2003; Morán-Tejeda et al., 2011; Naik & Jay, 2011; Vo et al., 2016). Long-term increase and earlier start to spring discharge have been linked to changes in precipitation pattern as well as high rate of snow/ice melt (Rood et al., 2017; Zampieri et al., 2015). Future discharge and monthly distribution may also alter in relation to changes in precipitation, evapotranspiration, LULC and other human activities (Frans et al., 2013; Tao et al., 2014; Thodsen, 2007). Maximum discharge is expected to increase in higher proportion of the world's major rivers, while minimum flow may decrease (Arnell, 1999; Van Vliet et al., 2013; Wijngaard et al., 2017).

Predictions of future discharge also vary depending on the type of model used and the inclusion/exclusion of various influencing factors. Based on an atmospheric circulation model, Nakaegawa et al. (2013) projected significantly increasing discharge from 15 out of 24 major catchments of the world examined, by the end of the 21st century. Arnell and Gosling (2013) estimated a significant increase in river discharge across 49% of the world's land surface, while 36% area are expected to experience decreasing discharge. However, under Representative Concentration Pathways (RCP) 4.5 and 8.5 scenarios, Santini and Di Paola (2015) projected mean annual discharge to decrease in the majority of river basins examined globally, towards 2050 and 2100.

Despite the presence of large rivers such as the Ganges, Brahmaputra, Meghna, Indus and Godavari, water availability in South Asian and Himalayan region is highly imbalanced in relation to the distribution of population (Mirza et al., 2003; Whitehead et al., 2015). Annual average and monthly distribution of river discharge vary significantly depending on the characteristics of the main source because of the spatial diversity and substantial seasonality dominated by the Indian summer monsoon. For instance, the distribution of river discharge in lower to mid mountainous regions is highly dependent on rainfall patterns (Jeuland et al., 2013). However, the dependency on rainfall can be less in high altitude Himalayan mountains where most of the headwaters are snow fed (Hannah et al., 2005; Siderius et al., 2013). River discharge from high mountain regions also depends on snow to rainfall ratio and the rate of snow/ice melt. Human activities including LULC changes and water extraction affecting river discharge also vary between these regions (Sadoff et al., 2013).

Within the catchment of the Ganges, one of the very important transnational rivers of South Asia, historical changes in river discharge show a significant spatial variability (Mirza et al., 2003; Sadoff et al., 2013). Furthermore, predictions on future river discharge in the Himalayan mountain region and the Ganges basin are also inconclusive including indication of both increasing and decreasing discharge (Jeuland et al., 2013; Sadoff et al., 2013; Santini & Di Paola, 2015; Whitehead et al., 2015).

In Nepal, Hannah et al. (2005) analysed the flow regime of 28 rivers, while few others have studied discharge patterns in one or two catchments (Bharati et al., 2016; Dhital et al., 2011). Some studies have examined long-term historical trends of discharge at selected hydrometric stations across Nepal (Dahal et al., 2019; Dhital et al., 2013; Gautam & Acharya, 2012; Khatiwada et al., 2016). Water quality for some rivers in the region have also been assessed with a particular focus on urban rivers such as Bagmati (Kannel et al., 2007; Panthi et al., 2017). While an extensive knowledge of historical changes in river discharge is lacking, existing results indicate that the majority of changes in river discharge show a downward trend and seasonal changes are not uniform (Gautam & Acharya, 2012; Khatiwada et al., 2016; Pandey et al., 2020; Shrestha & Aryal, 2011). Some studies (e.g. Bharati et al., 2016; Dahal et al., 2020; Mishra et al., 2018) have modelled future water availability in different river catchments of Nepal in relation to climate change, while a few have aimed to predict the influence of LULC change on discharge (e.g. Lamichhane & Shakya, 2019). Some studies have examined the contribution of snow and glacier melt to the discharge from various rivers (Alford & Armstrong, 2010; Kayastha et al., 2020), while a few have highlighted the impact of climate change on glaciers and river flow in the Himalayan region (Miller et al., 2012). Discharge pattern and changes in the Bagmati catchment have been analysed by some studies, mostly focusing on monsoon discharge (e.g. Dhital et al., 2011; Sharma & Shakya, 2006), while only limited studies have examined river discharge variability in the catchment of the Marsyangdi River (Gupta et al., 2019; Parajuli et al., 2015).

As mentioned in Chapter 4, the minimum amount of water available in some of the low-flow months (e.g., November, December) is particularly valuable compared to that in other months. Thus, even a small decrease in such months can have marked consequences on the biotic community, agriculture and water availability for general use. On the other hand, an increase in maximum discharge in July and August resulting in increase of associated events such as landslides and floods can have serious impacts on property, lives and agriculture. Therefore, a detailed understanding of changes in annual discharge as well as monthly variabilities is important for water resource management in the region.

This chapter aims to analyse spatial and long-term variability in monthly and annual discharge from Bagmati and Marsyangdi River catchments. The influence of changes in precipitation, temperature and LULC on river discharge is analysed in Chapter 6. The Bagmati and its tributaries are mostly rain-fed, whereas most of the major tributaries of the Marsyangdi River are snow-fed. Hence, the distribution and historical changes in river discharge from these two sub-catchments of the Ganges system can be different, given their geographical settings. A focus is also put on analysing similarities and differences between the two river basins and their sub-catchments. The next section provides a brief description of the data and methods. Sections 5.3.1 and 5.3.2 provide results on spatio-temporal variability in river discharge from these two catchments, respectively. Section 5.4 provides some discussions, while a chapter summary is provided in Section 5.5.

5.2. Data and methods

Observed daily discharge records, between 1970 and 2017 at three river gauge stations in both catchments were used to study discharge variability in Bagmati and Marsyangdi catchments. The detail of the hydrometric stations is presented in Chapter 2 (cf. Figure 2.2 and 2.3, Table 2.3). The Bagmati River gauge station located at Karmaiya was replaced by the Pandheradovan station (approximately 1.5 km upstream), in 1979. Similarly, the Marsyangdi River gauge station located at Gophlinghat was moved approximately 9 km upstream to Bimalnagar in 1986, because of the construction of a hydropower dam at the original location. Considering the absence of major tributaries and the small percentage of area in between the original and new location, discharge records from both the original and relocated stations are used to represent discharge from the entire catchments.

Most of the river discharge as recorded at Sundarijal station, especially during the dry season is diverted for hydropower generation and drinking water purposes. However, long-term mean of this diverted discharge is less than 1% of the discharge at Pandheradovan, and the diversion had started before the study period. Likewise, most of the discharge from the Kulekhani river catchment has been diverted to the Rapti basin for hydropower generation since 1982 (Babel et al., 2014; Sharma & Shakya, 2006). This diverted discharge accounts for less than 3% of the annual discharge at the Pandheradovan station and is expected to remain unchanged in the future (Babel et al., 2014; Dahal et al., 2016). Further analysis by adjusting 3% discharge on observed discharge at Pandheradovan station from 1982 onwards, showed that this would not change the direction and/or significance of long-term trend results shown in this study. Hence, these diversion schemes were not considered in the analysis of temporal change in river discharge. Two hydro-electricity power plants viz. Middle Marsyangdi and

Upper Marsyangdi hydropower are operational in the lower mid-section of the Marsyangdi River since 2000 and 2016, respectively. However, since both operations are based on run-of-river type dams, the observed river discharge records are considered to be reasonably unaffected, especially for the analysis at monthly and annual scale.

The daily average discharge records were checked for homogeneity and gaps in records that were less than 15 months were filled as detailed in Section 2.3.1. Average, minimum and maximum discharge at monthly and annual scale were calculated from the daily discharge series. Monthly distribution of standardised (z-score) value for long-term (1970–2017) mean discharge was used to analyse the discharge regime at sub-catchment level. Long-term trend in river discharge were then tested using non-parametric Mann-Kendall technique, including pre-whitening process and Sen's slope estimator (see Section 2.3.3 to 2.3.5). Additionally, decadal departures of river discharge from long-term mean were also derived to identify behaviour of long-term changes.

5.3. Results

5.3.1. River Discharge variability in the Bagmati catchment

Records from Sundarijal, Khokana and Karmaiya/Pandheradovan stations along the Bagmati River were used to analyse spatio-temporal variability of the river discharge in the headwater, upper and the entire catchment, respectively. Monthly flow regimes, long-term trends in annual and monthly discharge as well as decadal variability in these sub-catchments are presented in this section.

5.3.1.1. Monthly distribution of river discharge and timing of peak discharge in Bagmati catchment

The left panel of Figure 5.1 shows the distribution of standardised long-term (1970–2017) mean of monthly river discharge from headwater, upper and the entire catchment of the Bagmati River. In general, river discharge from all sub-catchments starts increasing from May, with a substantially large discharge between July and September. Discharge from headwater and upper Bagmati catchment is highest in August, while discharge from the entire catchment peaks in July with a similar volume of discharge in August. Discharge from all sub-catchments starts decreasing from October and becomes lowest in March and April. Both the May–July increase and the September–November decrease in discharge from headwater catchment are delayed, relative to those in upper and the entire catchment.

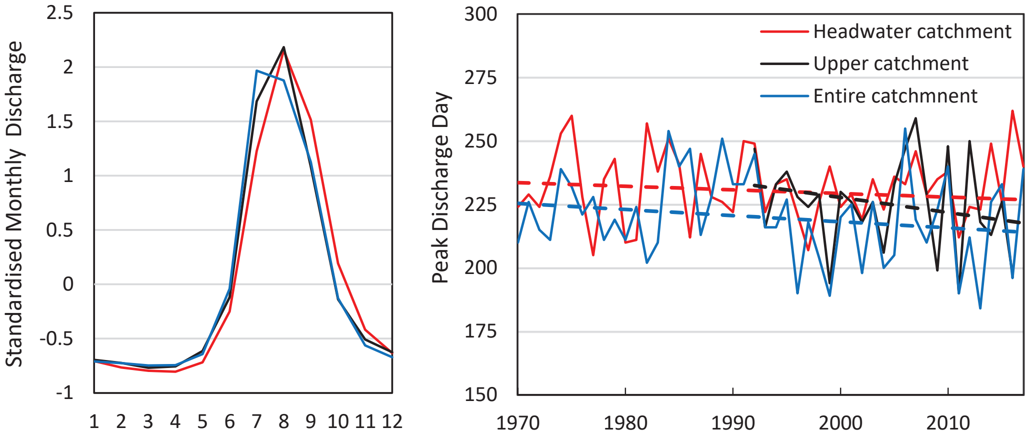


Figure 5.1 Monthly discharge regime (left) and long-term change in the timing of peak discharge (right) from headwater, upper and the entire Bagmati catchment. Note: none of the trends in peak discharge day is statistically significant (at 90% CI).

The right panel of Figure 5.1 shows the long-term variation in peak discharge day of the year. It shows that the timing of peak discharge from the sub-catchments of Bagmati are generally shifting forward, however the trend test showed no significant change for any sub-catchments. Annual discharge from headwater and upper catchments represents approximately 1% and 12% of the total discharge from the catchment, respectively (Table 5.1).

5.3.1.2. Trend in annual discharge

Long-term trends in annual minimum, average and maximum discharge from headwater, upper and the entire Bagmati catchment are shown in Figure 5.2. Annual average discharge from upper and the entire Bagmati catchment is decreasing significantly. The rate of change is highest in upper catchment followed by the entire catchment. Long-term trends in annual minimum and maximum discharge are statistically non-significant. However, minimum discharge from upper and the entire catchment shows a negative trend, whereas the change in maximum discharge from the entire catchment is positive.

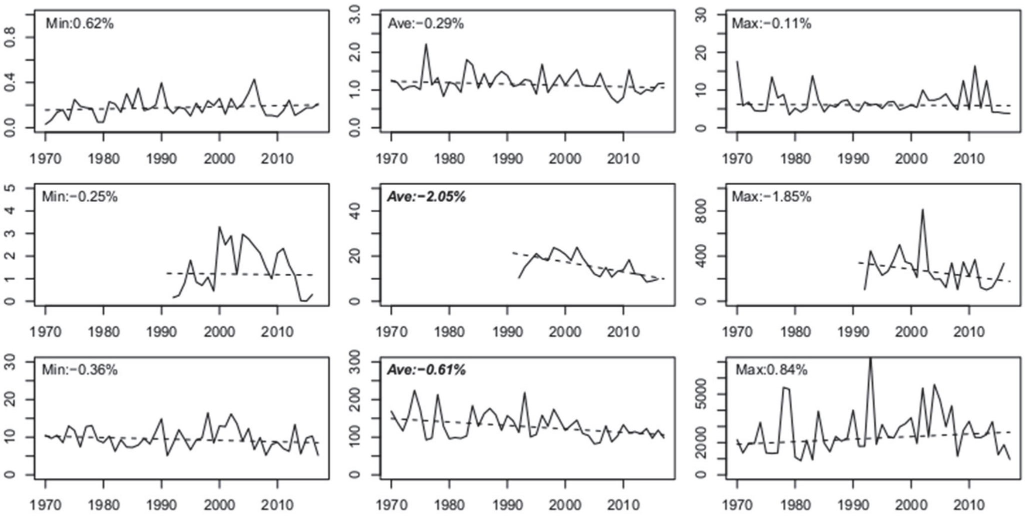


Figure 5.2 Trend in annual minimum (left), average (centre) and maximum (right) discharge from headwater (top), upper (middle) and entire (bottom) Bagmati catchment (in cumec). Note: change percentage values shown in bold represent statistically significant trend (at 90% CI), while bold-italics value represent trend significant at (95% CI).

5.3.1.3. Trend in monthly discharge

Long-term trends in monthly average, minimum and maximum discharge from the headwater catchment are illustrated in Figure 5.3. A summary of long-term trends in monthly minimum, average and maximum discharge along with their corresponding long-term means in Bagmati sub-catchments are presented in Table 5.1. Trends in monthly minimum, average and maximum discharge from headwater catchment are generally non-significant. However average discharge shows negative changes between June and October including a moderately significant decrease of 0.68% per year in July, while the maximum discharge is decreasing in the majority of months including a significant decrease of 1.01% per year in June. Changes in monthly minimum discharge from headwater catchment are also negative between July and September, however all other months show positive changes including a significant trend in June.

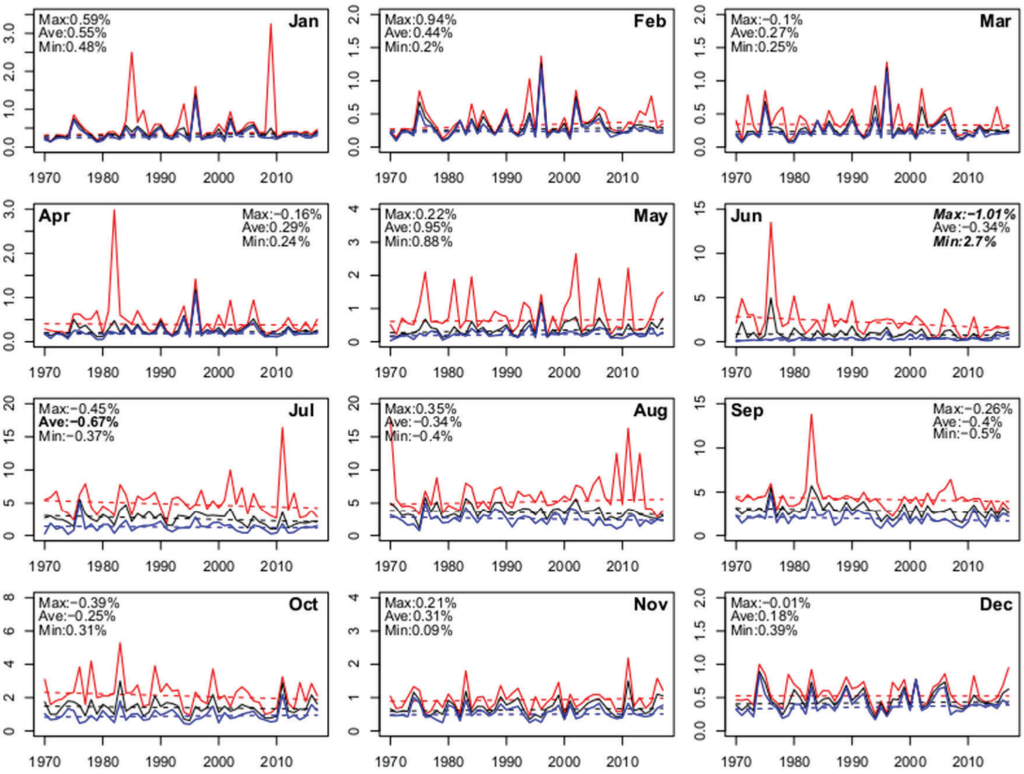


Figure 5.3 Trend in monthly minimum, average and maximum discharge from headwater catchment (in cumec). Note: lines in blue, black and red represent monthly minimum, average and maximum discharge, respectively. Change percentage values shown in bold represent statistically significant trend (at 90% CI), while bold-italics value represent trend significant at (95% CI).

Figures 5.4 and 5.5 show the trends in monthly river discharge from upper and the entire Bagmati catchment, respectively. Unlike headwater catchment, which had some positive changes in monthly average discharge, upper and the entire catchments show decreasing trends in all months. Decreases in average discharge from upper catchment are statistically significant in all months except February to May and July. Average discharge from the entire catchment is also decreasing in all months but the trend is significant or moderately significant only in July, August and December. The rates of statistically significant decrease in monthly average are also highest (1.5% to 2.8% per year) in upper catchment, while the rate of significant decrease for the entire catchment is between 0.66% and 0.73% per year.

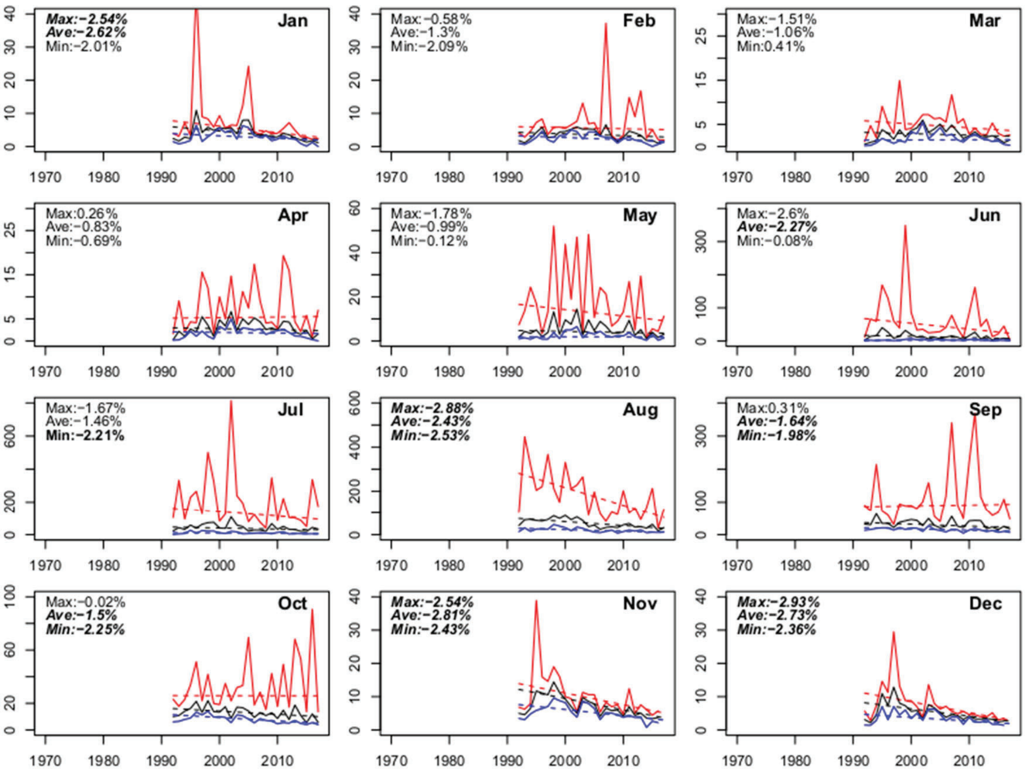


Figure 5.4 Trend in monthly minimum, average and maximum discharge from upper catchment (in cumec). Note: lines in blue, black and red represent monthly minimum, average and maximum discharge, respectively. Change percentage values shown in bold represent statistically significant trend (at 90% CI), while bold-italics value represent trend significant at (95% CI).

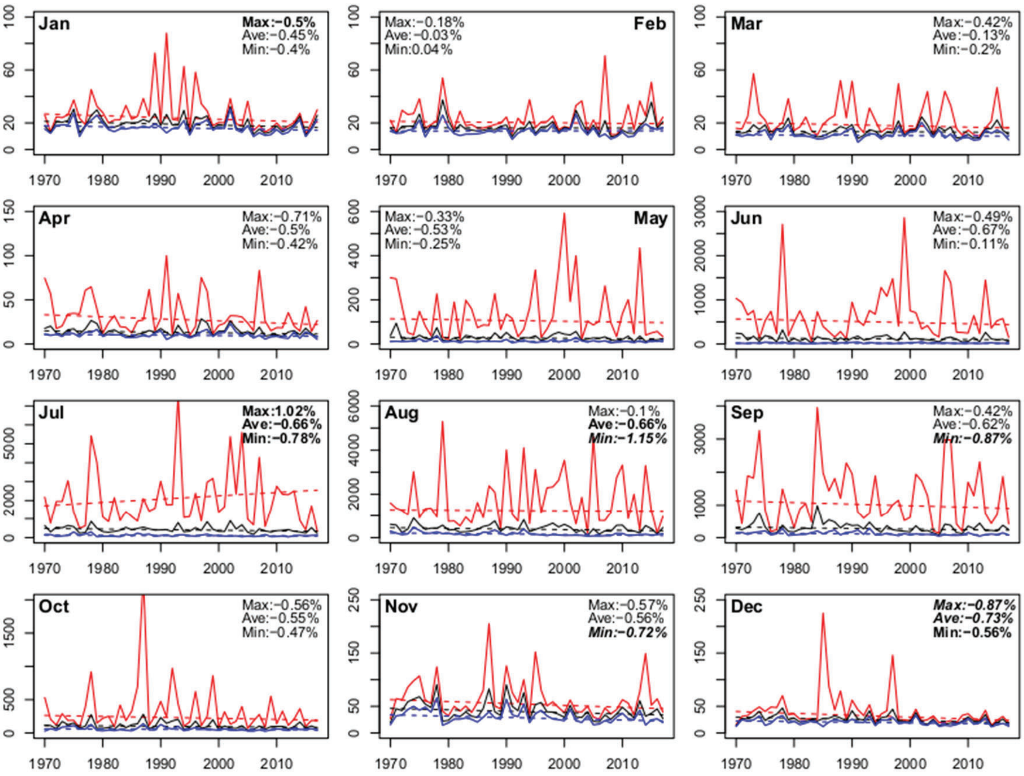


Figure 5.5 Trend in monthly minimum, average, minimum and maximum discharge from entire Bagmati catchment (in cumec). Note: lines in blue, black and red represent monthly minimum, average and maximum discharge, respectively. Change percentage values shown in bold represent statistically significant trend (at 90% CI), while bold-italics value represent trend significant at (95% CI).

Monthly minimum and maximum discharges from upper and the entire catchment are also decreasing in general. Even though trends in annual minimum and maximum discharge from upper and the entire catchment are statistically non-significant, some of the monthly trends are significant. For instance, the decreasing trend in minimum discharge from upper catchment is significant between August and December with a moderately significant trend in July, while the negative changes for the entire catchment are also similarly significant in these months except October. However, July maximum from the entire catchment shows a moderately significant increase, despite a non-significant decrease in upper and headwater catchments.

Table 5.1 Long-term mean and summary of trend in minimum, average and maximum discharge from Bagmati sub-catchments at monthly and annual scale. Note: values represent the long-term mean, while values within parenthesis represents the percentage of change per year. Bold italics and bold values represent statistically significant changes at 95% and 90%, respectively. Decreasing changes are shown in red.

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Headwater catchment													
Min	0.3 (0.48)	0.3 (0.2)	0.2 (0.26)	0.2 (0.24)	0.2 (0.88)	0.3 ***(2.7)***	1.3 (-0.37)	2.5 (-0.4)	2.0 (-0.5)	0.9 (0.31)	0.6 (0.09)	0.4 (0.39)	0.2 (0.62)
Ave	0.4 (0.55)	0.3 (0.44)	0.3 (0.27)	0.3 (0.29)	0.4 (0.95)	0.9 (-0.34)	2.6 **(-0.68)**	3.6 (-0.34)	2.9 (-0.4)	1.4 (-0.25)	0.7 (0.31)	0.5 (0.18)	1.2 (-0.29)
Max	0.6 (0.59)	0.4 (0.94)	0.4 (-0.1)	0.5 (-0.16)	0.8 (0.22)	2.4 ***(-1.01)***	5.1 (-0.45)	6.2 (0.35)	4.3 (-0.26)	2.2 (-0.4)	1.0 (0.21)	0.6 (-0.01)	6.9 (-0.11)
Upper catchment													
Min	2.8 (-2.01)	2.4 (-2.09)	1.8 (0.41)	1.7 (-0.7)	2.4 (-0.12)	2.8 (-0.08)	10.4 **(-2.22)**	20.1 ***(-2.53)***	14.4 ***(-1.98)***	7.7 ***(-2.25)***	5.2 ***(-2.43)***	3.6 ***(-2.36)***	1.5 (-0.25)
Ave	4.0 ***(-2.62)***	3.5 (-1.3)	2.8 (-1.06)	3.0 (-0.83)	5.3 (-0.99)	13.4 ***(-2.27)***	42.7 (-1.46)	50.8 ***(-2.44)***	32.9 ***(-1.64)***	13.0 ***(-1.5)***	7.0 ***(-2.81)***	5.1 ***(-2.73)***	15.6 ***(-2.05)***
Max	7.7 ***(-2.54)***	7.3 (-0.58)	5.2 (-1.51)	7.5 (0.26)	18.0 (-1.78)	66.3 (-2.6)	202.2 (-1.67)	179.6 ***(-2.88)***	111.9 (0.31)	33.5 (-0.02)	10.3 ***(-2.54)***	7.7 ***(-2.93)***	279.8 (-1.85)
Entire Bagmati catchment													
Min	16.7 (-0.4)	14.2 (0.04)	11.3 (-0.2)	10.4 (-0.42)	12.9 (-0.25)	20.8 (-0.11)	114.0 **(-0.78)**	168.3 ***(-1.15)***	120.1 ***(-0.87)***	57.6 (-0.47)	30.9 ***(-0.72)***	20.4 **(-0.56)**	9.7 (-0.36)
Ave	19.7 (-0.45)	17.3 (-0.03)	14.0 (-0.13)	14.3 (-0.5)	30.3 (-0.53)	123.7 (-0.67)	436.1 **(-0.66)**	422.1 **(-0.66)**	305.1 (-0.62)	110.3 (-0.55)	42.6 (-0.56)	25.8 ***(-0.73)***	131.1 ***(-0.61)***
Max	27.7 **(-0.5)**	23.9 (-0.18)	23.2 (-0.42)	33.0 (-0.71)	141.7 (-0.33)	675.3 (-0.49)	2056.5 **(1.02)**	1698.2 (-0.1)	1246.1 (-0.42)	334.7 (-0.56)	64.6 (-0.57)	41.1 ***(-0.87)***	2666.2 (0.84)

5.3.1.4. Decadal departure from long-term mean

Departure of decadal minimum, average and maximum discharge from sub-catchments of Bagmati River in relation to their long-term means are shown in Figure 5.6. Decadal departure of average discharge suggests a generally decreasing trend. Decadal average discharges from all sub-catchments were substantially lower than long-term mean during 2010–2017 and average discharge from headwater and the entire catchment is lower or substantially lower after 2000. However, apart from decreasing maximum discharge from the upper catchment since the 1990s, minimum and maximum discharge show multi-decadal behaviour. Further examination of decadal departure at monthly scale (Appendix C - Figure 1 to 3) also shows that departures of decadal minimum and maximum discharge behave differently to that of average discharge. Furthermore, there is no consistent pattern in substantial decadal departures of monthly discharge compared with the departure of annual minimum, maximum or average. For instance, monthly departure in low (high) discharge months do not align consistently with departure in annual minimum (maximum) discharge.

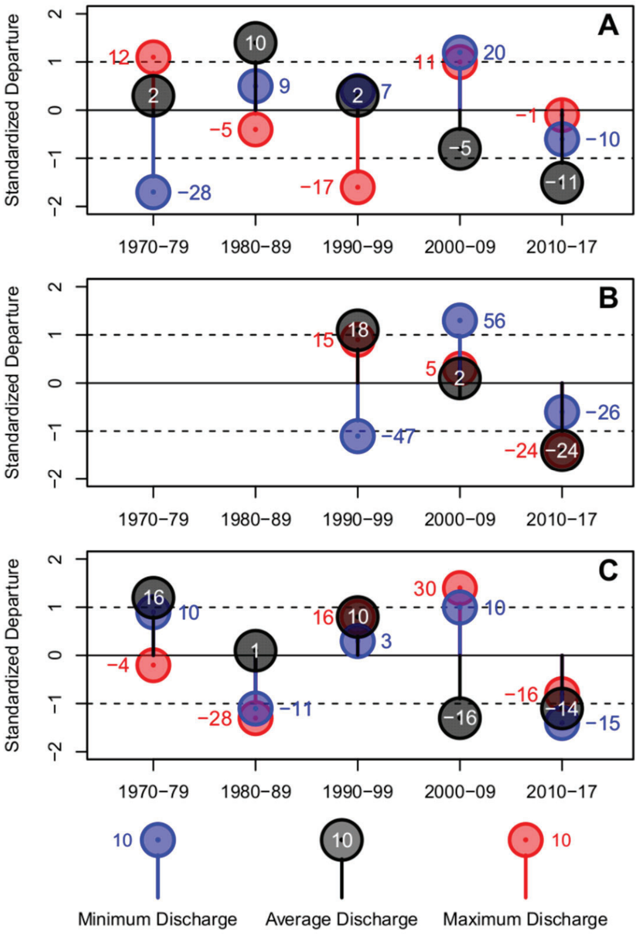


Figure 5.6 Decadal departure of annual minimum, average and maximum discharge from headwater (A), upper (B) and entire (C) Bagmati catchment in relation to their corresponding long-term mean. Note: labels in blue, white and red represent percentage of minimum, average and maximum discharge departure, respectively.

5.3.2. River Discharge variability in the Marsyangdi catchment

Daily discharge records from Garambesi and Gophlinghat/Bimalnagar are used to examine variability in discharge from Chepe and Marsyangdi catchment, respectively. Records at Bhakundebesi station which represents discharge from mid to upper catchment (referred as upper catchment), only exist from 2000, therefore they are only used for analysing monthly flow pattern but not for assessment of long-term trend.

5.3.2.1. Monthly distribution of river discharge in Marsyangdi catchment

The left panel of Figure 5.7 shows monthly discharge pattern of Chepe sub catchment, upper catchment and the entire Marsyangdi catchment. Monthly river discharge patterns of both sub-catchments and the entire catchment are very similar, with substantially high discharge between July and September, peaking in August and decreasing from October. Discharge from upper and the entire Marsyangdi catchment is lowest in February and March, whereas discharge from Chepe sub-catchment is similarly low in April as well. On the other hand, monthly discharge from upper and the entire catchment starts to increase from May, whereas a noticeable increase in Chepe sub-catchment starts only from June.

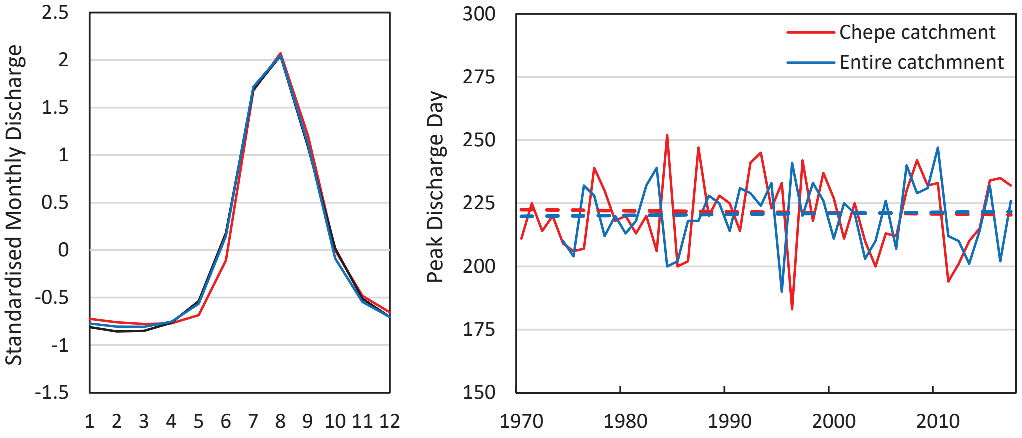


Figure 5.7 Monthly discharge regime (left) and long-term change in the timing of peak discharge (right) from Chepe, upper and the entire Marsyangdi catchment. Note: none of the trends in peak discharge day is statistically significant (at 90% CI).

The right panel of Figure 5.7 shows long-term variation in the timing of peak discharge for Chepe and Marsyangdi River. The trend test showed that there is no statistically significant change in peak discharge day between 1970 and 2017. Annual discharge from Chepe and upper catchment, respectively represent approximately 11% and 60% of the total discharge from the catchment (Figure 5.8 and Table 5.2).

5.3.2.2. Trend in annual discharge

Long-term trends in annual minimum, average and maximum discharge from Chepe sub-catchment and Marsyangdi catchment are presented in Figure 5.8. Annual average discharge from the entire catchment is increasing significantly but a positive change in Chepe sub-catchment is statistically non-significant. While the changes in minimum and maximum discharge from Chepe and Marsyangdi catchments are not changing in statistically significant manner, the results suggest a negative trend in minimum discharge and a positive trend in maximum discharge from both catchments.

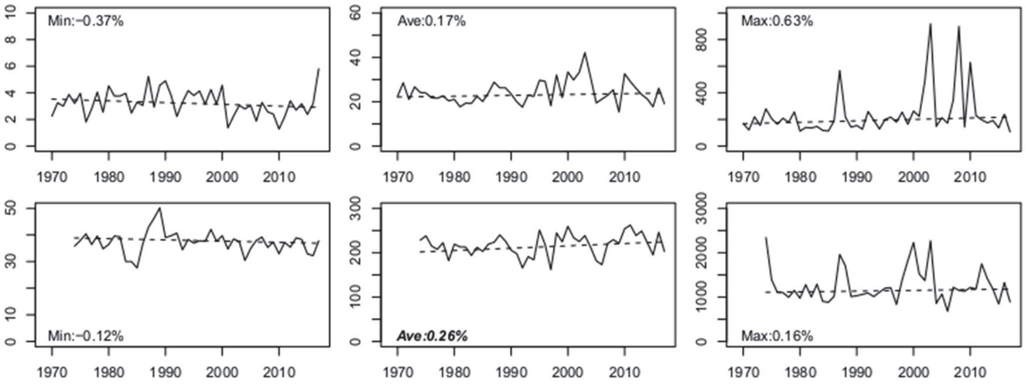


Figure 5.8 Trend in annual minimum (left), average (centre) and maximum (right) discharge from Chepe (top) and entire Marsyangdi (bottom) catchment

5.3.2.3. Trend in monthly discharge

Long-term trends in monthly minimum, average and maximum discharge from Chepe sub-catchment and the entire Marsyangdi catchment are shown in Figure 5.9 and 5.10 respectively, while the summary of changes in relation to corresponding long-term means are presented in Table 5.2. In Chepe sub-catchment, none of the trends in monthly minimum, average and maximum discharge is statistically significant. However, all of the changes in monthly average and maximum discharge are positive between June and October, while majority of other months also show positive changes. Minimum discharge from Chepe sub-catchment is also positive between July and October but a higher number of changes in other months are negative compared to changes in monthly average and maximum.

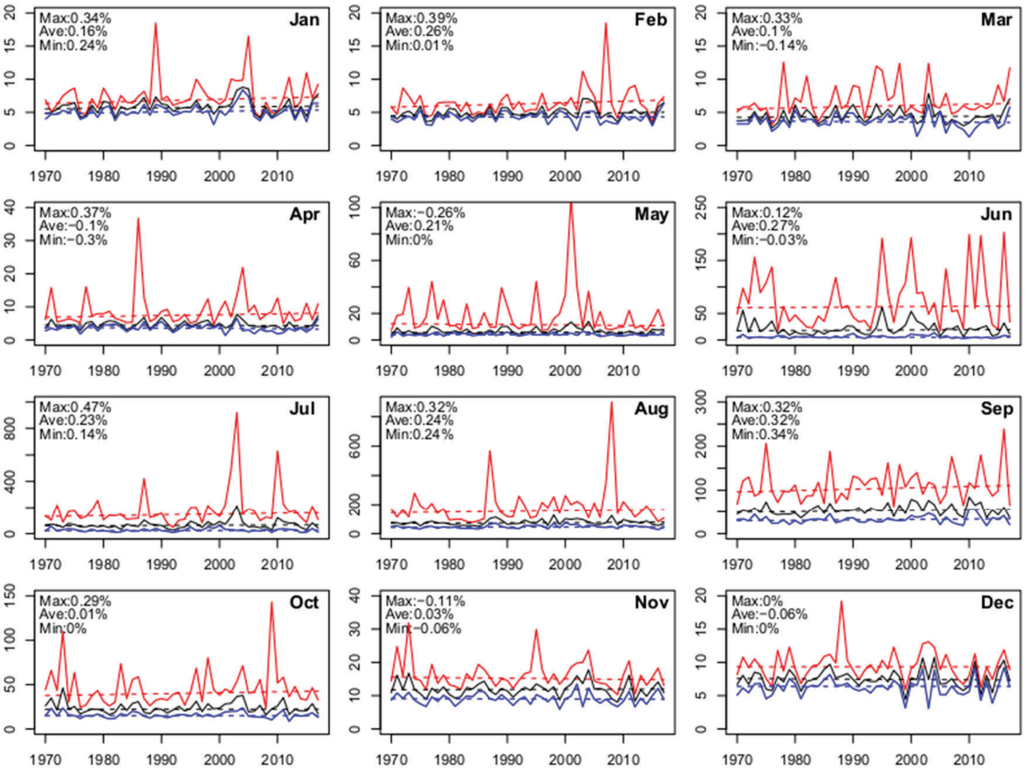


Figure 5.9 Trend in monthly minimum, average and maximum discharge from Chepe sub-catchment (in cumec). Note: lines in blue, black and red represent monthly minimum, average and maximum discharge, respectively. Change percentage values shown in bold represent statistically significant trend (at 90% CI), while bold-italics value represent trend significant at (95% CI).

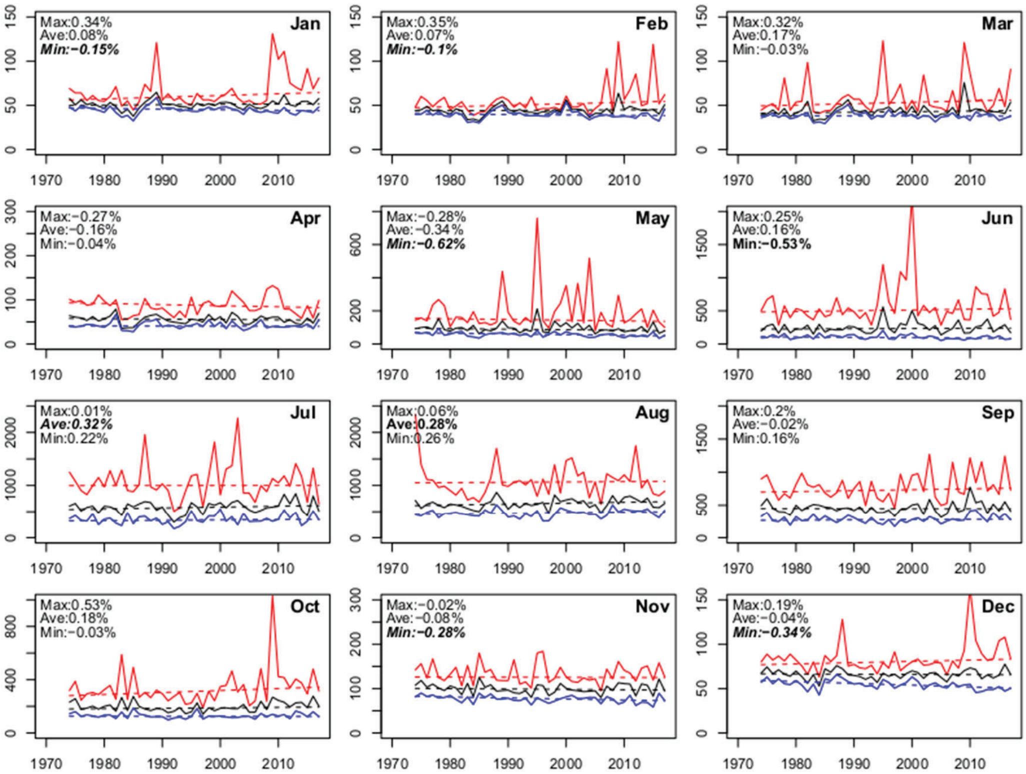


Figure 5.10 Trend in monthly minimum, average and maximum discharge from the entire Marsyangdi catchment (in cumec). Note: lines in blue, black and red represent monthly minimum, average and maximum discharge, respectively. Change percentage values shown in bold represent statistically significant trend (at 90% CI), while bold-italics value represent trend significant at (95% CI).

Long-term change in minimum discharge from Marsyangdi catchment is negative in all months except between July and September, including a significant trend in the low discharge months between November and February. However, the majority of trends in monthly average and maximum discharge are positive. The increases in average discharge in July and August are significant and moderately significant, respectively but none of the trends in monthly maximum is statistically significant.

Table 5.2 Long-term mean and summary of trend in minimum, average and maximum discharge from Marsyangdi and Chepe sub-catchment at monthly and annual scale. Note: values represent the long-term mean, while values within parenthesis represents the percentage of change per year. Bold italics and bold values represent statistically significant changes at 95% and 90%, respectively. Decreasing changes are shown in red.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Chepe													
Min	5.1 (0.24)	4.2 (0.01)	3.6 (-0.14)	3.6 (-0.3)	4.2 (0)	6.0 (-0.03)	26.0 (0.14)	46.3 (0.24)	32.1 (0.34)	15.7 (0)	9.1 (-0.06)	6.2 (0)	3.3 (-0.38)
Ave	5.9 (0.16)	4.9 (0.26)	4.5 (0.1)	4.7 (-0.1)	6.9 (0.21)	21.4 (0.27)	66.4 (0.23)	76.4 (0.24)	54.6 (0.32)	24.1 (0.01)	12.0 (0.03)	7.6 (-0.06)	24.3 (0.17)
Max	7.5 (0.34)	6.5 (0.39)	6.8 (0.34)	8.9 (0.37)	19.1 (-0.26)	76.1 (0.12)	183.1 (0.47)	184.3 (0.32)	111.6 (0.32)	46.3 (0.29)	16.2 (-0.11)	9.6 (0)	238.4 (0.63)
Marsyangdi													
Min	44.6 ***(-0.15)***	39.4 ***(-0.1)***	38.1 (-0.03)	42.2 (-0.04)	57.1 ***(-0.62)***	104.7 **(-0.53)**	350.2 (0.23)	465.1 (0.26)	282.3 (0.16)	129.8 (-0.03)	76.3 ***(-0.28)***	54.4 ***(-0.34)***	37.2 (-0.12)
Ave	51.0 (0.08)	44.2 (0.07)	43.9 (0.17)	55.3 (-0.16)	95.4 (-0.34)	247.3 (0.16)	582.9 ***(0.32)***	653.9 **(0.28)**	455.0 (-0.02)	197.6 (0.18)	99.8 (-0.08)	66.0 (-0.04)	217.3 ***(0.26)***
Max	65.9 (0.35)	55.7 (0.35)	58.7 (0.32)	86.3 (-0.27)	193.7 (-0.28)	590.5 (0.25)	1066.0 (0.01)	1083.7 (0.06)	784.7 (0.2)	339.6 (0.53)	133.3 (-0.02)	83.9 (0.19)	1253.2 (0.16)

5.3.2.4. Decadal departure from long-term mean

Decadal departures of annual minimum, average and maximum discharge from Chepe sub-catchment and the entire Marsyangdi catchment are shown in Figure 5.11. It generally demonstrates a multi-decadal cycle of decadal departure, however average discharge from Chepe sub-catchment and the entire Marsyangdi catchment are higher or substantially higher than long-term means after 2000. Minimum discharge from both catchments is lower or substantially lower in the recent two decades, while the preceding two decades had higher or substantially higher discharge. Further analysis of departure from long-term mean at monthly scale (Appendix C - Figure 4 to 5) showed that there is no certain combination of substantial monthly departures resulting in a specific annual departure.

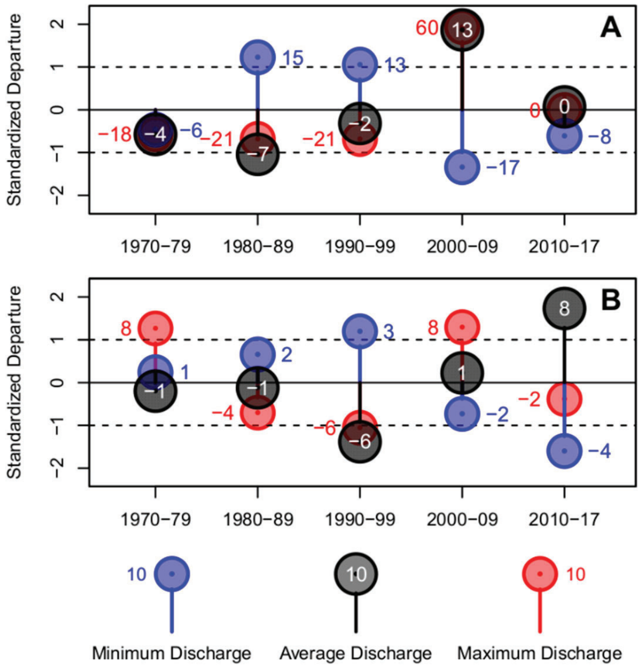


Figure 5.11 Decadal departure of annual minimum, average and maximum discharge from Chepe (A) and entire (B) Marsyangdi catchment in relation to their corresponding long-term mean. Note: labels in blue, white and red represent percentage of minimum, average and maximum discharge departure, respectively.

5.4. Discussion

Results showed that long-term mean discharge from Marsyangdi catchment is highest in August, whereas discharge from the entire Bagmati catchment peaks in July, even though water flow from headwater and upper catchments is also high in August. Hannah et al. (2005) also found a marked August peak for most of the river catchments in western Nepal including that of the Chepe River, whereas upper Bagmati River had a July/August peak. These results are generally consistent with monsoon dominated precipitation distribution as seen in Chapter 4.

The headwater catchment only covers 0.5% of the entire Bagmati catchment, but has a relatively high percentage of annual discharge (close to 1%) which can be attributed to a high number of natural springs in the sub-catchment. On the other hand, despite covering 31% of the area, upper Bagmati catchment provides only 12% of total discharge and this can be related to less rainfall in Kathmandu valley compared to southern parts as well as to high extraction for human use (Shrestha, 2012; Tuladhar et al., 2019b). At the same time, relatively high discharge (11%) from Chepe sub-catchment in relation to 7% area and lower discharge (60%) from upper catchment in relation to 75% of catchment area can be related to higher precipitation in southern parts compared to high elevation regions. Further analysis of the influence of rainfall and LULC in the sub-catchments of Bagmati and Marsyangdi are presented in Chapter 6.

Based on the 5-year average monthly discharge between 1965 and 2001, Sharma and Shakya (2006) concluded that the peak discharge from the Bagmati River has shifted from July to August after 1985. However, examination of the timing of annual peak discharge, based on 30-day moving average of daily series between 1970 and 2017, showed no statistically significant change in the Bagmati or any of its sub-catchments. The contrasting result can be related to the difference in length of data series as well as analytical techniques used. Similar examination of the peak discharge period of Chepe sub-catchment and the entire Marsyangdi catchments also showed no significant change. Results of Bajracharya et al. (2018) indicating no near future change in peak discharge pattern in Kali Gandaki catchment adjacent to Marsyangdi catchment also supports the results of this study.

Annual discharge from Bagmati catchment was found to be decreasing significantly, including a negative trend in all months. Further examination of all available data from the earliest measurements at Karmaiya station (1965) also confirmed that discharge from Bagmati catchment was decreasing significantly. Decreasing annual discharge from Bagmati catchment during 1965–2001 (Sharma & Shakya, 2006) and the Rosi River catchment adjacent to Bagmati catchment during 1971–2014 (Dahal et al., 2019) also support the results of this study. On the other hand, annual discharge from Marsyangdi catchment was found to be increasing significantly including positive changes in most months. Part of the contrasting findings between the two catchments can be related to the dominance of snow-fed headwaters in Marsyangdi catchment compared to rain-fed rivers in Bagmati catchment. According to Bookhagen and Burbank (2010) and Kayastha et al. (2020), 15–21% of the annual river discharge from Marsyangdi River is contributed by snow and ice melt with significant contribution in the pre and early monsoon periods. As identified by Rood et al. (2017), higher rates of snow melt and permafrost thawing in relation to increased temperature can also be attributed to increased discharge in spring and early monsoon months.

Considering the availability of records from 1992 only, the trend results of the upper catchment are not directly comparable with those of the entire catchment. However, further examination showed that the rate of decrease in discharge at Karmaiya station between 1992 and 2017 was slightly higher than that during 1970–2017, but not as high as the change in upper catchment. This, together with highest rate of decrease in precipitation (Tuladhar et al., 2019a) and most steadily decreasing decadal discharge from the upper catchment, support the conclusion that the rate of change is the highest in the upper catchment.

Overall increase in annual maximum discharge from the entire Bagmati catchment was non-significant, however maximum discharge in July was increasing with a moderately significant trend. Increasing monthly average discharge in the majority of months, including significant trend in July and a moderately significant trend in August, support the significantly increasing annual average from entire Marsyangdi catchment. Considering the peak flow in July and August, increase in average and maximum discharge in these months also indicates potential intensification of issues associated with such high runoff events. In this regard, flooding and landslides causing loss and damage to properties and lives have been commonly reported in the region including both of the catchments (e.g. Acharya & Pathak, 2017; Khadka & Pathak, 2016; Mishra & Herath, 2014).

On the other hand, long-term trends in the minimum discharge in most of the low flow months (viz. November to March) were negative in upper and entire Bagmati catchment. There were similar changes in minimum discharge in Marsyangdi catchment as well, including the highest number of negative changes in monthly minimum compared to average and maximum discharge. Dhital et al. (2013) also found seasonal discharge from the Bagmati catchment between 1980 and 2010 was decreasing in all seasons except pre-monsoon. Manandhar et al. (2012) also found a non-significant but decreasing trend in annual minimum discharge from Kali Gandaki catchment which is adjacent to Marsyangdi catchment. Considering the small amount of river discharge in the low flow months, this can exert further pressure on water availability in the region.

A moderately significant decrease in average discharge from Bagmati catchment in July and August, together with negative change in most of the monthly average discharges can be related to a significant decrease in annual discharge from the Bagmati catchment. Decreasing minimum discharge and increasing maximum discharge from Marsyangdi catchment in most of the months also support annual trends in the same direction. At the same time, the negative change in annual minimum discharge from upper and the entire Bagmati catchment can be related to mostly negative monthly changes with significant trend in nearly half of them.

The results of departure from long-term mean showed that decadal average, minimum and maximum discharge have multi-decadal fluctuations. Nevertheless, the departure of average discharge supports the statistically significant trend results found in upper and the entire Bagmati catchment as well as the entire Marsyangdi catchment. As in the case of long-term trend assessment, decadal departure of minimum, average and maximum discharge at monthly scale also could not establish a consistent pattern in specific months in relation to any annual departure. This is comparable with results of departures of monthly rainfall in the Bagmati (Tuladhar et al., 2019b) and Marsyangdi catchment as discussed in Chapter 4.

5.5. Chapter summary

River discharge from a basin is important for the ecosystem and socio-economic development of the region therefore, any long-term changes in water flow can have a range of implications on the management of valuable natural resources. Historical changes in river discharge are spatially variable, however the majority of rivers across the world including those in South Asia are found to have decreasing discharge. Considering the huge and growing demand for freshwater, which is also affected by seasonality, water availability in the South Asian region is under tremendous pressure. The distribution of river discharge and temporal changes within the Ganges and Himalayan region vary substantially depending on climatic and other geographical settings. This chapter aimed at analysing spatio-temporal variability in river discharge from two mountain river catchments of Bagmati and Marsyangdi within the Ganges basin.

Observed river discharge records at Sundarijal, Khokana and Karmaiya/Pandheradovan between 1970 and 2017 were used to study discharge variability in headwater, upper and the entire Bagmati catchments, respectively. Records from Garambesi, Bhakundebesi and Gophlinghat/Bimalnagar were used to study river discharge from Chepe, upper and the entire Marsyangdi catchment, respectively. The daily records were pre-processed including homogenization and gap filling steps. Discharge patterns as well as long-term trend and decadal variability in minimum, average and maximum discharge were analysed at monthly and annual scale.

Upper catchment of Bagmati and Marsyangdi rivers cover 31% and 75% of the total catchment area but represents only 12% and 60% of the total discharge, respectively. On the other hand, Bagmati headwater catchment and Chepe sub-catchment have relatively high discharges in relation to their area. The distribution of long-term monthly average showed that river discharge from the entire Bagmati catchment is highest in July, even though the discharge from headwater and upper catchment peaks in August.

Discharge from the Marsyangdi River including its sub-catchments peaks in August. Headwater catchment of Bagmati and Chepe sub-catchment of Marsyangdi featured a slower increase between May and June compared to the rest of the catchment. Analysis of long-term trend in peak discharge period based on 30-day moving average showed that there is no significant shift in peak discharge period for both river catchments and their sub-catchments.

Annual average discharge from all parts of Bagmati catchment was found to be decreasing, including significant trend in upper and the entire catchment, but the average discharge from Marsyangdi catchment was increasing, including significant trend for the entire catchment. Except for the Bagmati headwater catchment, annual minimum discharge was decreasing non-significantly in all sub-catchments of the two rivers. However, maximum discharge from both of the entire catchments was increasing non-significantly. Any aggravation of such changes can put further pressure on the management of water resource.

Monthly breakdown of the trends showed that average discharge from upper and the entire Bagmati catchment was decreasing in all months. However, the trends in discharge from upper catchment were significant in seven months, while the decrease in the entire catchment was significant or moderately significant in only three months. On the other hand, average discharge from Marsyangdi catchment was positive in seven months with significant trends in July and a moderately significant trend in August. Monthly minimum discharge from upper and the entire Bagmati catchment as well as the Marsyangdi catchment was also decreasing in most of the months and the trend in five to six months including November and December were significant or moderately significant. Compared to lower catchments, Bagmati headwater catchment and Chepe sub-catchment showed fewer months with negative changes in average and minimum discharge with no significantly decreasing trend. Most of the changes in monthly maximum discharge from Chepe sub-catchment and Marsyangdi catchment are positive but none of them are statistically significant. On the other hand, monthly maximum discharge from upper and entire Bagmati catchment was mostly decreasing including a significant trend in up to four months. However, July maximum from the entire Bagmati was increasing by 1.02% per year.

Analysis of decadal departure from long-term mean also showed a generally decreasing average discharge from Bagmati catchment, however minimum and maximum discharge showed a multi-decadal cycle with no clear trend. Average discharge from Chepe sub-catchment and Marsyangdi are generally higher or substantially higher after

2000, however minimum discharge was lower or substantially lower after 2000. These results especially on average discharge support the decreasing and increasing long-term trend in Bagmati and Marsyangdi catchments, respectively. Month-wise examination of the decadal departure suggested that there is no consistent monthly pattern in relation to any specific annual departure.

6 INFLUENCE OF PRECIPITATION, TEMPERATURE AND LAND USE LAND COVER ON THE VARIABILITY OF RIVER DISCHARGE FROM BAGMATI AND MARSYANGDI CATCHMENTS

6. 1 Introduction

River discharge from a catchment depends on various hydro-climatic factors such as precipitation, surface air temperature and evapotranspiration as well as anthropogenic factors including land use/land cover (LULC) and extraction of water (Frans et al., 2013; Shi et al., 2011; Wang et al., 2012; Zhang & Schilling, 2006). As shown in previous chapters, historical changes in climatic variables and human activities can vary substantially between and within river catchments. As a result, changes in river discharge from major river catchments around the world also vary substantially in terms of direction and the rate of change, including increasing discharge in some rivers while others show decreasing discharge (Frans et al., 2013; Wang et al., 2012). Furthermore, depending on the topographical setting of a catchment, future changes in any of these factors may have varying influence on river discharge.

Increase in agricultural areas at the expense of grazing and forested land have been related to reduced infiltration of precipitation, resulting in increased surface runoff and river discharge during rainy season (Bewket & Sterk, 2005; Costa et al., 2003). For example, Githui et al. (2009) found that a substantial increase (~25%) in agricultural area contributed to a considerable increase in runoff, while Kashaigili (2008) found a reduction in low-flow and increase in high-flow in relation to increasing agricultural area and decreasing forest in some river basins in Central East Africa. Zhang and Schilling (2006) suggested that conversion of permanently vegetated land to cropland decreased evapotranspiration, leading to higher runoff in the Mississippi River catchment. On the other hand, an increase in forest cover may result in higher interception of precipitation and significant decrease in surface runoff (Wang et al., 2011; Wei et al., 2008).

Increases in area of impermeable surfaces such as roads and settlements associated with urbanisation can increase surface runoff, resulting in higher peak discharge and flood volume (Poelmans et al., 2011; Song et al., 2020; Zhou et al., 2013). Consequently, ground water recharge may decrease resulting in reduced flow in dry season. However, the overall influence of urbanization on river discharge may vary from one place to another depending on other hydro-geophysical characteristics (Eng et al., 2013; Zhou et al., 2013).

Changes in temperature can also influence river discharge in various ways. Labat et al. (2004) showed a positive correlation between changes in global average annual temperature and river discharge during 1925–1995. Morán-Tejeda et al. (2011) found a marked reduction in winter and spring flow in the Duero basin as a result of decreasing winter precipitation together with increasing temperature in winter and spring. Dry season river discharge from the Volta River basin decreased while discharge during rainy season increased in relation to increasing temperature and changes in monthly rainfall (Neumann et al., 2007). Minaei and Irannezhad (2018) concluded that, despite increasing rainfall in general, decreasing river discharge from north-east Iran between 1953 and 2013 was due to the significantly rising temperature resulting in higher evapotranspiration. Dorjsuren et al. (2018) also linked a significant rise in temperature with decreasing river discharge from a semi-arid river catchment in Mongolia. Kong and Pang (2014) however, found no significant trend in river discharge from the Urumqui River catchment in Northwest China in relation to a significant rise in both temperature and precipitation between 1959 and 2006.

Even though changes in climatic factors and LULC have their combined influence on surface runoff and river discharge, their contribution tends to vary spatially. Gerten et al. (2008) suggested that precipitation had the most important influence on global river discharge over the past century. Shi et al. (2011) and Shi et al. (2019) identified changes in climate as the main driver of significant decrease in river discharge between 1948 and 2010 over most parts of the world with only a minor influence from LULC changes. Frans et al. (2013) suggested that most of the changes in river discharge from the upper Mississippi River basin during 1918–2007 were related to progressively wetter climate while a substantial (10%) increase in crop land had very little influence on river discharge. Zhang et al. (2014) identified significant influence of precipitation change on river discharge from the Yellow River after the 1950s, however analysis of climatic and anthropogenic contributions (Wang et al., 2012) revealed that human activities were the dominant factor, especially after the 1980s. Bewket and Sterk (2005) also found decreasing river flow in a sub-catchment of the Blue Nile basin, as the result of declining rainfall and increasing evapotranspiration related to increasing forest cover during 1960–1999.

The influence of climate change on surface runoff and river discharge is expected to continue in the near future (Arnell & Gosling, 2013; Thodsen, 2007). Arnell (1999) estimated an increase in potential evaporation globally (by 2050 and 2080), however changes in precipitation are expected to be spatially variable even though it may increase globally under the Hadley Centre Coupled Model (HADCM2 and HADCM3). Hydrological regimes are also expected to go through significant changes by 2050 in considerable parts of the Earth's land surface (Arnell & Gosling, 2013). Decreasing snow to precipitation ratio, related to rising surface air temperature may result in considerably reduced snow cover (Arnell, 1999) which may aggravate the imbalance in water supply by increasing excess water in the rainy season and causing shortages in other seasons (Cai et al., 2014).

Water availability in the South Asian region is highly dependent on the variability of precipitation, including frequency of extreme wet and drought events. Decline in monsoon rainfall as shown by some studies (e.g. Chatterjee et al., 2016; Tiwari et al., 2009) can also result in the depletion of surface and ground water storage. The influence of changing precipitation and increasing temperature, together with LULC changes associated with high population growth pose serious threats to the sustainability of water resource in the region (Rodell et al., 2009; Tiwari et al., 2009).

Glaciers in the high Himalayan region of Nepal cover an area larger than 5000 km^2 with an estimated ice mass of 480 km^3 (Mool et al., 2001). Snow cover and glaciers of the Himalaya act as natural reservoirs storing annual precipitation (Sadoff et al., 2013). Therefore, decrease in snow cover and glacier melt as the result of faster melting related to recent climate change will have a significant impact on seasonal discharge, especially during low flow periods (Barnett et al., 2005; López-Moreno & García-Ruiz, 2004).

Impacts of future climate change on hydrological regimes and water availability in selected catchments of Nepal have been documented by some studies (e.g. Bajracharya et al., 2018; Dahal et al., 2020; Devkota & Gyawali, 2015; Mishra et al., 2018). The contribution of snow and glacier melt to river discharge as well as the impact of climate change on the glaciers and river flow in various river catchments of the Himalayan region have been examined by a few studies (Alford & Armstrong, 2010; Kayastha et al., 2020; Miller et al., 2012). Lamichhane and Shakya (2019) assessed influence of future LULC in the upper Bagmati catchment under climate scenarios RCP 4.5 and RCP 8.5. Parajuli et al. (2015) evaluated the impact of climate change in order to predict future water availability in the Marsyangdi river catchment based on 1988–2009 data. However, comprehensive studies examining the influence of climatic factors and LULC on river discharge focusing on local variabilities are clearly lacking.

Previous chapters provided insights into the spatial and long-term changes in LULC, precipitation, surface air temperature and river discharge in the Bagmati and

Marsyangdi river catchments. The results showed that changes in climatic factors and LULC had a notable spatial variability between and within the two catchments as a result of contrasting elevation, topography, general climate and population distribution. This chapter aims to analyse the influence of precipitation, temperature and LULC changes on river discharge from the two catchments. The next section provides a brief description of the techniques used, while Section 6.3 presents results on the association of climatic and LULC variables with river discharge in the Bagmati and Marsyangdi catchments. Section 6.4 provides a discussion and a chapter summary is presented in Section 6.5.

6. 2 Methods

Basin-wide areal average (hereafter referred as basin average) of precipitation, T_{min} and T_{max} according to sub-catchments were derived based on spatial interpolation of daily records available at meteorological stations within and around the catchments (see Section 2.3.7). Direct surface runoff was also estimated from daily precipitation, LULC and soil type data using Soil Curve Number (SCN) method (see Section 2.3.9). Correlation analysis was used to determine the association between basin average precipitation, T_{min}, T_{max}, estimated surface runoff and the (observed) river discharge while multiple regression technique was used to investigate the influence of climatic variables and major LULC changes on river discharge as described in Section 2.3.10. Other variables such as evapotranspiration and ground water extraction are also important factors influencing the changes in river discharge from a catchment, however analysis of these variables is beyond the scope of this study.

6. 3 Results

6.3.1 Influence on river discharge from the Bagmati catchment

The influence of precipitation and LULC changes on river discharge from sub-catchments of the Bagmati River is included in (Tuladhar et al., 2019a). This section provides some results on association between basin-wide average precipitation, T_{min}, T_{max}, estimated surface runoff and river discharge. In addition, the influence of climatic factors and major LULC changes on river discharge from Bagmati and its sub-catchments is presented.

6.3.1.1 Association of river discharge with precipitation and estimated surface runoff

Figure 6.1 shows the association of annual river discharge with precipitation and surface runoff estimated based on precipitation and LULC changes, in headwater, upper and the entire Bagmati catchment.

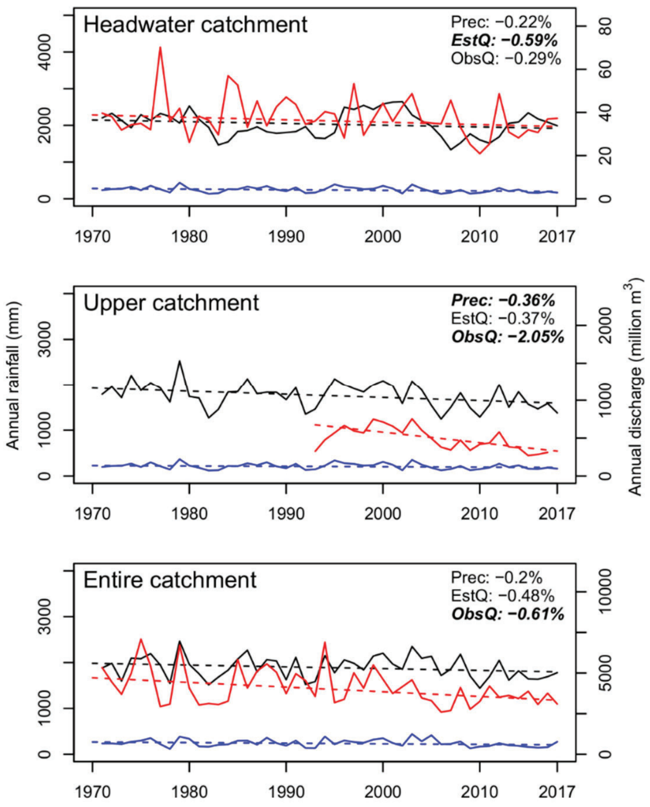


Figure 6.1 Basin-wide annual average precipitation, estimated surface runoff and observed river discharge from headwater, upper and entire catchment of the Bagmati River. Note: lines in black, blue and red represent precipitation (Prec), surface runoff (EstQ) and river discharge (ObsQ), respectively. Y-axis on left shows precipitation and surface runoff in mm, y-axis on right represents the river discharge volume in million cubic metres. Change percentage values shown in bold represent statistically significant trend (at 90% CI), while bold-italics value represent trend significant at (95% CI).

The patterns of estimated surface runoff and observed river discharge at annual scale are closely related to the amount of precipitation, even though the proportion of river discharge in relation to the total precipitation vary between the sub-catchments. However, there is no consistency in statistical significance of long-term (1970-2017) trends in precipitation, estimated surface runoff and river discharge. The proportion of river discharge in relation to basin average precipitation is lowest in upper catchment while it is highest in headwater catchment. On average, river discharge from the entire

Bagmati catchment accounts for 77% of total annual precipitation, however the proportion seems to have decreased consistently from the second half of the 1990s. Long-term average percentage of estimated surface runoff in relation to total precipitation in the three sub-catchments is between 12% and 13%.

6.3.1.2 Correlation between hydro-climatic variables

Table 6.1 shows the summary of correlations between precipitation, T_{min}, T_{max}, estimated surface runoff and observed river discharge at annual scale. There is a highly significant and strong positive correlation (r =0.80, p=0.0) between precipitation and river discharge in the upper catchment. A moderate positive association (r=0.55) between precipitation and river discharge in the entire catchment is also highly significant (p=0.0), however the correlation is weak and non-significant in the headwater catchment. Estimated surface runoff also has a statistically significant correlation with precipitation in all sub-catchments. Correlation of estimated surface runoff with observed river discharge is highly significant (p=0.0) in all sub-catchments, however the correlation is weak in headwater catchment. Both T_{min} and T_{max} have negative correlations with precipitation and the river discharge in all sub-catchments. A weak negative correlation of T_{max} with precipitation is significant and moderately significant in the upper and entire catchments, respectively. A moderate negative correlation between T_{max} and river discharge is significant in upper and the entire catchments, while the association is weak and only moderately significant in headwater catchment. Correlation of T_{min} is only significant with river discharge in the entire catchment.

Table 6.1 Correlation between climatic variables, estimated surface runoff and observed river discharge in headwater, upper and the entire Bagmati catchment. Note: underlined r and *p* value represent moderately significant correlation (at 90% CI) and underlined bold values represent significant correlation (at 95% CI).

Association	**Catchment**	**Correlation Coefficient (r)**	***p*-value**
Precipitation - T_{max}	Headwater	-0.03	0.86
	Upper	**-0.32**	**0.03**
	Entire	-0.34	0.05
Precipitation - T_{min}	Headwater	-0.07	0.63
	Upper	-0.23	0.12
	Entire	-0.01	0.98
Precipitation - river discharge	Headwater	0.22	0.13
	Upper	**0.80**	**0.00**
	Entire	**0.55**	**0.00**
T_{max} - river discharge	Headwater	-0.28	0.06
	Upper	**-0.41**	**0.04**
	Entire	**-0.52**	**0.00**
T_{min} - river discharge	Headwater	-0.21	0.17
	Upper	-0.33	0.11
	Entire	**-0.39**	**0.03**
Precipitation - estimated runoff	Headwater	**0.63**	**0.00**
	Upper	**0.90**	**0.00**
	Entire	**0.94**	**0.00**
Estimated runoff - river discharge	Headwater	**0.31**	**0.03**
	Upper	**0.77**	**0.00**
	Entire	**0.57**	**0.00**

6.3.1.3 Influence of climatic and LULC changes on river discharge

Results of multiple regression analysis of the climatic variables and major LULC changes on the river discharge is presented in Table 6.2. Precipitation has a statistically significant positive influence on river discharge for the entire catchment and about 30% of the changes in river discharge can be attributed to changes in precipitation. A positive influence of precipitation on the river discharge is significant in both the upper and entire catchments. Negative influence of increasing urban areas and decreasing agricultural area in the upper catchment is statistically significant, however influence of precipitation change is the most dominant factor resulting in decreased river discharge. The changes in T_{min}, T_{max} and forest cover do not seem to have statistically significant influences on the historical changes in river discharge from any of the Bagmati sub-catchments. In headwater catchment however, even the influence of precipitation on river discharge is statistically non-significant.

Table 6.2 Summary of multiple regression results showing contribution of climatic and major LULC changes on river discharge in headwater, upper and the entire Bagmati catchment. Note: “Importance” denotes the ratio of change in r^2 (when the predictor variable of interest is not considered) to the overall r^2 (when all predictor variables are considered). “Change %” indicates percentage of regression coefficient in relation to intercept value. Underlined r and *p* value represent moderately significant correlation (at 90% CI) and underlined bold values represent significant correlation (at 95% CI).

Catchment	No. of Observations	r^2	*p*	Predictor	*p*	Importance	Change %
Headwater catchment	47	0.16	0.18	Agriculture	0.57	0.04	0.09
				Forest	0.42	0.08	-0.58
				Precipitation	0.13	0.30	0.07
				T_{max}	0.20	0.21	-0.44
				T_{min}	0.57	0.04	0.14
Upper catchment	25	0.87	0.00	Agriculture	**0.05**	**0.04**	**-0.72**
				Forest	0.41	0.01	-0.18
				Precipitation	**0.00**	**0.20**	**0.04**
				T_{max}	0.48	0.00	0.05
				T_{min}	0.96	0.00	0.00
				Urban area	**0.03**	**0.05**	**-0.16**
Entire catchment	33	0.49	0.00	Agriculture	0.64	0.01	0.45
				Forest	0.88	0.00	0.48
				Precipitation	**0.01**	**0.29**	**0.06**
				T_{max}	0.51	0.02	0.13
				T_{min}	0.65	0.01	-0.06
				Urban area	0.82	0.00	-0.01

6.3.2 Influence on river discharge from the Marsyangdi catchment

Association of the climatic variables with estimated surface runoff and river discharge as well as influence of climatic and major LULC changes on river discharge in Marsyangdi catchment are presented in this section.

6.3.2.1 Association of river discharge with precipitation and estimated surface runoff

Figure 6.2 shows the variability of river discharge in relation to basin average annual precipitation and estimated surface runoff in the Chepe, upper, and the entire catchments of the Marsyangdi River. There is a close relationship between annual precipitation and estimated surface runoff, however the long-term change in estimated surface runoff generally has a higher rate compared to the change in precipitation in all sub-catchments. Overall, total annual river discharge is approximately the same as total precipitation volume in the catchment with the highest percentage in the upper catchment. Percentage of estimated surface runoff in relation to total precipitation is also highest (42%) in upper catchment, while the overall percentage in the entire catchment is 36%.

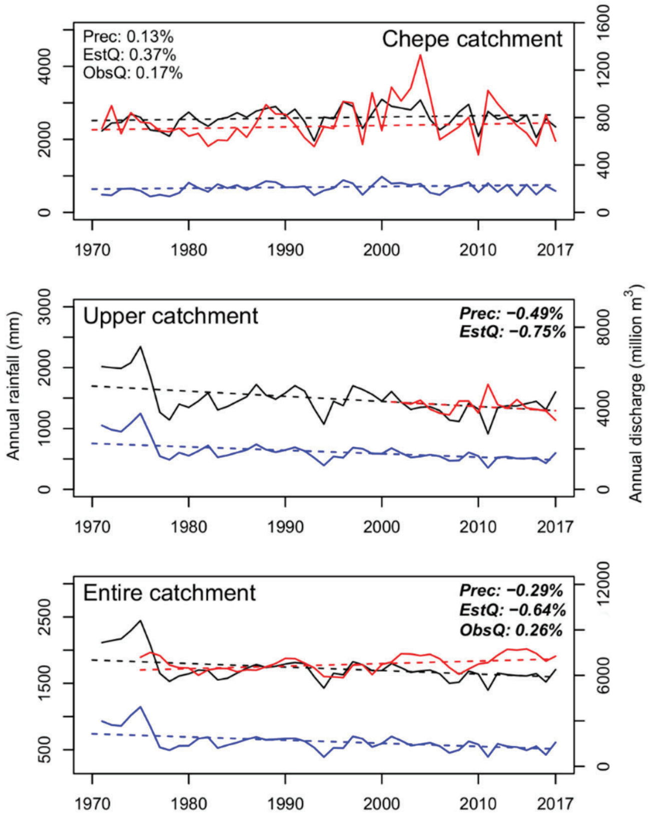


Figure 6.2 Basin average annual precipitation, estimated surface runoff and observed river discharge from Chepe, upper and the entire catchment of the Marsyangdi River. Note: lines in black, blue and red represent precipitation (Prec), surface runoff (EstQ) and river discharge (ObsQ), respectively. Y-axis on left shows precipitation and surface runoff in mm, y-axis on right represents the river discharge volume in million cubic metres. Change percentage values shown in bold represent statistically significant trend (at 90% CI), while bold-italics value represent trend significant at (95% CI).

There is a statistically significant positive change in river discharge from the entire catchment despite decreasing basin average precipitation in upper and the entire catchments. In the Chepe sub-catchment, long-term changes in precipitation, estimated surface runoff and discharge are positive but statistically non-significant.

6.3.2.2 Correlation between hydro-climatic variables

The correlation between precipitation, T_{min}, T_{max}, estimated surface runoff and observed river discharge are presented in Table 6.3. The estimated surface runoff has a highly significant and strong positive correlation (r >0.85) with the average precipitation in all sub-catchments. Furthermore, the correlation of river discharge with precipitation as well as estimated surface runoff is also highly significant (p=0.0) in Chepe and the entire catchment.

Table 6.3 Correlation between climate variables, estimated surface runoff and river discharge in Chepe, Upper and the entire catchment of Marsyangdi. Note: underlined r and *p* value represent moderately significant correlation (at 90% CI) and underlined bold values represent significant correlation (at 95% CI).

Association	Catchment	Correlation Coefficient (r)	*p*-value
Precipitation - T_{max}	Chepe	-0.02	0.87
	Upper	-0.05	0.78
	Entire	-0.08	0.62
Precipitation - T_{min}	Chepe	-0.18	0.23
	Upper	0.08	0.62
	Entire	-0.08	0.63
Precipitation - river discharge	Chepe	**0.64**	**0.00**
	Upper	0.27	0.30
	Entire	**0.38**	**0.01**
T_{max} - river discharge	Chepe	0.10	0.49
	Upper	0.05	0.85
	Entire	0.17	0.30
T_{min} - river discharge	Chepe	-0.18	0.23
	Upper	0.12	0.66
	Entire	0.28	0.08
Precipitation - Estimated runoff	Chepe	**0.86**	**0.00**
	Upper	**0.95**	**0.00**
	Entire	**0.95**	**0.00**
Estimated runoff - river discharge	Chepe	**0.41**	**0.00**
	Upper	0.44	0.08
	Entire	**0.33**	**0.03**

Results of correlation between precipitation, T_{min} and T_{max}, classified in relation to the elevation below and above 2000 m are presented in Table 6.4. The correlation between precipitation and T_{max} is non-significant but negative in both elevation zones as well as all sub-catchments. There is a statistically non-significant positive correlation between precipitation and T_{min} in the elevation zone above 2000 m, which mostly represents the upper catchment, but the association is negative below 2000 m. T_{min} and T_{max} have a positive relationship with each other, however the correlation is only significant below 2000 m.

Table 6.4 Correlation between precipitation and temperature below and above 2000 m elevation in Marsyangdi catchment. Note: underlined r and *p* values represent moderately significant correlation (at 90% CI) and underlined bold values represent significant correlation (at 95% CI).

Variables	**Catchment**	**Correlation Coefficient (r)**	***p*-value**
Precipitation - T_{max}	Above 2000 m	-0.03	0.84
	Below 2000 m	-0.17	0.26
Precipitation - T_{min}	Above 2000 m	0.08	0.64
	Below 2000 m	-0.21	0.15
T_{min} - T_{max}	Above 2000 m	0.10	0.55
	Below 2000 m	**<u>0.75</u>**	**<u>0.00</u>**

6.3.2.3 Influence of climatic and LULC changes on river

Table 6.5 shows a summary of multiple regression of climatic variables and major LULC changes on river discharge from Marsyangdi and its sub-catchments. Precipitation has a highly significant (*p*=0.0) positive influence on river discharge in the Chepe and the entire catchment. T_{min} shows a small but significant positive influence on river discharge from the entire catchment, while the influence is negative in the Chepe sub-catchment. However, changes in precipitation and T_{min} seems to have not contributed to change in river discharge from upper the catchment. T_{max} has a moderately significant positive influence on river discharge from the Chepe sub-catchment. None of the changes in agriculture, forest and shrub/grass area show any significant influence on river discharge in the Marsyangdi catchment. Results show that 55% of the changes in river discharge from Chepe river catchment can be attributed to the changes in precipitation while 70% of the changes in river discharge from the entire catchment are related to changes in precipitation.

Table 6.5 Summary of multiple regression results showing contributions of climatic and major LULC changes on river discharge in Chepe, upper and the entire Marsyangdi catchment. Note: “Importance” represents the ratio of change in r^2 (when the predictor variable of interest is not considered) to the overall r^2 (when all predictor variables are considered). “Change %” indicates percentage of regression coefficient in relation to intercept value. Underlined r and *p* value represent moderately significant correlation (at 90% CI) and underlined bold values represent significant correlation (at 95% CI).

Catchment	No. of Observation	r^2	*p*	Predictor	*p*	Importance	Change %
Chepe catchment	48	0.55	0.00	Agriculture	0.38	0.02	0.16
				Forest	0.25	0.03	0.63
				Shrub/grass	0.80	0.00	0.02
				Precipitation	**0.00**	**0.55**	**0.13**
				T_{max}	0.07	0.07	0.27
				T_{min}	**0.04**	**0.09**	**-0.11**
Upper catchment	18	0.81	0.00	Agriculture	0.14	0.05	-1.64
				Forest	0.14	0.06	1.02
				Shrub/grass	0.15	0.05	1.54
				Precipitation	**0.00**	**0.44**	**0.00**
				T_{max}	0.73	0.00	0.00
				T_{min}	**0.00**	**0.30**	**0.00**
Entire catchment	40	0.45	0.00	Agriculture	0.85	0.00	-0.03
				Forest	0.43	0.02	-0.69
				Shrub/grass	0.23	0.06	-0.23
				Precipitation	**0.00**	**0.70**	**0.14**
				T_{max}	0.86	0.00	-0.02
				T_{min}	**0.01**	**0.34**	**0.02**

6. 4 Discussion

River discharge from both Bagmati and Marsyangdi catchments was significantly correlated with precipitation, even though the degree of association differed among the sub-catchments. Significantly decreasing long-term trends in precipitation and river discharge supported the strong correlation between the two variables in the upper Bagmati catchment. At the same time, a statistically significant but moderate association for the entire catchment aligns with significantly decreasing river discharge despite the non-significant trend in precipitation. Annual river discharge from the Chepe and entire Marsyangdi catchment also had a statistically significant correlation with precipitation. However, annual river discharge from Marsyangdi catchment was increasing with significant trend despite decreasing basin average precipitation. Furthermore, a lack of statistically significant correlation between precipitation and river discharge in the

Bagmati headwater can be partly related to high forest cover (>85%). Substantial coverage by glaciated areas and a high contribution of snow and glaciers to river discharge in higher mountain regions, as suggested by Siderius et al. (2013) and Kayastha et al. (2020), can be related to the lack of significant correlation between precipitation and river discharge from the upper Marsyangdi catchment.

Fluctuations of annual river discharge are closely related to that of annual precipitation and estimated surface runoff. Annual river discharge being approximately the same as the volume of total precipitation in the Marsyangdi catchment with the highest proportion in upper catchment, suggests that loss related to evapotranspiration is offset by a contribution from snow/glacier melt in Marsyangdi catchment. A greater than 20% contribution from snow and glacier melt (e.g. Kayastha et al., 2020) and strong negative correlation of evapotranspiration with elevation in Nepal as suggested by Lambert and Chitrakar (1989) support the higher proportion of river discharge in Marsyangdi catchment. Relatively low discharge (77%) in the Bagmati catchment with lowest percentage (47%) in the upper Bagmati also confirms the higher loss via evapotranspiration in the rainfed basin, especially considering its higher percentage of urban area. Results of estimated surface runoff based on precipitation as well as soil type and LULC changes also suggested a higher river discharge from Marsyangdi catchment compared to that in Bagmati. However, a higher proportion of river discharge in relation to total precipitation in Bagmati headwater catchment could partly be related to potential underestimation of precipitation in the headwater catchment as well as to lower evapotranspiration in relation to elevation. The strong influence of local orography in the region, as highlighted in Tuladhar et al. (2019b), suggests higher monsoon precipitation in the upper parts of the headwater catchment compared to precipitation at the available meteorological stations.

Monthly minimum river discharge from Marsyangdi catchment was decreasing in general, including a significant trend in the six months between November and June even though the majority of changes in average and maximum discharge were positive. Considering the strong significant influence of precipitation on river discharge in the upper and the entire catchment, generally decreasing monthly discharge can be related to decreasing total precipitation including that in monsoon months. However, a larger number of significant decreases in monthly minimum and average river discharge compared to maximum discharge, as well as significantly increasing maximum discharge from the entire Bagmati catchment in July indicate generally lower precipitation but an increase in high precipitation events. Prediction of continued influence of climate change resulting in higher frequency of flood events in Bagmati catchment and reduced water availability in dry months (Mishra & Herath, 2014) also aligns with these results.

Even though the monthly T_{max} were generally increasing in Marsyangdi catchment including those at the stations in the high mountain zone (>2500 m), changes in T_{min} did not show such a pattern of increase. Most of the high mountain zone stations in Marsyangdi catchment showed a generally decreasing T_{min} including a few significant changes between June and December. Such decreases in T_{min} (in monsoon and post-monsoon) could result in increases in the snow to rain ratio, but as suggested by Burn and Elnur (2002) increasing T_{max} may result in earlier onset and higher melt of snow cover. Considering generally higher river discharge from headwater glaciers during daytime compared to that during night-time (Mingjie et al., 2013), the significant increase in maximum temperature seen in the catchment including those in the high mountains might have had more influence on snow/glacier balance compared to the changes in minimum temperature.

Significantly increasing T_{max} had a significant negative correlation with river discharge in all sub-catchment of Bagmati while increasing T_{min} also had a significant correlation with discharge from the entire Bagmati catchment. This is in contrast to the findings of Dahal et al. (2019), suggesting a lack of significant correlation between temperature and decreasing streamflow in the Rosi river catchment which is adjacent to Bagmati catchment. At the same time, river discharge from entire Marsyangdi catchment had a significant positive correlation with T_{min} but not with T_{max}. This also suggest that there is a high local variability in influence of climatic factors on river discharge.

Further investigation of correlation between the climatic variables at a monthly scale (Appendix C - Table 5) suggested that, below 2000 m elevation, T_{max} and precipitation have significant negative correlations in all months except August and September, whereas the correlation at elevations above 2000 m was significant in only five months including one positive correlation in May. Correlation between T_{min} and T_{max} was also more consistent (all significant except November) below 2000 m compared to that above 2000 m elevation of the catchment.

An increase in days with no rain (dry days) and decreasing precipitation can also result in a rise of temperature during the rainy season. However, further investigation showed that the number of dry days in a year as well as in pre-monsoon months was decreasing significantly in both the upper and entire Bagmati catchments (Appendix C - Table 6).

In Marsyangdi catchment, the number of dry days between March and May were mostly decreasing even though there was no significant change at annual scale (Appendix C - Table 7).

As pointed out by Van Der Schrier et al. (2013), a rise in maximum temperature can increase the rate of potential evapotranspiration which is partly related to drying conditions in recent decades. Changes in cloud cover, precipitation and atmospheric circulation are linked to change in DTR (Dai et al., 1998; Lobell et al., 2007; Vose et al., 2005). Considering this, generally increasing DTR with increasing T_{max} in both catchments can be related to decreasing cloud cover and decreasing precipitation in the region contributing towards lower river discharge, especially in the rainfed catchment of Bagmati.

Other than the influence of changes in urban and agricultural land in the upper catchment of Bagmati, LULC changes did not show any statistically significant influence on river discharge from the two catchments. While most of this can be related to the lack of substantial LULC changes in other parts of the two catchments. It is notable that the influence of changes in snow/glacier cover wasn't analysed due to the seasonal variability inherent in results derived from Landsat image related to different months. As indicated by Arnell and Gosling (2013) spatially variable changes in precipitation and temperature may also have likely offset some of the influences. Hannah et al. (2005) also indicated that the relationship between precipitation and river discharge in the region varies from basin to basin depending on LULC. Within the Bagmati catchment also, the ratio of decrease in river discharge in relation to change in precipitation was higher compared to that in the entire catchment. Despite a reduction in potential infiltration related to the increase in urban area (e.g. Githui et al., 2009; Koneti et al., 2018), the urban expansion and a decrease in agriculture area negatively influenced river discharge from the upper Bagmati catchment. As noted by Davids et al. (2018) and Shrestha (2012), increasing population and urbanisation in Kathmandu valley have resulted in significant stress on quantity as well as quality of stream water available. For example, many of the headwater streams in Kathmandu valley are exploited for the purpose of drinking water, especially during the dry season. Furthermore, the water table in the Kathmandu valley was reported to be lowering substantially due to low recharge and increase in extraction of ground water (Shrestha, 2012; UNEP, 2001). Hence, urban expansion and pressure on water sources along with rising temperature and decreasing precipitation seem to be related to the long-term decrease in river discharge from the upper catchment.

As suggested by Bewket and Sterk (2005) expansion of farmland and settlements can lead to increase in surface runoff and the increase in stream discharge. Based on district level population data (CBS, 2013), area-weighed population in Marsyangdi catchment increased from 0.15 million to 0.2 million. It indicates that even though results of this study did not highlight the increase in human settlements and smaller town etc., they can be expected to have increased in Marsyangdi catchment. However, considering a minimal scale of such changes in relation to LULC of the overall catchment as discussed in Chapter 3, the contribution on river discharge from the catchment can be deemed to be negligible.

Precipitation had the most important influence on river discharge in the Bagmati and Marsyangdi catchments while the influence of LULC changes on river discharge from the two catchments were not significant except in the upper Bagmati catchment. Considering the fact that many tributaries in the middle catchment are unaffected by major urban usage, it can be concluded that decreasing precipitation together with increasing temperature and higher evapotranspiration influence river discharge from the middle Bagmati catchment. Shi et al. (2011) also suggested that most of the decreases in simulated river flow during 1948–2004 in the South Asian region including Nepal were due to climatic changes while the contributions of LULC changes were minor and inconclusive. Some other studies in India and China also suggest generally higher influence of climate factors on river discharge (e.g. Koneti et al., 2018; Zhao et al., 2015).

6. 5 Chapter summary

River discharge from catchments vary spatially depending on geographical settings including hydroclimate, topography and human activities. Historical changes in precipitation, air temperature and LULC as seen in previous chapters can also influence the long-term changes in river discharge from a catchment, including the flow regime. The associations between the climatic variables (viz. basin average precipitation, T_{min} and T_{max}) as well as estimated surface runoff and river discharge for the Bagmati and Marsyangdi sub-catchments were examined using correlation analysis. Furthermore, influence of the climatic variables and major LULC changes on river discharge was examined using multiple regression analysis.

In general, variabilities of annual river discharge were closely related to basin average annual precipitation and estimated surface runoff. The proportion of river discharge from all sub-catchments of Marsyangdi and headwater sub-catchment of Bagmati was as high as the amount of total precipitation while it was lowest (47%) in upper Bagmati catchment. The average percentage of estimated surface runoff in relation to the precipitation was 12–13% in Bagmati catchment, while it ranges between 25% and 42% in Marsyangdi catchment.

There were a substantial local variabilities in the level of influence of precipitation, temperature and LULC changes on river discharge from the two catchments, and some of these variabilities can be attributed to elevation and topography. For instance, changes in T_{min} were positively related to T_{max} below the elevation of 2000 m, while the changes were opposite at higher elevations. Except the positive relationship with T_{min} in upper Marsyangdi catchment, which is mostly above 2000 m elevation, precipitation had an inverse association with T_{min} and T_{max} in all sub-catchments. River discharge from the upper and entire Bagmati catchment, as well as the Chepe and entire Marsyangdi catchment were significantly correlated with precipitation.

Estimated surface runoff that was derived based on precipitation, LULC and soil type, was strongly correlated with precipitation in both catchments. Correlation between precipitation and discharge aligns with variability in long-term trend in basin average precipitation and river discharge in both catchments. Results of multiple regression also suggested that changes in precipitation had the most significant influence on river discharge in both catchments. Changes in agriculture and urban area in upper Bagmati catchment had statistically significant negative influence on river discharge. Despite the T_{max} showing a moderately significant correlation with river discharge, changes in temperature did not have significant influence on discharge from Bagmati catchment. However, in Marsyangdi catchment, a moderately significant positive correlation between T_{min} and river discharge from the entire catchment aligns with the statistically significant positive influence on river discharge.

Long-term change in basin average precipitation from all sub-catchments of Bagmati were negative, resulting in decreases in both estimated surface runoff and observed river discharge. Increasing pressure on water resource related to the population growth and urban expansion together with significantly increasing temperature and decreasing precipitation have resulted in significantly decreasing river discharge from the upper Bagmati catchment. Despite significantly decreasing precipitation in upper and the entire catchment, river discharge from the entire Marsyangdi catchment had a significant positive trend as the result of increased contribution from snow and glacier melt related to significantly increasing T_{max}. However, this may result in future water availability to decrease eventually, when the contribution from reduced snow/glacier mass can no longer offset the decrease in precipitation. Furthermore, a decrease in minimum river discharge in most of the dry months, despite positive changes in average and maximum discharge, poses challenges related to decreased water supply in the dry season. There was no significant change in the number of days in a year without rain in the two catchments. Therefore, an increasing temperature, especially the T_{max}, in both catchments and increasing DTR also seem to have influenced the decreasing river discharge in Bagmati and increasing discharge in Marsyangdi catchment.

7 CONCLUSIONS AND RECOMMENDATIONS

The main findings of this study support the proposition that together with precipitation variabilities, changes in surface air temperature and land use/land cover (LULC) of a mountain catchment can influence surface runoff, evapotranspiration, groundwater recharge, and therefore, river discharge. Major rivers in the South Asian region including the Ganges, have their headwaters originated in the Himalayan mountains. Considering the fragile environment, climatic changes such as rise in temperature resulting in a high rate of snow melt as well as increased human activities due to growing population can have cascading impacts on water availability and on ecosystems in the region. This highlights the importance of detailed studies on hydro-climatic variables (e.g. precipitation, temperature, river discharge) and LULC changes in Himalayan region however, most of the previous studies focus on only one or two of these variables or generalise the study over large regions. The work reported here was a comprehensive study undertaken to evaluate long-term variability in precipitation, T_{min}, T_{max}, DTR, LULC as well as their association with river discharge at a fine spatial scale.

The first objective of the study was to quantify long-term (1970–2017) and spatio-temporal variability in hydro-climatic and anthropogenic factors in the Bagmati and Marsyangdi mountain sub-catchments of the Ganges, in Nepal, in relation to their contrasting geographical settings. This was accomplished by examining in-situ precipitation, T_{min}, T_{max}, river discharge records and historical LULC changes extracted from satellite images. Distribution of precipitation, temperature, LULC and river discharge showed a substantial variability in relation to elevation and local topography. Long-term trend analysis at annual and monthly scales suggested that, over the period studied, precipitation was decreasing, while T_{max} and DTR were increasing in both catchments. T_{min} was generally increasing in Bagmati catchment and in the low mountain zone (<1000 m) of Marsyangdi catchment, however it was decreasing in the high mountain zone (>2500 m) of Marsyangdi catchment. The average river discharge from the upper and entire Bagmati catchment was decreasing significantly, whereas discharge from Marsyangdi catchment was increasing significantly. The most significant LULC change in Bagmati catchment was an increase in urban land while a decrease in snow/glacier cover was important in Marsyangdi catchment. Overall, long-term changes in precipitation and temperature did not show a clear relation with elevation, however the spatial distribution of the hydro-climatic variables and LULC had a considerable variability in relation to elevation and the overall geographical setting.

The second objective of the study was to examine the influence of climatic and anthropogenic changes on river discharge in the two river catchments and this was achieved using results of estimated surface runoff, correlation and multiple regression analyses. Precipitation had a significant positive correlation with river discharge in both catchments. T_{max} had a negative correlation with discharge in Bagmati catchment while the association was positive in Marsyangdi catchment. Apart from the influence of changes in urban land in upper Bagmati catchment, precipitation was the dominant factor influencing river discharge in the two catchments. However, the association between hydro-climatic variabilities, LULC changes and influence on river discharge also varied remarkably within and between the two catchments.

Considering the substantial variability observed in the spatial distribution as well as long-term changes in hydro-climatic factors and LULC, the results of this study in relation to the topography and overall geographic settings in the Himalayan mountain region enables better understanding of hydrological process and water budget in the South Asian region. An accurate knowledge of hydro-climatic changes at monthly scale identified in this study is also significant for managing water scarcity during low flow months as well as for the planning to minimise the potential risks associated with water induced disasters such as landslides and floods that are common in the region. Specific findings of this study are presented in the next two sections.

7. 1 Spatial variability in hydro-climate and LULC

The spatial distribution of monthly precipitation at meteorological stations within and around the two catchments confirmed substantial local orographic effects. For instance, stations located south of mountain ranges (>1500 m) extending from east to west in Bagmati catchment, receive higher precipitation, while mountains surrounding the Kathmandu valley (which are taller than 2000 m) also appeared to play an important role in the distribution of precipitation in Kathmandu valley. Similarly, stations located south of high mountain ranges (e.g. >4000 m) in Marsyangdi catchment received the highest precipitation (>2500 mm) while high mountain zone stations in the north receive very little annual precipitation (<500 mm). However, monsoon circulation moving along river valleys also seems to deliver relatively higher precipitation at some stations located in the north (e.g. Chame, Larke Samdo and Kakani).

Monthly precipitation in the two catchments generally peak in July, however most of the high mountain zone stations of Marsyangdi catchment and two stations located at northern part of Bagmati catchment receive peak precipitation in July and August. High mountain zone stations of Marsyangdi catchment have a secondary peak in March while February and March precipitation related to the westerly disturbances was lower at the lower foothill (<500 m) and low mountain stations (<1000 m) in the southern part of Bagmati and Marsyangdi catchments, respectively. The distribution of T_{min} and T_{max} was consistent with elevation in both catchments, however they also seemed to be affected by topographic location and precipitation.

Analysis of LULC showed that forest areas cover 60% of Bagmati catchment including a high coverage in low mountains below 1000 m (Siwalik) as well as mountains above 2000 m. However, only 30% of total land, mostly in the elevation between 1000 m and 3500 m is covered by forest in Marsyangdi catchment. Agricultural activities are mostly concentrated below 2000 m elevation and cover approximately 30% and 10% of Bagmati and Marsyangdi catchment, respectively. As a result of low temperatures related to elevation and low precipitation in the high mountain zone, as highlighted in the study, agriculture and forest covers are limited in upper parts of Marsyangdi catchment. Furthermore, the coverage by shrub/grass is also limited above 4500 m due to poor soil, rocky conditions and low water retention, while unvegetated areas and snow cover increase above 4500 m.

River discharge from all sub-catchments of Marsyangdi catchment as well as headwater and upper Bagmati catchment peaks in August, whereas discharge from the entire Bagmati catchment peaks in July. Despite a reported delay in monsoon departure, the annual peak discharge period showed no statistically significant change in any of the sub-catchments of the Bagmati and Marsyangdi River. The almost equal proportion of annual river discharge in relation to precipitation noticed in Marsyangdi catchment, with the highest proportion in upper catchment, suggests that losses related to evapotranspiration are compensated by the contribution of snow/glacier melt in Marsyangdi catchment. Yet, due to substantially lower precipitation compared to other parts, discharge from upper catchment is only 60% even though it covers 75% of catchment. At the same time, since precipitation is the only source of water input and Kathmandu valley receives it less compared to the rest of the catchment, discharge from upper Bagmati catchment only provides 12% of total discharge, despite covering 31% of the entire catchment. On the other hand, the high number of natural springs and relatively higher precipitation results in a larger percentage of discharge from Bagmati headwater catchment and Chepe sub-catchment, respectively.

7. 2 Long-term variability and association between hydro-climatic and LULC changes

Consistent with rapid population growth in the Kathmandu valley, there was a 10-fold increase in urban areas in the upper catchment between 1970 and 2015. The analysis also confirmed that as the population continues to grow, human settlements and mixed urban land use expanded into agricultural areas which eventually transformed to built-up areas. The forest area in Bagmati catchment, especially the low to mid mountain region outside Kathmandu valley, increased by over 4%, however there was no notable change in forest cover (<1%) in Marsyangdi catchment. Other than a decrease related to urban expansion in upper Bagmati catchment, there was more than 10% decrease in agricultural area in the elevation between 1000 and 1500 m in both catchments as well as above 3000 m in Marsyangdi catchment. Part of such loss in agriculture area can also be related to abandonment of some of agricultural activities on the mountain slopes, due to various factors such as uncertainties in precipitation, lack of irrigation as well as internal and external migration resulting in shortage of appropriate human resource.

Even though part of the changes in snow/glaciated areas of Marsyangdi catchment identified using Landsat images were related to monthly variations, there was a notable decrease in snow/glacier cover between 1975 and 2015. Results from MODIS products also showed more than 11% loss of pre-winter minimum snow cover during 2000–2017. A case study of the Thulagi glacier, which feeds one of the critical glacier lakes in Nepal at 4045 m elevation showed a retreat of more than 1000 m between 1976 and 2015. Given similar geographic and climatic conditions across upper parts of the Marsyangdi catchment, these results together with a high rate of increase in T_{max} in high mountain zone and decrease in precipitation suggests that other glaciers and snow cover can be expected to be decreasing similarly. Such changes and any loss of vegetation in the high mountains can potentially have a detrimental effect on the fragile mountain environment and ecosystems of the region.

Most of the 12 stations examined in and around Marsyangdi catchment, showed decreasing precipitation between 1970 and 2017 with a significant or moderately significant trend at five stations. Precipitation was decreasing at most of the 12 stations examined in and around the Bagmati catchment as well, including a significant decrease at four stations, although there was an increasing trend at one of the stations in the lower part of the catchment. Results of long-term trend did not show a very consistent relationship with topography, however, the rate of significant decrease which was generally between 0.5% and 1% per year was highest (>1% per year) at two of the high mountain zone stations of Marsyangdi catchment. Despite inconclusive precipitation changes in South Asian region exemplified by other studies, decreasing average precipitation in the two catchments suggest possible role of other regional factors such as the aerosol concentration on precipitation distribution in the Himalayan region.

Generally, monthly T_{max} was found to be increasing in both catchments including significantly increasing trends in the majority of cases. T_{min} was also mostly increasing in Bagmati catchment, however in Marsyangdi catchment the increase was limited to stations below 1000 m, while high mountain zone stations showed decreasing trends. Significant increase in T_{max} was between 0.01 ˚C and 0.09 ˚C per year while the increase in T_{min} was somewhat lower (0.01 ˚C to 0.06 ˚C per year). Results of correlation analysis also suggest that changes in T_{min} and T_{max} were more consistent below 2000 m compared to higher elevation. However, despite potential increase in snow to rainfall ratio as the result of the decreasing T_{min} noticed at high mountain zone stations, a significant increase in T_{max} including those in the high mountain zone might have had more influence on snow/glacier melt and the overall snow/ice balance. Unlike in the case of precipitation, monthly trends in T_{min} and T_{max} were generally consistent with annual trend in both catchments, yet there was no clear relationship in the rate of changes with elevation.

Despite generally decreasing DTR reported in other parts of the world, DTR was found to be increasing in both catchments with significant trends in the majority of months at most stations. Increase in monthly DTR was related to higher rate of increase in T_{max} compared to T_{min} in general as well as decreasing T_{min} at high mountain zone stations. Increasing DTR also indicates a reduction of cloud cover resulting in decreasing precipitation in both catchments.

None of the stations examined in the two catchments showed any positive change in November and December precipitation. Furthermore, basin-wide areal average precipitation for November was decreasing significantly in the entire Marsyangdi catchment as well as both of its sub-catchments. Any decrease in precipitation and increase in T_{max} during the low-precipitation months of November to February can have a significant impact on winter crops in the region. There was no significant change in the number of days without rain in Marsyangdi catchment while it was decreasing in Bagmati catchment. However, considering the cooling effect of precipitation on maximum temperature and significant negative correlation between the two, generally decreasing precipitation could also have contributed to higher temperature in summer months especially below 2000 m elevation.

Annual river discharge from Bagmati catchment was decreasing by 0.61% per year with 0.66% change in July and August as the result of significant influence of the decreasing precipitation and increase in T_{max}. However, despite significantly decreasing precipitation, annual discharge from Marsyangdi catchment was increasing significantly by 0.26% per year. This is possibly linked to the dominance of snow-fed headwaters in Marsyangdi catchment and significant increase in T_{max} resulting in accelerated rate of snow melt and thawing of permafrost. Considering the predicted continuation of significant temperature increase in the near future, this can result in higher discharge for a period of time. However, reduced precipitation and depletion of glaciers and snow cover will eventually impact seasonal discharge during low-flow period affecting water availability for agriculture, domestic/industrial use and hydropower generation in longer term.

An analysis of departure from long-term means supported corresponding long-term trend results of precipitation and river discharge. Given the dominance of the Indian summer monsoon, substantially higher (lower) annual departures of both precipitation and discharge were generally related to higher (lower) departures in the majority of months including those between June and August. Results of monthly trends also showed that the majority of changes are in the same direction as annual trends, with more consistent changes in temperature compared to precipitation and river discharge. However, a lack of conclusive patterns in significant monthly trends or substantial monthly departures resulting in certain annual change in both catchments indicates that long-term changes in precipitation and river discharge are highly variable in the region.

Even though annual discharge from Bagmati catchment was decreasing, there was a significant increase in maximum discharge in July. Increase in the average discharge from Marsyangdi catchment was also significant in July and August. Considering the precipitation and discharge peaking between July and August, these changes and increasing extreme precipitation events can have serious implications for property, lives and agriculture as the results of high precipitation events such as landslides and flooding. On the other hand, considering the already small amount of river discharge during low flow months, negative trend in minimum discharge from both catchments in most of these months (viz. November to March) is remarkable and can exert further pressure on water availability for agriculture and hydropower in the region. This together with degradation of water quality in relation to high rate of population growth and urbanisation, as already seen in the Bagmati River, can have serious impacts on aquatic life and other biotic communities. Therefore, the detailed findings of the changes in annual discharge as well as monthly variabilities is expected to be helpful in the efficient management of water resource in the region.

Even though increases in urban area are generally related to higher river discharge as a result of reduction in potential infiltration, the urban expansion and decrease in agricultural area in upper Bagmati catchment showed a negative influence on river discharge. Increasing water demand resulting in exploitation of available sources including increased extraction of groundwater along with rising temperature and decreasing precipitation are related to the long-term decrease in river discharge from the upper Bagmati catchment. Considering the low rate of economic growth in the region leading to a heavy reliance and overuse of natural resources, such climatic and LULC changes can significantly impact the overall ecosystem, hydrology and socio-economic conditions of the Himalayan and South Asian region.

7. 3 Limitations and recommendations

Changes in dispersed settlements and small towns in Marsyangdi and middle Bagmati catchment, could not be mapped adequately due to the limitation of Landsat images to derive comparable results. Considering the scale of such changes in relation to the total catchment area, their contribution to overall river discharge from the catchment was estimated to be minimal. Despite this, access to comparable higher resolution images for the entire study period (1975 – 2015) and resources to map the LULC in further detail would be beneficial to confirm these expectations. A further study utilising available high resolution image may focus on mapping fine scale changes in spatial and attribute detail of main LULC changes identified in the study such as urban land in upper Bagmati catchment and snow and vegetation changes in high mountain zones of Marsyangdi catchment.

Large-scale climatic phenomena such as El Niño-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) are also reported to affect annual climatic variability in the region. Since this study focused on long-term changes in hydro-climatic variables, analysing the influence of such phenomena was beyond the scope of this work. However, a further study analysing long-term changes in such phenomena and their contribution to variation of local hydro-climate in the region would enable better understanding of the likelihood of precipitation and temperature variabilities into the future.

Because of the unavailability of gauging stations with long-term records, climate data especially temperature observations, did not have a uniform spatial coverage in the two catchments that would be beneficial for further detail analysis in relation to the geographic settings. The available in-situ data are very important for fine scale study of long-term changes due to limitations in spatial resolution and lack of long historical coverage (e.g. 30–35 years) with remotely sensed data. Therefore, it is recommended that a long-term strategy with objectives to cover diverse topography in terms of elevation and location (e.g. valley, slope and ridge) be considered as a high priority while selecting locations for new meteorological or river gauge stations in the region. Pre-processing and validation of daily gauge records were impacted by lack of metadata, especially on historical changes. Therefore, it is recommended that important information about any details including accurate location and changes that can affect the observation value be recorded and managed appropriately.

Results of long-term trend for discharge from upper Bagmati catchment was not directly comparable to other results due to availability of records from 1992 only. However, highest rate of change compared to rest of the catchment between 1992 and 2017 as well as highest decrease in precipitation during 1970–2017 suggest that the decrease in discharge from upper catchment for the entire period could also be similarly high. Estimated surface runoff based on a lumped soil curve number model was used to analyse the potential surface runoff from the catchment for this study. This could be augmented by a further study with the use of distributed hydrological models utilising detail information on climatic variables, soil condition and topographic information to estimate river discharge for ungauged period for better understanding of long-term variabilities.

There are two hydropower dams within the Marsyangdi catchment, however since they are both based on run-of-river system, results of this study which are mostly derived from monthly and annual aggregate were deemed to be unaffected. However, records of river discharge immediately upstream of the obstructed flow enabling estimation of natural flow downstream of the power plant would be useful for better understanding of the daily temporal variability. In Bagmati catchment, most of the river discharge from headwater catchment is diverted for drinking water and hydropower purposes while discharge from Kulekhani sub-catchment is diverted out of the catchment for hydropower purpose. Considering a small contribution (<3%) to total discharge and lack of significant difference on long-term changes, both of these diversions were not factored in for the analysis. Again, measurements of diverted flow and estimation of discharge for ungauged period using an accurate distributed model can be considered in a future study to confirm that the differences are indeed negligible.

Considering the monthly variability present in snow cover data derived from Landsat images captured in different months and the availability of MODIS snow cover product only from 2000, the influence of snow cover change on river discharge from Marsyangdi catchment was not analysed. Hydrograph separation method is recommended to be undertaken in a future study which can support estimating the contribution of precipitation and snow/glaciers melt to river discharge. This would enable a better understanding of historical as well as potential long-term changes in river discharge from Marsyangdi catchment in relation to the changes in precipitation and the snow/glacier melt.

APPENDIX A – JOURNAL ARTICLE 1

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ORIGINAL PAPER

Spatio-temporal rainfall variability in the Himalayan mountain catchment of the Bagmati River in Nepal

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Abstract

Rainfall records between 1970 and 2015 from 12 rain gauge stations are used to examine the variability of rainfall patterns in the Himalayan mountain catchment of the Bagmati River. Based on monthly and annual rainfall distributions derived from daily records, this study analyzes the spatial and temporal variation of long-term trends and departures of 5-yearly average rainfall from the long-term mean. Both monthly and annual results show considerable spatial variabilities over rather short distances (< 25 km). Long-term trend results based on the Mann-Kendall test on homogenized time series showed a significant decrease in annual rainfall at four stations and significant increase at one of the stations. The 5-yearly departures from long-term mean showed that most of the stations received higher rainfall in the 1970s while the rainfall between 2005 and 2015 was substantially lower at several stations. Monthly breakdown of long-term trends and 5-yearly departures provided additional insight in rainfall variations that are not necessarily reflected by the annual results. Some stations have significant changes in rainfall for few months even though the annual rainfall does not change significantly, while a few of the significant monthly trends were, in fact, opposite to the annual trend. Month-wise investigation of 5-yearly departures from the long-term mean also suggests that the annual results are cumulative results of varying combinations of monthly changes rather than due to any particular group of months behaving similarly. The valuable information derived from monthly analysis is expected to assist in planning and management of water resources.

Keywords Rainfall · Trend · Spatial variation · Climate change · Bagmati · Himalayan mountain · Nepal

1 Introduction

Precipitation plays a major role in balancing the fresh water budget of a region. Long-term and seasonal variations in precipitation, combined with spatial variations within a region, can add significant challenges for the understanding and modeling of water resources on global, regional, and even localized scales. Due to increased atmospheric moisture content caused by the increase in global average temperature, it is expected that extreme precipitation events become more frequent and intense, especially in mid latitudes and wet tropics (Dore 2005; Pachauri et al. 2014; Stocker 2014). Future variability in precipitation related to the El Niño–Southern Oscillation (ENSO) is also expected to intensify at regional scales (Stocker 2014). Some large-scale patterns of precipitation changes in different parts of the world have already been linked to climate change (Trenberth 2008). On a global scale, as the result of delayed retreat coupled with either earlier or unchanged onset, monsoon periods are projected to be longer toward the end of the twenty-first century (Stocker 2014). In general, it is projected that many wet regions, especially in mid to high latitude areas, will receive increased precipitation while corresponding dry areas become drier (Dore 2005; Mishra and Herath 2014; Trenberth 2011).

In Southeast Asia, average precipitation increased by up to 10% between 1986 and 2005 (Pachauri et al. 2014). Indian monsoon rainfall in peninsular India is expected to increase in future while it may decrease in central India and around the Bay of Bengal (Stowasser et al. 2009). Also, local variations in topography and atmospheric circulation paths can cause significant differences in spatial distribution and long-term changes in regional rainfall (Anders et al. 2006; Barros 2004; Diodato et al. 2010; Gadgil 1977). Analyzing rainfall data between 1961 and 2000 for 141 stations, Jiang et al.

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(2007) found that summer monsoon precipitation increased significantly for the lower Yangtze River basin. However, based on precipitation time series between 1901 and 2002 for 319 stations in central India, Chatterjee et al. (2016) showed that 43% of the stations had a significant downward trend while only 5% of the stations had an upward trend. That same study also found three significant downward and five upward trends among 18 stations in West Bengal.

On a more regional scale, within Nepal, significant variations in precipitation distributions have been found by previous studies (Bohlinger and Sorteberg 2018; Diodato et al. 2010; Kansakar et al. 2004). The summer monsoon delivers less rainfall in the western mountain region compared with the east, while winter precipitation is higher in the western parts (Nayava 1980). The Chure and Mahabharat ranges receive more rainfall than the Terai region (Nayava 1980; Pokharel and Hallett 2015); however, the relationship between elevation and precipitation is not always uniform (Ichiyanagi et al. 2007).

Simulated modeling based on large-scale general circulation model (GCM) predicted that future precipitation will increase in the region (Babel et al. 2014). However, there is a general perception that temporal rainfall patterns in Nepal have become more unpredictable than they were in the past (Pandey 2017; Uprety et al. 2017). Inter-annual and decadal variations in precipitation are also significant in Nepal (Shrestha 2000). Some of the temporal fluctuations are found to be associated with ENSO, but the correlations are not consistent (Bohlinger and Sorteberg 2018; Ichiyanagi et al. 2007; Shrestha 2000). Due to substantial seasonal variation, scarcity of water during dry months is a significant issue in the region. On the other hand, landslides, floods, and other disasters associated with heavy rainfall regularly result in considerable loss of lives and property during the rainy season.

Rainfall variability and water availability in the mountain catchment of the Bagmati River not only is important for the millions of people living in the catchment but also affects the livelihood of larger populations living downstream. In fact, increasing population and changes in land use and land cover in the mountainous part of the Bagmati catchment are representative of the current situation in many other parts of the Himalayan region.

Previous studies in the region have looked at classification of rainfall regimes, and annual and seasonal trends of hydroclimatological variables as well as extreme events with focus on summer monsoon rainfall. For example, Kansakar et al. (2004) provided large-scale classification of the precipitation regime at 222 stations across Nepal. A study covering the larger Bagmati catchment including the lower plain of the Terai region (Dhital and Kayastha 2013) focused on frequency analysis of future rainfall and peak flood events. Babel et al. (2014) modeled potential changes in temperature, precipitation, and stream flow in the Bagmati catchment for the A2 and B2 emission scenarios. Pokharel and Hallett (2015) analyzed the distribution of rainfall intensity in Kathmandu valley during the summer monsoon using single station data. Bohlinger and Sorteberg (2018) also focused on trends in monsoon rainfall and the occurrence of extreme events in Nepal. Shrestha (2000) analyzed inter-annual and decadal fluctuations of rainfall in relation to large-scale climatological events in sub-physiographic regions of Nepal. Shrestha and Sthapit (2015) examined annual fluctuation of generalized rainfall based on Thiessen polygon interpolation of 1980–2008 records. Despite these studies, very little is known about small-scale spatial and temporal variations specific to the mountainous parts of the country.

While existing knowledge about annual and seasonal rainfall is valuable, detailed understanding of monthly rainfall changes is also important. For example, in Nepal, occasional rainfall events in November–December are essential to grow winter crops while regular rain during May–June is crucial for rice seedlings. On the other hand, more rain in September and October can hamper rice production. Increasingly frequent delay of monsoon retreat in the region indicates that monthly rainfall distribution may have changed, even when seasonal and annual distribution may not have (Gautam et al. 2010). However, variations in monthly rainfall in the region remain less understood.

To address these gaps, this study aims to analyze local variability in rainfall distributions as well as long-term trends of monthly and annual rainfall at selected stations in and around the Bagmati River catchment. A particular focus is to assess the contribution of monthly variations to annual changes as well as differences between monthly and annual variations. To highlight long-term changes in rainfall that may be obscured in naturally fluctuating annual series, this study also focuses on analyzing 5-yearly departures of annual and monthly rainfall from the corresponding long-term means.

An introduction to the study area is provided in the next section while data and methods are explained in Section 3. Section 4 presents results of rainfall distribution, trend, and departures from long-term mean on annual and monthly scales. Section 5 provides discussion of the results while major outcomes and conclusions are provided in Section 6.

2 Study area

This study focuses on the mountainous part of the Bagmati River catchment, upstream of Karmaiya in central Nepal (Fig. 1). Originating from mountain springs north of Kathmandu, the Bagmati River flows south through mid to lower elevation mountains into the Terai plain to converge with the Ganges River system flowing toward the Bay of Bengal. The catchment extends approximately from 85° 1′ E to 85° 59′ E and 27° 6′ N to 27° 50′ N and includes the Kathmandu, Lalitpur, and Bhaktapur districts as well as parts of the Kavre, Sindhuli, and Makwanpur districts. Based on Shuttle Radar Topography Mission (SRTM)

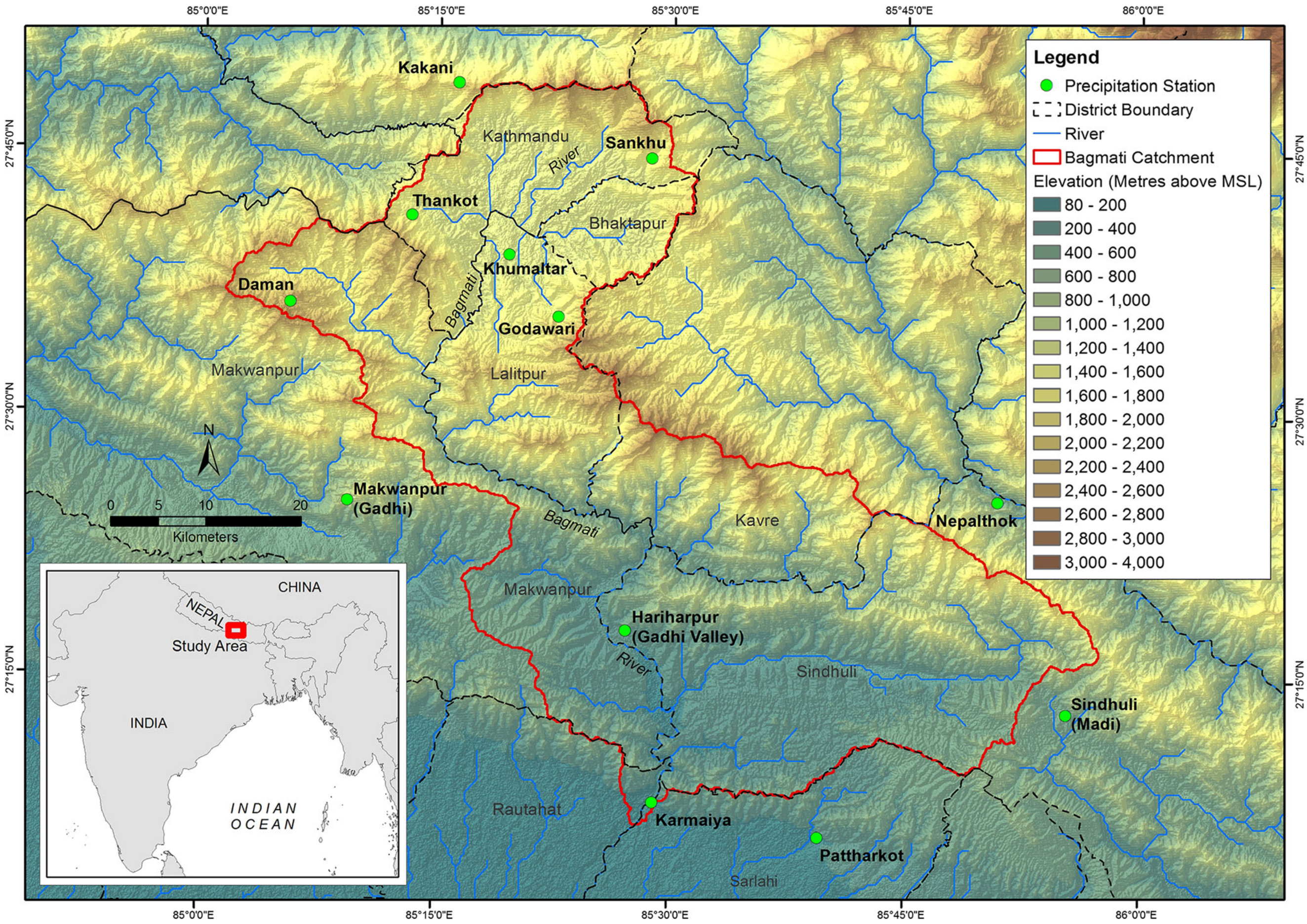


Fig. 1 Bagmati catchment and location of rainfall stations used in the study (elevation source: SRTM)

data (Jarvis et al. 2008), general elevation of the Kathmandu valley ranges from 1170 to 1500 m while surrounding mountains rise up to 2780 m. Elevations of the lower parts of the catchment range from 140 to 600 m while higher parts of Kavre, Sindhuli, upper Makwanpur, and southern Lalitpur districts range from 1500 to 2800 m. Twelve rain gauge stations (cf. Fig. 1 and Table 1) were selected to cover the study area as uniformly as possible based on their location and availability of associated records.

The general climate of the southern low lands (approximately < 1000 m elevation) including the Siwalik region and lower valleys is sub-tropical. The mid-elevation mountain ranges and valleys (1000–2000 m) have a warm temperate climate while the higher mountain ridges experience a cold temperate climate (Kansakar et al. 2004; Mishra and Herath 2014; Pokharel and Hallett 2015). On average, minimum temperatures within the catchment range from 0–12° in winter and 9–24° in summer while maximum temperatures can be between 9 and 24° in winter and 21 and 39° in summer (Chalise et al. 1996).

Precipitation, mostly in the form of rainfall, is a very important source of water supply in the study area. Snowfalls are negligible and restricted to small areas such as the higher altitude mountains around Kathmandu valley and upper Makwanpur district. Throughout the catchment, there are four distinct seasons, viz., winter, spring, summer, and autumn.

Precipitation within the catchment is largely driven by the Indian summer monsoon arriving from the southeast which delivers more than 80% of annual rainfall between June and September (Nayava 1974). Westerly systems originating from the Mediterranean region bring some winter and spring precipitation from the northwest between November and March (Pokharel and Hallett 2015). Upslope winds are pronounced during daytime while nights are calm. Generally, winds from the southern plain follow the path of the river valleys of the Trishuli and Bagmati River to Kathmandu and the Himalayan region further north (Regmi et al. 2003).

3 Materials and methods

3.1 Data

Due to limitations of resources, the mountain areas of Nepal are not adequately and uniformly covered by meteorological stations (Kansakar et al. 2004). However, the limited records

Table 1 Details of rainfall stations in and around the Bagmati catchment. Station ID are as used by the Department of Hydrology and Meteorology, Nepal

Station ID	Station name	Latitude	Longitude	Elevation (m)	Record length	Missing data (%)
905	Daman	27.60440	85.09280	2265	1970–2011	5.7
919	Makwanpur (Gadhi)	27.41620	85.15620	1050	1975–2015	4
1007	Kakani	27.83107	85.26985	2034	1972–2015	0.7
1015	Thankot	27.68820	85.22131	1457	1970–2015	0.1
1022	Godavari	27.59292	85.37883	1527	1970–2015	2.9
1029	Khumaltar	27.65175	85.32578	1334	1970–2015	1.9
1035	Sankhu	27.74437	85.47690	1436	1971–2015	3.9
1107	Sindhuli (Madi)	27.21829	85.92267	556	1986–2015	13.8
1109	Pattharkot	27.09985	85.65964	189	1970–2015	1.4
1115	Nepalthok	27.41983	85.84864	690	1970–2015	0.6
1117	Hariharpur (Gadhi)	27.33333	85.50000	250	1978–2015	0
1121	Karmaiya	27.13181	85.48380	139	1984–2015	3

available are still very valuable since alternative sources such as remotely sensed Tropical Rainfall Measurement Mission (TRMM) data do not offer very long historical coverage. In addition, the spatial resolution of TRMM may limit its use for analysis of small-scale spatial variations. Daily precipitation records for the selected rain gauge stations obtained from the Department of Hydrology and Meteorology (DHM), Nepal, are the primary source of data for this study. Since most of the records start in the early 1970s (Table 1), this study focuses on rainfall variation between 1970 and 2015.

3.2 Pre-processing of time series data

The daily precipitation time series were tested for homogeneity using the RHtestsV4 package of the R software (R Core Team 2013). This has been done to detect any “non-natural” variations introduced by gradual or abrupt changes in data collection and processing components (Costa and Soares 2009; Wang et al. 2010). The RHtests integrates a data adaptive Box-Cox transformation procedure with the penalized maximal F test and also takes account of the non-normal distribution of daily precipitation series (Wang and Feng 2013). Inhomogeneous daily time-series data were homogenized by applying mean-based adjustments with respect to the change points detected in monthly series.

Amounts of missing data for all stations except one were between 0 and 5.7% (cf. Table 1). The largest percent of missing data was for Sindhuli Madi station (13.7%), but it is included in this study due to lack of alternative station. Considering the lack of strong correlation between monthly rainfall at nearby stations, data gaps in daily time series were filled with 5-year daily averages (e.g., Shrestha 2000) based on the daily records for two earlier and two latter years for the same station. Based on the gap-filled homogeneous daily series, monthly and annual rainfall time series were created for further analysis.

3.3 Monthly rainfall distribution

Monthly rainfall distributions were averaged over 5-year intervals as well as for the whole period to analyze the 5-year and long-term mean rainfall. Standard scores (z-scores) were calculated for long-term average monthly rainfall at each station. The rainfall regimes at each stations were then classified based on the distribution of standardized long-term monthly means (e.g., Hannah et al. 2005; Kansakar et al. 2004).

3.4 Trend analysis

3.4.1 Mann-Kendall test

The Mann-Kendall (MK) test is a widely used non-parametric test to determine the existence of a significant monotonic trend in climatic variables. Such non-parametric methods use ranks of data rather than actual values which reduces the impact of outliers in the time series (Hamed 2008). Furthermore, the MK test is also suitable for data such as rainfall series that are not normally distributed (Hamed 2008). In this study, annual and monthly rainfall time series were tested for the presence of significant long-term trends using the MK test. In the remainder of this study, monotonic trends at 95% and 90% significance level are considered significant and moderately significant, respectively.

3.4.2 Autocorrelation and pre-whitening

The MK trend test result can be affected by the presence of autocorrelation in the series. Positive autocorrelation in the series can increase the probability of obtaining a significant trend (Hamed 2008) while negative autocorrelation may decrease such probability (Yue et al. 2002). Therefore, the Ljung Box test statistic (Ljung and Box 1978) was used in this study to determine if the autocorrelation in the series is significant at 95% confidence interval.

The effect of autocorrelation can be eliminated either by removing it from the series before performing the trend test or by using a method that addresses the issue of autocorrelation such as a modified MK test (Hamed and Ramachandra Rao 1998; Hirsch et al. 1982). In this study, the pre-whitening option with Auto Regressive Integrated Moving Average (ARIMA) modeling (Box et al. 2008) has been used on the precipitation time series with significant autocorrelation. It also uses the differencing process to accommodate the potential non-stationarity of the series. Based on ARIMA results, an optimal model fitting the time series with the smallest number of significant parameters and highest degree of freedom was then selected based on Bayesian information criterion (BIC) statistics (Machiwal and Jha 2012) for trend tests.

3.4.3 Sen's slope

Sen's slope estimator is based on a linear model to estimate the rate of change and is a commonly used method in analyzing hydro-meteorological time-series data (e.g., Da Silva et al. 2015; Gocic and Trajkovic 2013; Javari 2017). In this study, Sen's slope and its percentage in relation to the intercept are used to represent the magnitude of the changes.

3.5 Departure from long-term mean

Five-yearly annual and monthly average rainfall departures (differences) were calculated in relation to the long-term mean of the corresponding annual and month-wise precipitation time series. The departure values were then standardized with respect to standard deviation of the corresponding time series. Positive (negative) departure from the long-term mean of greater than one standard deviation is referred in this study as "substantially" higher (lower) rainfall.

4 Results

4.1 Rainfall distribution

4.1.1 Annual rainfall distribution

The spatial distribution of long-term mean annual rainfall for 1970–2015 is shown in Fig. 2. Mean annual rainfall among the stations examined ranges from around 900 mm to more than 2900 mm. Nepalthok and Khumaltar stations receive the lowest annual rainfall of 901 and 1229 mm, respectively (cf. Table 2). Makwanpur (Gadhi), Kakani, Sindhuli (Madi), and Hariharpur (Gadhi) stations, located at the lower to mid mountain ranges, have the highest amount (2428–2937 mm) of annual rainfall compared with others. Thankot, Godavari, and Sankhu stations located in the inner foothills of the Kathmandu valley, and Pattharkot and Karmaiya located in the southern foothills of lower mountain ranges as well as Daman station receive 1772–1936 mm of annual rainfall.

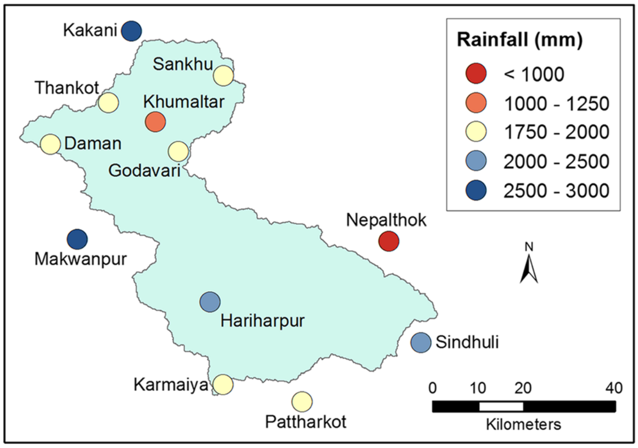


Fig. 2 Spatial distribution of long-term mean annual rainfall (1970–2015) at stations in and around Bagmati catchment

4.1.2 Monthly rainfall distribution

Table 2 shows the summary statistics of monthly rainfall distribution. The values in the mean column, representing the average rainfall among all the stations analyzed are hereafter referred to as all-station average. It is less than 10 mm in November and remains under 20 mm in December and January as well. The all-station average monthly rainfall gradually increases in February and March. Pre-monsoon rainfall starts to intensify from April with all-station average of more than 60, 150, and 300 mm for April, May, and June respectively. The monsoon is most active in July and August with all-station average rainfall values of approximately 540 and 450 mm, respectively. Amount of rainfall in September is similar to that in June, while post-monsoon rainfall in October decreases sharply with all-station average below 80 mm. It is important to note that differences between minimum and maximum monthly rainfall and spread from average (cf. min, max, and standard deviation in Table 2) indicate considerable spatial variation in monthly rainfall distribution.

Classification of standardized monthly rainfall distribution at the 12 stations (Fig. 3) also shows noticeable variations in the monthly rainfall regime. Kakani and Sankhu stations located along the northern mountain ranges of Kathmandu valley get their peak rainfall in July–August followed by a sharp decrease until October (right panel). Other stations have peak rainfall in July with decreasing rainfall until November (left

Table 2 Summary of mean monthly rainfall (1970–2015) among all stations examined

Month	Min (mm)	Max (mm)	Mean (mm)	Standard deviation
January	8	27	14	4
February	9	30	21	7
March	14	44	28	9
April	39	90	63	15
May	76	207	151	40
June	141	455	306	91
July	264	791	543	153
August	160	726	456	156
September	119	469	295	97
October	35	138	78	25
November	4	17	7	3
December	8	22	13	3

panel). However, Sindhuli, Pattharkot, and Nepalthok stations in the southeast and Daman (middle panel) have relatively smaller decrease in September rainfall compared with that in August.

Figure 4 shows the percentage of monthly rainfall at each station in relation to the all-station average highlighting some spatial variation in monthly rainfall distribution. Makwanpur and Kakani stations receive higher than the all-station average throughout the whole year. On the other hand, Nepalthok receives low rainfall in all months including less than half of the all-station average during June to October. Khumaltar has a low monthly rainfall pattern similar to Nepalthok; however, the proportion of rainfall is always higher than Nepalthok. The four stations with highest annual rainfall (viz., Makwanpur, Kakani, Sindhuli, and Hariharpur) receive noticeably higher rainfall compared with others during May to September. It is interesting to note that Daman and Thankot in the western part of the upper catchment receive higher than all-station average rainfall from December to May and November to April respectively, even though both stations receive less than the average rainfall during the monsoon period.

4.2 Trend analysis

4.2.1 Trend in annual rainfall

Spatial distribution of long-term trends and their magnitudes based on MK test and Sen's slope percentage are shown in Fig. 5. Statistically significant trends are identified at five stations with four downward and one upward trend. It also illustrates a considerable spatial variation among the stations examined and only a few of them have similar behavior based on their geographic proximity. A significant downward trend is found at Godavari and Thankot stations located at the inner foothills of Kathmandu valley. Rainfall at Sankhu station located at eastern foothills of the valley and Khumaltar station in the central part of the valley is also showing a downward trend, but the change is not statistically significant.

Pattharkot, Sindhuli, and Nepalthok stations which are located at low to mid elevation in southeastern part of the catchment also showed downward trends though the trend at Nepalthok is not significant. Annual rainfalls at Karmaiya and Hariharpur which are both in the central southern catchment have negligible trends. On the other hand, Makwanpur station which is further to the west showed an upward trend. Trends at other stations are not significant; however, most of them except Kakani station located at northwest of Kathmandu valley have shown long-term decrease in rainfall.

4.2.2 Trend in monthly rainfall

The spatial distributions of monthly trend results are shown in Fig. 6. Summary of monthly trend results are listed in Table 3, highlighting monthly changes that contribute to the annual rainfall trend. For instance, within the Kathmandu valley, significant trends in 3 to 4 months during June to October have resulted in a significant downward annual trend at Godavari and Thankot stations. Interestingly, the Sankhu and Khumaltar stations in the Kathmandu valley do have significant downward trends of − 1.15% and − 0.05% per year in the monsoon months of June and July, respectively, even though the annual trend is not significant.

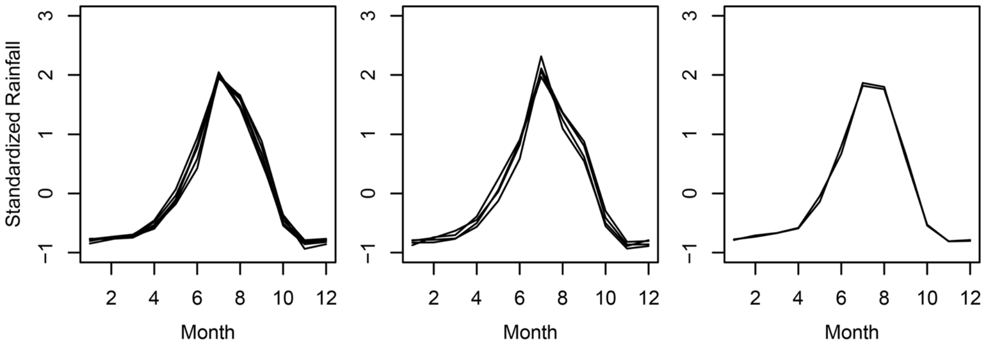


Fig. 3 Standardized monthly rainfall showing rainfall regime at (left panel) Godavari, Thankot, Khumaltar, Hariharpur, Makwanpur, Karmaiya; (middle panel) Daman, Sindhuli, Nepalthok, Pattharkot; and (right panel) Kakani, Sankhu stations

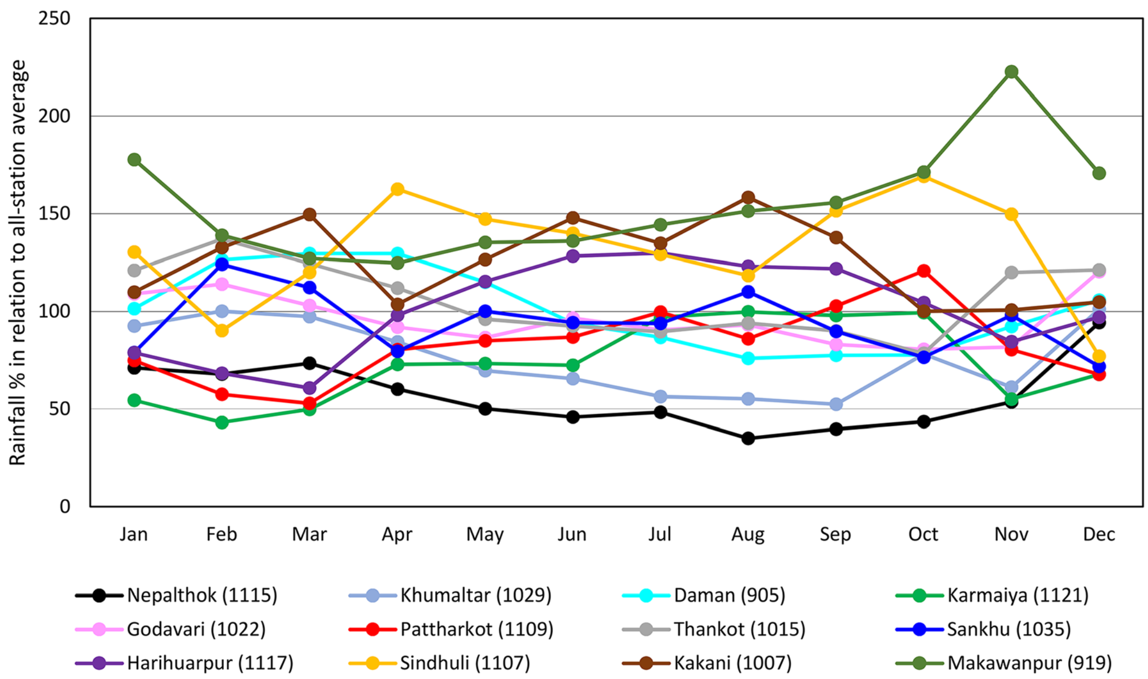
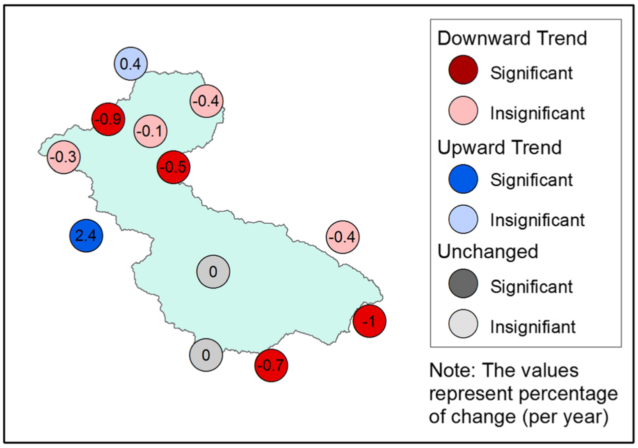


Fig. 4 Percentage of monthly rainfall at individual stations in relation to the all-station monthly average. Stations are listed in the order of lowest to highest annual rainfall

In the southern mid-elevation parts of the study area, upward trends in most of the months including significant trends in 6 months support the significantly increasing annual rainfall at Makwanpur. Pattharkot has a significant annual trend as the result of significant trends in June and September while most of the other months also show decreasing rainfall. Karmaiya showed significantly decreasing rainfall in December (− 3.2% per year) though the annual trend is negligible. June and October rainfalls are significantly increasing at Nepalthok, even though annual rainfall is decreasing non-significantly. It is notable to see significant upward trend of 3.5% per year in March at Daman though the annual trend is downward albeit non-significantly.



Note: The values represent percentage of change (per year)

Fig. 5 Spatial distribution of long-term (1970–2015) annual rainfall trend at stations in and around Bagmati catchment. The values represent percentage of Sen's slope in relation to the intercept

Month-wise classification of the trend results (cf. Table 3) shows that November and December rainfalls are decreasing significantly at one and two stations, respectively. Further, there is no station with any positive change in rainfall during November to January. March and May rainfall increases at more stations than it decreases, though only few of them had a statistically significant trend. All three significant monthly rainfall changes in June were downward while trend in July rainfall was significantly upward and downward at three stations each. Apart from upward trends at Makwanpur, September rainfall was decreasing significantly at three stations.

4.3 Departure from long-term mean rainfall

4.3.1 Five-yearly departure of annual rainfall from long-term mean

Figure 7 shows departures of 5-yearly average annual rainfall from the long-term mean during 1970 to 2015. The positive (negative) departures that are larger than one standard deviation of the series are highlighted as dark red (dark blue) while differences within the range of a standard deviation are shown in lighter colors.

Most of the stations received higher than long-term mean rainfall in both halves of the 1970s with three stations having substantially higher rainfall. On the other hand, most of the stations received less rainfall in the first half of the 1980s with Daman and Makwanpur in the west receiving substantially lower rainfall. Most of the stations have higher than mean rainfall in the 1985–1990 period with three stations in

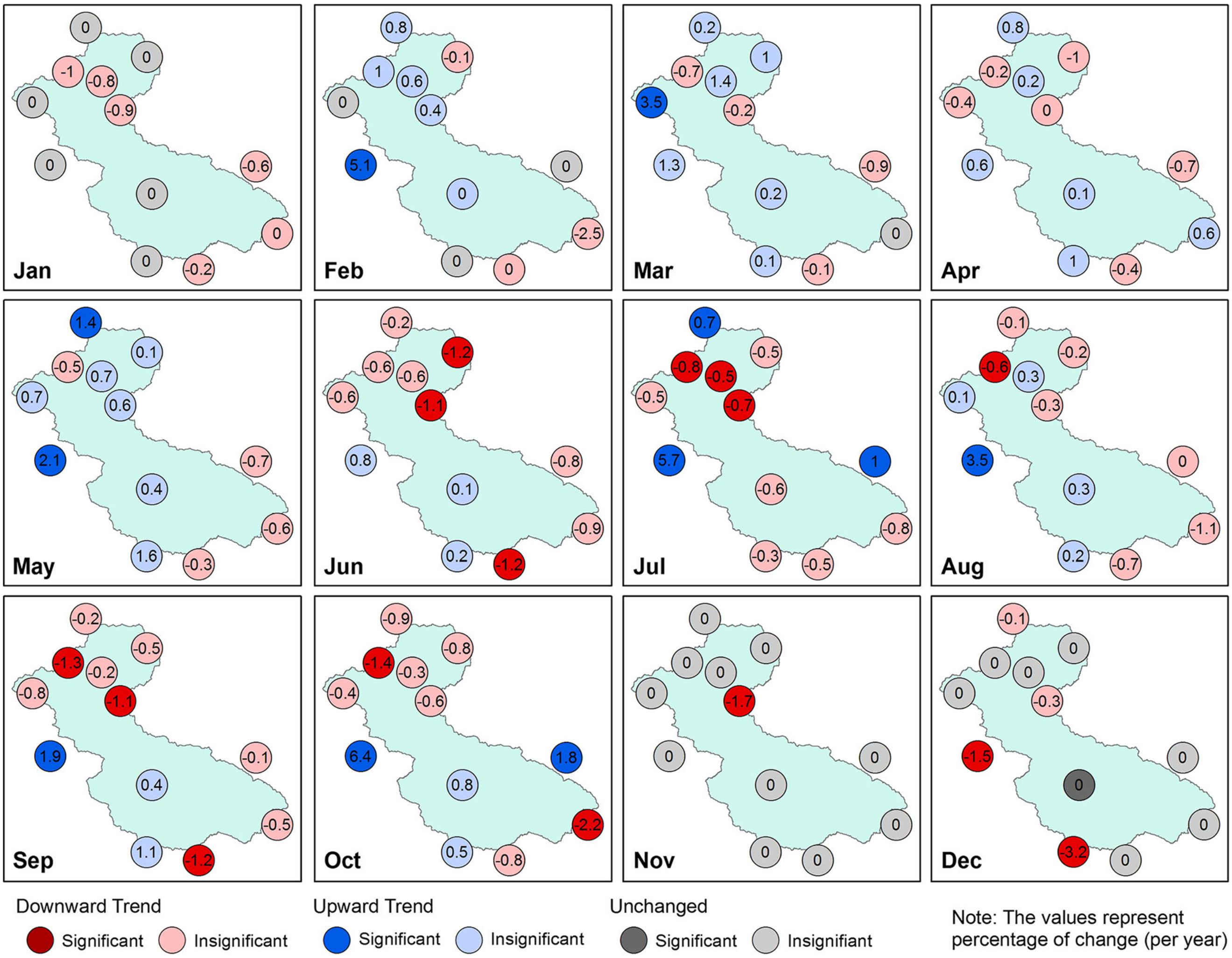


Fig. 6 Spatial distribution of long-term (1970–2015) monthly rainfall trend at stations in and around Bagmati catchment. The values represent percentage of Sen's slope in relation to the intercept

Kathmandu valley receiving substantially higher rainfall. Rainfalls during 1990–1995 were less than the long-term average at majority of the stations. Khumaltar and Nepalthok stations that receive the lowest rainfall among all the stations received substantially lower rainfall during this period. Increasingly more stations received substantially higher rainfall during the 1995–2000 and 2000–2005 periods. But, during 2005–2015, most of the stations received lower or substantially lower rainfall. Moreover, all the stations around the upper parts of the Bagmati catchment received substantially lower rainfall in 2005–2010.

4.3.2 5-yearly departure of monthly rainfall from long-term mean

Figures 8, 9, and 10 show departures of monthly rainfall from the long-term mean with respect to standard deviation of the month. They also highlight the comparison of monthly departures with the corresponding annual departures (cf. Section 4.3.1). The colors represent monthly departures in similar way to that shown for annual departures (cf. Fig. 7). The additional symbols explain whether the monthly result is in agreement with or contrasts to the annual departure. For example, a light (dark) red dot with × symbol representing same magnitude in different direction indicates that the monthly departure is lower (substantially lower) but the corresponding annual departure was higher (substantially higher).

Analysis suggests that there is no specific combination of monthly departures that leads to a certain annual departure (cf. Fig. 7). Substantially higher rainfall at Godavari and Nepalthok stations during 1970–1975 can be attributed to higher rainfall in June, July, and September as well as February, March, and April. Similarly, higher to substantially higher rainfalls in June–August, October, January, and April have resulted in substantially higher rainfall at Thankot and Pattharkot, during 1975–1980. However, September, October, and March rainfalls for the period were substantially lower at two to three stations.

Table 3 Summary of significant and non-significant monthly trends in relation to annual trend. "+" represents upward trend, "–" represents downward trend, and "o" represents no change. The changes inside () and [] bracket represent statistically significant trend at 95% and 90% confidence interval respectively

Station	Monthly trend												Annual trend
	1	2	3	4	5	6	7	8	9	10	11	12	
Daman	o	o	(+)	−	+	−	−	+	−	−	o	o	−
Godavari	−	+	−	−	+	(−)	(−)	−	(−)	−	(−)	−	(−)
Hariharpur	o	+	+	+	+	+	−	+	+	+	o	(o)	o
Kakani	o	+	+	+	[+]	−	[+]	−	−	−	o	−	+
Karmaiya	o	o	+	+	+	+	−	+	+	+	o	(−)	o
Khumaltar	−	+	+	+	+	−	(−)	+	−	−	o	o	−
Makwanpur	o	[+]	+	+	[+]	+	(+)	(+)	(+)	(+)	o	(−)	(+)
Nepalthok	−	o	−	−	−	−	(+)	−	−	(+)	o	o	−
Pattharkot	−	−	−	−	−	(−)	−	−	(−)	−	o	[o]	(−)
Sankhu	o	−	+	−	+	(−)	−	−	−	−	[o]	o	−
Sindhuli	−	−	o	+	−	−	−	−	−	(−)	o	o	(−)
Thankot	−	+	−	−	−	−	(−)	[−]	(−)	[−]	o	o	(−)

Substantially lower annual rainfall at Makwanpur station during 1980–1985 can be related to similarly lower rainfall during May to October and February. But, another station Daman with very low annual rainfall in this period had substantially lower rainfall in February and August only, while January rainfall was substantially higher.

During 1985-1990, higher rainfall in December, February, July, September, and October contributed to substantially higher annual rainfall at Thankot, Khumaltar, and Godavari. December rainfalls for this period were substantially higher for all stations except Karmaiya while April rainfalls were substantially lower at six stations. During 1995–2000, rainfalls in November, December, June, and August were substantially higher at the majority of the stations. However, February–May and September rainfalls were lower to substantially lower at most of the stations including some of the stations that had substantially higher annual rainfall.

Higher to substantially higher rainfall in January, February, April, May, and July supports higher annual rainfall at most of the stations for the 2000–2005 period. However, September–December, March, and June rainfalls for this period were lower to substantially lower at majority of the stations. In contrast to the 1970s, most of the stations exhibited lower to substantially lower rainfall during November–January and June–August in the 2005–10 and 2010–2015 periods. But, as an exception, February rainfall for 2010–2015 was substantially higher at eight stations including three stations that had substantially lower annual rainfall. March rainfalls were also higher at all stations except Sankhu during 2005–2010 including four stations with substantially higher rainfall.

Month-wise summary of the overall association between monthly and annual departures (cf. Figs. 8, 9, and 10) is presented in Table 4. It shows that monthly departures in July align with annual departure in 65% of cases while June and August departures have the same direction and magnitude of annual results little less than half of the times. Considering the changes in the same direction regardless of the magnitude, May to January rainfalls contribute to the same annual changes in roughly over 60% of the cases. On the other hand, February–April departures are seen to have changed in opposite direction of the annual departures in 43 to 57% of cases.

5 Discussion

5.1 Annual and monthly rainfall distribution

All stations in the Kathmandu valley except Sankhu receive their highest rainfall in July with a gradual decrease in the following months. Results indicating that the Sankhu and Kakani stations located north of Kathmandu have peak rainfall in July–August are in contrast to results obtained by (Kansakar et al. 2004). The differences between their result based on 1965–1995 records and the current result from 1970–2015 indicate some changes in the monthly distribution of rainfall at these stations in recent decades. Although comparable studies are lacking, an indirect inference supporting such changes can be drawn from river flow change results identified by Sharma and Shakya (2006) that peak rainfall in parts of the Bagmati catchment is shifting from July to August after 1985. Significant fluctuations in the length and timing of

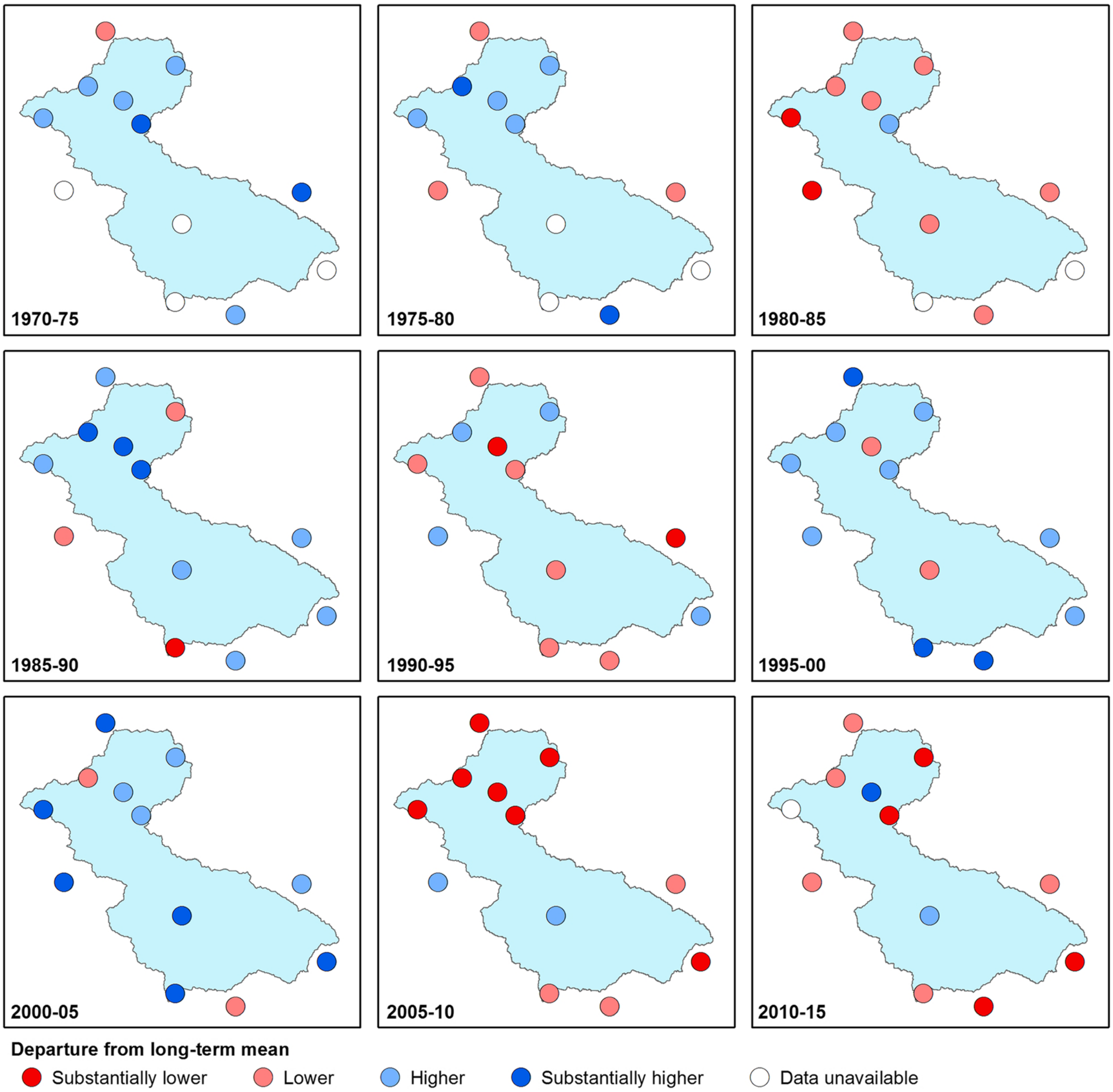
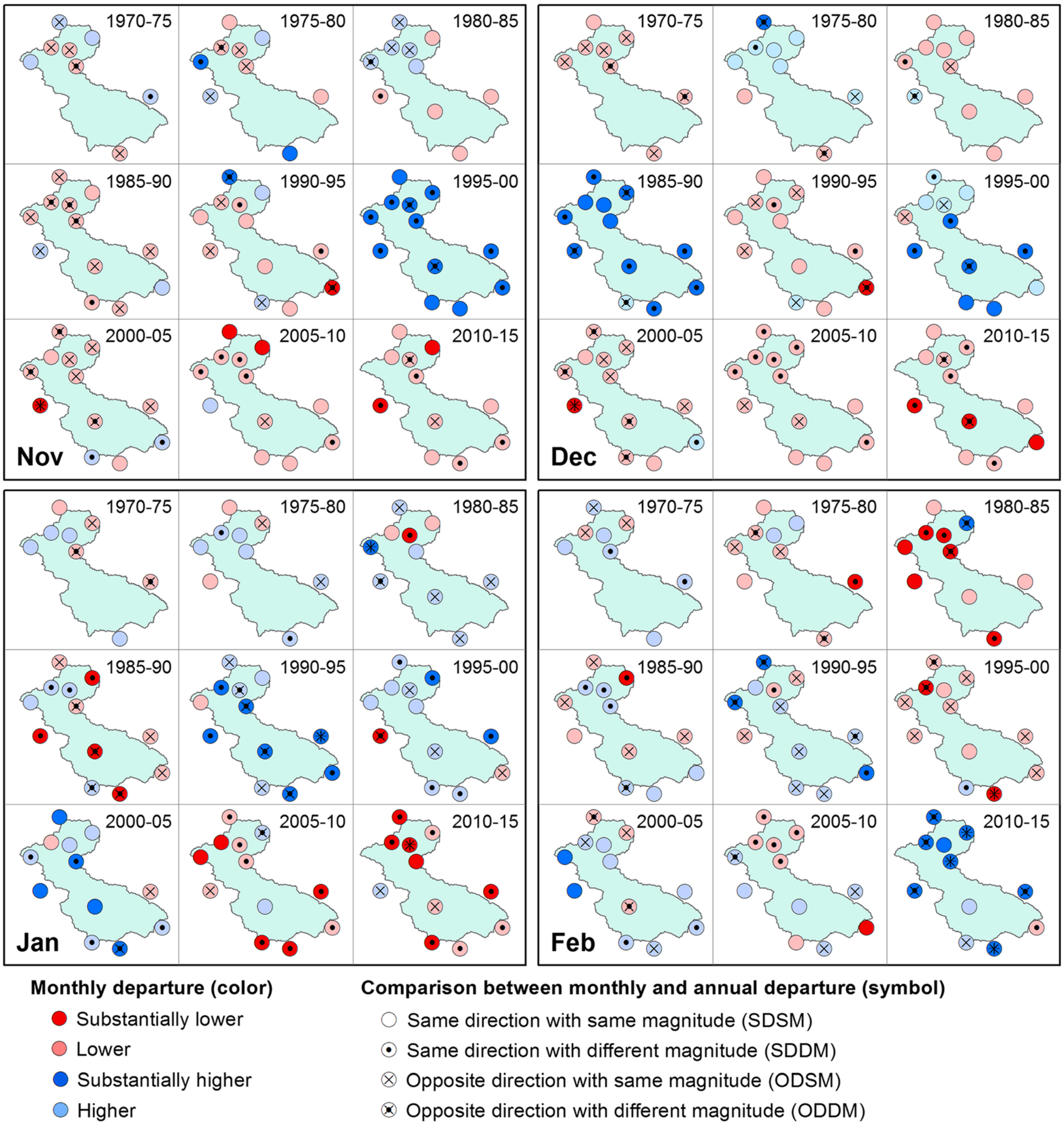


Fig. 7 Distribution of 5-yearly annual rainfall departure from long-term (1970–2015) mean at stations in and around Bagmati catchment. Positive (negative) standardized departure larger than the magnitude of a standard deviation is referred to as substantially higher (lower)

active/break phases of monsoon could also have influenced such intra-seasonal variations in the rainfall regime (Rodwell 1997; Virts and Houze 2016).

Studies suggest that rainfall distribution can be significantly influenced by orographic effects and smaller mountains are also effective in triggering convections in the central Himalayan region (Houze 2012). Such effects may, in part, explain the high spatial variability found in this work. In this regard, Makwanpur and Hariharpur stations located on the south (windward side) of mountain ranges above 1500 m stretching east-west receive high rainfall while Nepalthok station, located north of the mountain range, receives very little rainfall. In addition, stations in the inner foothills of Kathmandu valley receiving less rainfall compared with stations at the windward side of the monsoon (Singh and Kumar 1997) and further low rainfall at the middle of the valley both indicate the orographic effect in relation to the surrounding mountains as well. However, considering its location on the northern slopes of the higher mountain range northwest of Kathmandu, it is remarkable to note high rainfall at Kakani station. Dhital et al. (2013) also found that Kakani was receiving higher rainfall in relation to other stations in the region. A closer look at the regional rainfall distribution (Chalise et al. 1996) and topography of the surrounding region reveals that monsoon systems entering through the Trishuli River corridor may bring high rainfall in the area extending from Pokhara to Nuwakot and all the way to the Kakani area. Thus, larger differences in June–September rainfall at four of the stations receiving high annual rainfall which are at favorable location in terms of the summer monsoon path also support small-scale variation (Nayava 1980) being related to local orographic effects.



Note: Direction refers to lower/higher rainfall and magnitude indicates whether the departure is substantial

Fig. 8 Distribution of 5-yearly monthly rainfall departure in relation to the long-term (1970–2015) mean for November to February. Positive (negative) standardized departure larger than the magnitude of a standard deviation is referred to as substantially higher (lower)

During winter and pre-monsoon months, Daman and Thankot stations have higher than all-station average rainfall even though they receive less than the all-station average rainfall during the monsoon months. Kakani station also has higher than the all-station average rainfall during the January to March period. These three stations are located at the western edge of the upper mountainous part that are also higher than the neighboring western region. At the same time, Hariharpur, Pattharkot, and Karmaiya stations at lower elevation further southeast from these mountains receive significantly less rainfall compared with all-station average rainfall during November to April. Mediterranean systems bringing precipitation from the west in winter and the pre-monsoon period (Nayava 1980) can account for these differences in relation to annual rainfall.

5.2 Annual and monthly rainfall trend

Present results (cf. Section 4.2.1) showing five of the 12 stations to have a significant trend are somewhat different to the results of Bohlinger and Sorteberg (2018). Out of 42 stations tested across Nepal, they found significant trends only at 10 stations. However, due to lack of details about the stations

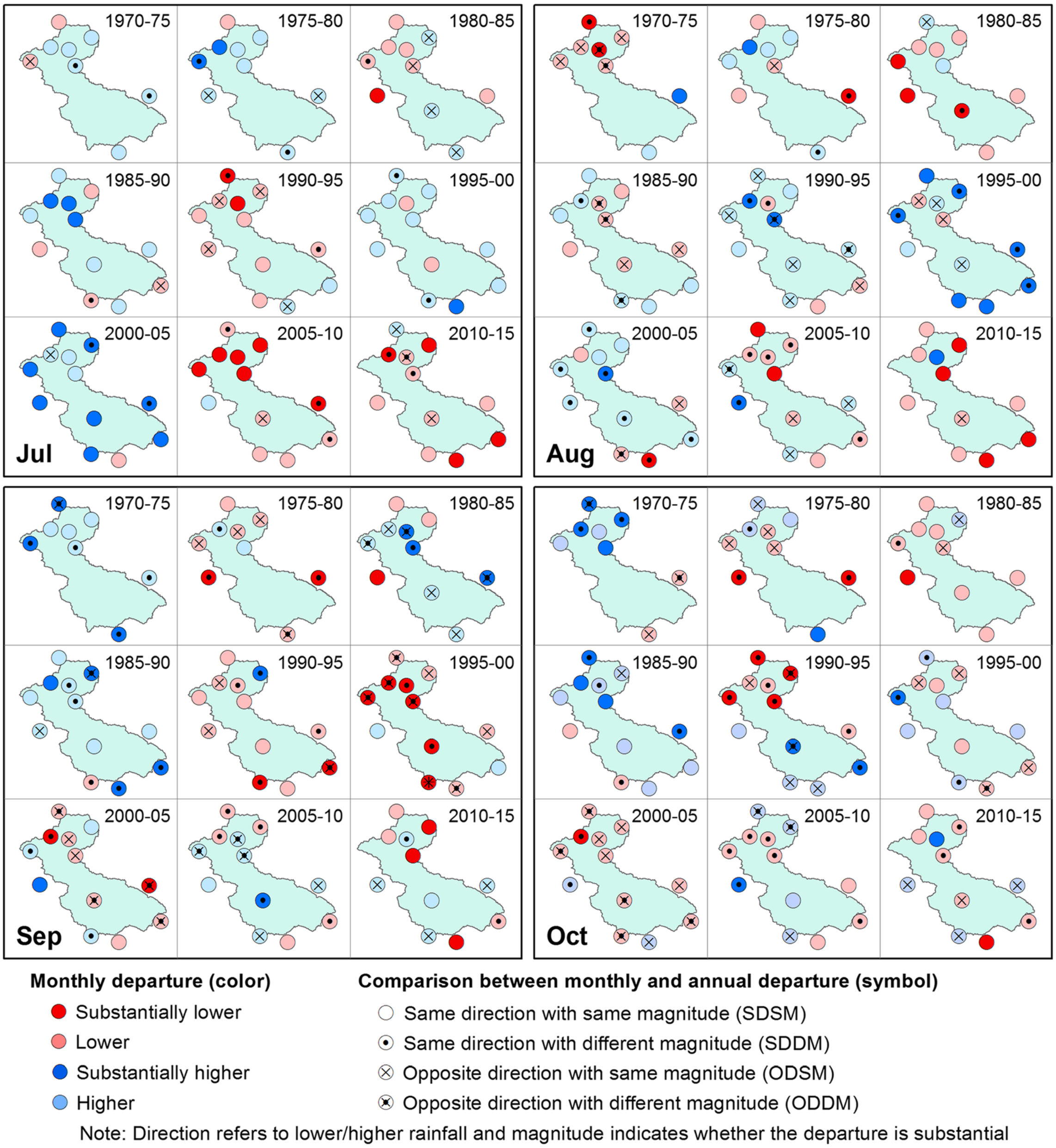


Fig. 9 Distribution of 5-yearly monthly rainfall departure in relation to the long-term (1970–2015) mean for March to June. Positive (negative) standardized departure larger than the magnitude of a standard deviation is referred to as substantially higher (lower)

tested for trend by Bohlinger and Sorteberg (2018), the corresponding results on common stations around the Bagmati catchment could not be ascertained individually.

Annual rainfall appears to be decreasing at the inner foothill locations of Kathmandu valley, though the trend at Sankhu is not significant. The results are mixed in the lower catchment with Sindhuli and Pattharkot, having significant downward trends, while Makwanpur in the west showed an upward trend. A closer look at the annual rainfall series for Makwanpur Gadhi (cf. Fig. 6), the only station with a significant upward trend, shows that there might be some long-term (multi-decadal) variation at this station. But in the absence of rainfall records earlier than 1975, it is difficult to verify.

The results demonstrated that the number of significant monthly trends by themselves does not necessarily determine significance of the annual change everywhere. For instance, significant change only in October is also associated to a significant change in annual rainfall when most of the non-significant changes also follow the same direction. Trend results at Hariharpur, Karmaiya, and Sindhuli should be interpreted with care when comparing with other stations in the study, since they only have records from 1978, 1984, and 1984, respectively.

In contrast to the results of Dhital et al. (2013) which show an upward trend at Godavari in the pre-monsoon season, the results of this study showed none of the months during March

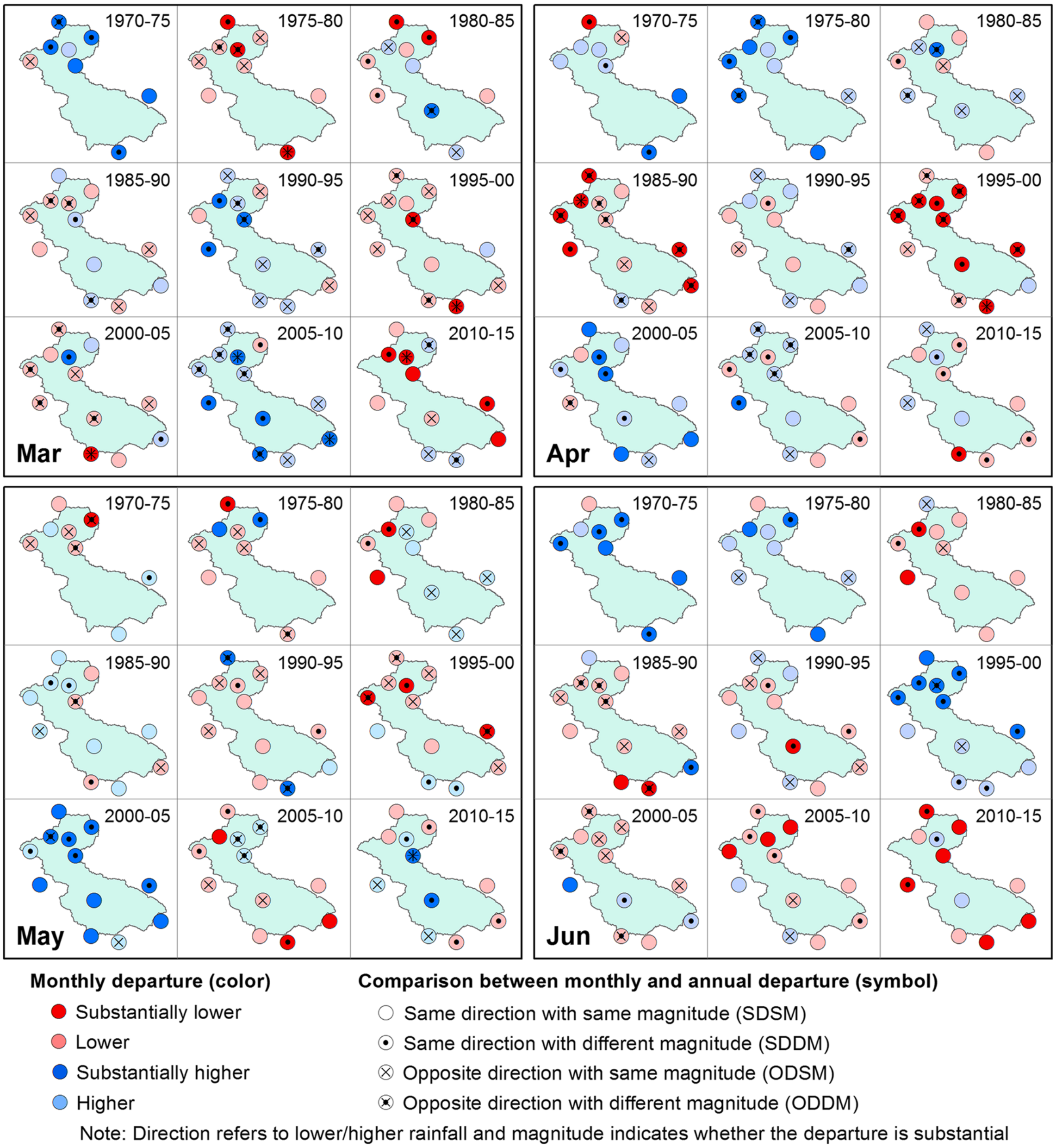


Fig. 10 Distribution of 5-yearly monthly rainfall departure in relation to the long-term (1970–2015) mean for July to October. Positive (negative) standardized departure larger than the magnitude of a standard deviation is referred to as substantially higher (lower)

to May to have a significant trend, even though the annual trend is downward. This difference could just be an example of how individual months can behave quite differently compared with seasonal aggregates and also because of the differences in length of data and methods used in identifying the trend. However, significant downward trends in June, July, and September agree with the significant downward trend during the monsoon found by Dhital et al. (2013).

Result on annual rainfall trend at Sindhuli (Madi) is consistent with the result of Dhital et al. (2013) showing significant downward trend at Sindhuli Gadhi station. However, in contrast to all seasonal rainfall found to be decreasing significantly, the current results show only the month of October has significantly decreasing rainfall at Sindhuli (Madi). The difference in the results can be attributed to records earlier than 1986 which were excluded from this study because they were found to be associated with Sindhuli Gadhi station that is 7 km north of Sindhuli (Madi) at 1460-m elevation. Considering highly variable rainfall patterns over short distances in the region, the records from these two stations might not be equivalent as treated by previous studies (e.g., Babel et al. 2014; Dhital et al. 2013). Based on 1970–2000 data, Babel et al. (2014) predicted increasing rainfall for 2020 and beyond at Daman, Sankhu, and Godavari stations under the B2 emission scenario and similar changes at Sindhuli Gadhi for both of the A2 and B2 scenarios. However, this study has shown

Table 4 Summary of comparison between monthly and annual departure for all 5-yearly cases at 12 stations. The values represent percentage of the relationship under each category, viz., departure in same direction with same magnitude (SDSM), departure in same direction with different magnitude (SDDM), departure in opposite direction with same (non-substantial) magnitude (ODSM–NS), departure in opposite direction with different magnitude (ODDM), departure in opposite direction with same (substantial) magnitude (ODSM–S)

Month	SDSM %	SDDM %	ODSM–NS %	ODDM %	ODSM–S %
1	30	34	19	14	3
2	30	21	28	17	4
3	24	18	27	24	6
4	33	24	16	24	2
5	36	27	23	13	1
6	46	28	18	8	0
7	65	17	16	1	0
8	46	23	21	9	0
9	32	30	18	19	1
10	33	31	24	12	0
11	35	24	26	14	1
12	37	27	19	16	1
Average	37	25	21	15	2

decreasing rainfall at these stations including significantly downward trends at Godavari and Sindhuli. This also supports that decreases in rainfall after 2000 are substantial in the region.

According to Shrestha and Sthapit (2015), trends of interpolated monthly rainfall for the bigger Bagmati catchment were significantly upward for June and July with all other months except December to have non-significant increasing rainfall. In contrast, the results of this study show June rainfall is decreasing significantly at four stations and decreasing non-significantly at four other stations. The dissimilarity in the results can be associated with the difference in the stations analyzed as well as rainfall changes at stations representing the lower catchment of the Terai region included by Shrestha and Sthapit (2015).

5.3 Annual and monthly rainfall departure from long-term mean

Results of this study show higher to substantially higher rainfall at most of the stations in the 1970s. This agrees with smoothed annual monsoon precipitation result derived by Shrestha (2000) for the eastern region of Terai to mid elevation mountains. Similarly, lower to substantially lower rainfall in June, July, and September, despite mostly higher rainfall in August, also agrees with lower rainfall in eastern sub-regions of low to mid elevation mountains. Two stations received substantially lower rainfall, and the rainfalls at six other stations were also lower than the mean rainfall during 1980–1985. This aligns with generalized catchment results of Shrestha and Sthapit (2015) that found lower rainfall for the period in relation to the mean of 1981–2008.

Directions of monthly departure in May to January and June–August in particular have been found to contribute substantially to the departure of annual rainfall. On the other hand, monthly rainfall in February–April can be different from annual departures in as much as half of the cases. Significantly higher rainfall during 2002–2004 (Shrestha and Sthapit 2015) also supports higher to substantially higher rainfall for most of the stations during the 2000–2005 period. An important observation is that lower than average rainfall has become more pronounced during 2005–2015 even though higher and lower rainfall periods were alternating in the past. This signifies some drying conditions noticed in many regions in recent times.

In fact, 5-yearly annual and monthly departures from the long-term mean show most of the stations received higher rainfall in 1970s and lower rainfall between 2005 and 2015, which support the results of the trend assessment. As identified by Shrestha et al. (2000), ENSO phases might also have influenced the departure of rainfall from the long-term mean in the region by delivering more rain (less rain) during La Niña (El Niño) phases. However, investigating the influence of such oscillations is beyond the scope of this study.

6 Conclusions

The study aimed to analyze spatial and temporal rainfall variations in and around the mountain catchment of the Bagmati River using historical records between 1970 and 2015 at 12 rain gauge stations. Annual rainfall time series created based on homogeneous daily data were tested for significance of monotonic trends using the non-parametric MK test. Departures of 5-yearly rainfall from long-term mean were examined at each station to highlight substantially higher/lower rainfall periods. Rainfall trend and departure from long-term mean were also analyzed at a monthly scale to investigate the intra-seasonal variabilities with respect to annual results.

As an important conclusion, results of monthly and annual rainfall distributions, trend, and departure from long-term mean exhibited considerable spatial variability over short distances of 10–25 km. Spatially variable rainfall characteristics shown by other studies (Bohlinger and Sorteberg 2018; Hannah et al. 2005;

Ichiyanagi et al. 2007; Nayava 1980; Shrestha et al. 2019) also support local variability in rainfall found in this study. Local orographic effects associated to mountain ranges (above ~ 1500 m) extending through middle of the catchment and those around Kathmandu valley appear to play a major role in explaining the high spatial variability of rainfall within the region. However, detailed assessment of local circulation, their interaction with monsoon and the Mediterranean system in relation to the regional topography (Barros and Lang 2003) are required for better understanding of small-scale variability within the Himalayan region.

Four stations at varying geographic location have shown significantly downward annual rainfall trends while one station has significant upward trend. However, most of the other stations in the region showing non-significant but downward changes suggest that the region is receiving less rainfall in recent times. Study of 5-yearly departures from the long-term mean also supports the trend results. Rainfall being the main source of water for the catchment, decrease in annual rainfall puts further pressure on management of water resource including hydropower generation and drinking water supply (e.g., Sharma and Shakya 2006; Shrestha et al. 2014; Uprety et al. 2017) to the large population within and downstream of the catchment.

Even though this study confirmed that the amount of annual rainfall is generally determined by precipitation during May to September, monthly breakdown of trends and departures from long-term mean does not show such consistent patterns in relation to annual results and other months of the season. However, the monthly results have revealed the detail of spatial and temporal variability as well as highlighted the monthly changes that contribute or contrast with annual results. Hence, analyses of rainfall variabilities in monthly or more detailed time scales are still important depending on the purpose of the study.

Decreasing rainfalls in June were noticed at most of the stations including three significant downward trends while July rainfall is also decreasing at majority of the stations. Considering predominantly rain-based agriculture, insufficient water availability during the plantation period can significantly hamper the production of rice (e.g., Pandey 2017; Shrestha and Shrestha 2017), the main crop of the region. The study also showed that rainfall amounts in November, December, and January are mostly unchanged or decreasing with no stations indicating any upward changes. Even though the variations in these months might not have contributed to changes in the annual rainfall, less than average rainfall in these low rain months can have a critical impact on production of winter crops.

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APPENDIX B – JOURNAL ARTICLE 2

water

Article

The Influence of Rainfall and Land Use/Land Cover Changes on River Discharge Variability in the Mountainous Catchment of the Bagmati River

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Abstract: Changes in rainfall and land use/land cover (LULC) can influence river discharge from a catchment in many ways. Homogenized river discharge data from three stations and average rainfall records, interpolated from 13 stations, were examined for long-term trends and decadal variations (1970–2017) in the headwater, upper and middle catchments of the Bagmati River. LULC changes over five decades were quantified using multitemporal Landsat images. Mann–Kendall tests on annual time series showed a significant decrease in river discharge (0.61% per year) from the entire Bagmati catchment, although the decrease in rainfall was statistically insignificant. However, declines in river discharge and rainfall were both significant in upper catchment. Decadal departures from long-term means support these trend results. Over tenfold growth in urban area and a decrease in agricultural land were observed in the upper catchment, while forest cover slightly increased in the entire catchment between 1975 and 2015. Correlation analysis showed a strong association between surface runoff, estimated using the curve number method, observed river discharge and rainfall in the upper catchment, while the relationship was weaker in the headwater catchment. These results were also supported by multiple regression analysis, suggesting that human activities together with climate change have contributed to river discharge changes in the Bagmati catchment.

Keywords: river discharge; rainfall; land use land cover; LULC; climate change; influence; Nepal; Himalayan mountain

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1. Introduction

Atmospheric and ocean temperatures are rising at an unprecedented rate and the rise is projected to continue during the 21st century [1]. This warming can alter rainfall patterns, including the frequency of extreme precipitation/drought events, evaporation and total runoff patterns, and hence, the availability of water resources [1,2]. Despite general agreement on increasing temperature, changes in rainfall and runoff can vary widely from one region to another [3–5]. For example, the Nile River showed a decreasing discharge in the 20th century [6], while high summer precipitation and rainstorms are linked to increased summer discharge and floods in the lower Yangtze River basin [7]. Nakaegawa et al. [4] projected the Amazon River to have increased discharge during the rainy season while it may decrease in dry season. In the Ganges basin (of which the Bagmati catchment forms part), some studies have predicted increasing monsoon discharge [8,9], while others suggested a likely decrease of annual and monsoon discharge [10,11].

In addition to climate change, land use/land cover (LULC) changes can increase the uncertainty of hydrological variability within a catchment as a result of changes in surface runoff, natural recharge processes and evapotranspiration [12–14]. Based on a review of 94 catchments across the world, Bosch and Hewlett [15] suggested that clearing of forests increases river discharge while recovery of vegetation or afforestation decreases the discharge. Growth in urban areas can increase surface runoff while evaporation and ground water recharge may have varying response [16,17]. Increasing river discharge is also linked with expansion of agricultural land and decrease in shrubs and forests [18,19]. In the Ganges basin, natural and climatic variability in precipitation and river discharge are further affected by rapid population growth and subsequent LULC changes, including urbanization and deforestation [20]. Nevertheless, a few studies also reported no significant changes in rainfall, evapotranspiration and river discharge in relation to forest-cover changes [21,22].

Within Nepal, significant LULC changes have occurred, especially with conversion from forest to agriculture. Forest cover in Nepal decreased from 45% in 1966 to 29% in 1994 [23,24]. However, recent forest assessments over 20 districts of Terai region suggest that, the rate of decrease has slowed down to 0.06% per year during 1990–2010 [24]. Forest conditions are estimated to be improving with community-based forest management and government regulations [23–25]. However, increasing frequency of weather-related extreme events in the region [26] such as excessive rainfall, long drought spells, landslides and floods have already had negative impacts on agriculture, forestry and biodiversity in Nepal [23].

The Bagmati River is not only important in relation to the initial settlement of Kathmandu valley, its tributary systems are also crucial for meeting the water demand of millions of people living in Kathmandu Valley and its downstream region [27]. In fact, per capita water availability in the catchment is one of the lowest in the country [28] and pressure on water resources is growing consistently due to high population growth [29,30].

Chalise et al. [31] examined a method to estimate low flow in the mountainous regions and also attempted to estimate runoff for ungauged areas of Nepal based on 52 mountain catchments. Bohlinger and Sorteberg [32] found both increasing and decreasing trends in monsoon rainfall, and spatial variation in the occurrence of extreme events across Nepal. Studies conducted in different catchments of the country (e.g., [33,34]) suggest that changes in rainfall and river discharge are different from place to place. Analyzing rainfall and river flow regimes in eight different river basins of Nepal, Hannah et al. [35] found no clear spatial pattern though the relationship between rainfall and river discharge varied based on basin characteristics, including LULC. Various LULC maps of Nepal have been prepared for 1978, 1986, 1994 and 2010 [36–38] while some have focused on mapping LULC of Kathmandu valley [39,40]. However detailed comparisons of LULC based on such results are difficult, due to the use of different methods. Some studies have modelled future water availability under various climate change scenarios for some mountain catchments located in different parts of Nepal [41,42]. Considering local variabilities in topography, precipitation and river discharge patterns, there are significant limitations in generalizing the results of macro level studies or inferring from studies of nearby catchments [35].

Few studies have analyzed the rainfall and/or river discharge of the Bagmati River catchment. Based on a hydrological model calibrated with 1999–2001 data, Babel et al. [43] predicted increasing annual precipitation in the Bagmati catchment. Based on Thiessen polygon interpolation of 1981–2008 data, Shrestha and Sthapit [44] found increasing rainfall in the Bagmati catchment with higher chances of future flooding during monsoon. Dhital et al. [45] analyzed data from 1980 to 2009 to estimate seasonal trends of temperature, precipitation and river discharge in the larger Bagmati catchment that includes the lower catchment in Terai region as well. Dhital and Kayastha [46] and Dhital et al. [47] performed frequency analysis of high rainfall and peak flood events in the Bagmati catchment. Examining monthly discharge between 1965 and 2000 with regression analysis, Sharma and Shakya [28] found decreasing monsoon discharge in the Bagmati catchment. These studies, however, have not provided detail on spatial variability within the catchment. Rainfall variability at individual stations were analyzed by Tuladhar et al. [48]. However, comprehensive studies analyzing the association between rainfall, LULC and river discharge changes are lacking, and this study aimed to fill this void. Considering multi-decadal fluctuations in hydro-climatic variables, analysis of data for longer periods (>45 years) was expected to provide better understanding of long-term variabilities.

The aims of this study were to: (a) investigate the long-term trend in average rainfall and river discharge in the Bagmati catchment and its sub-catchments; (b) analyze decadal variability of rainfall, LULC and river discharge; and (c) examine the association between river discharge, regional average rainfall and LULC changes.

2. Materials and Methods

2.1. Study Area

Originating from mountain springs north of Kathmandu, the Bagmati River flows south through the Kathmandu valley, a mid to low elevation mountain region, and the Terai plain, to eventually converge with the Ganges River system. This study focuses on the 2823 km^2 area of middle and upper Bagmati River catchment in Central Nepal (Figure 1). The small area (15 km^2) upstream of Sundarijal hydrometric station located at 1600 m elevation is described in this study as the headwater catchment. This area is within the Shivapuri–Nagarjun national park and has been protected since 1976 [27] with human activities being limited. The 605 km^2 catchment, upstream of Khokana station (1250 m) mostly comprising the urbanized area of the Kathmandu valley is referred to as the upper catchment [43,49,50]. The 2215 km^2 catchment downstream of Khokana yet upstream of Pandheradovan station (180 m), mostly representing lower/mid mountain region, is referred to as the middle catchment [43,49]. Thus, the three sub-catchments of Bagmati River, delineated based on the three available river gauge locations, represent contrasting geographical settings within the catchment. The study area covers the Kathmandu, Lalitpur and Bhaktapur districts, and parts of the Kavre, Sindhuli, Makwanpur, Rautahat and Sarlahi districts. Based on Shuttle Radar Topography Mission (SRTM) data [51], the elevation of the Kathmandu valley ranges between 1170 and 1400 m whilst the surrounding mountains extend up to 2780 m. Elevations in the lower parts of the middle catchment range between 140 and 600 m while higher parts of Kavre, Sindhuli, upper Makwanpur and southern Lalitpur range from 1500 to 2800 m (Figure 1).

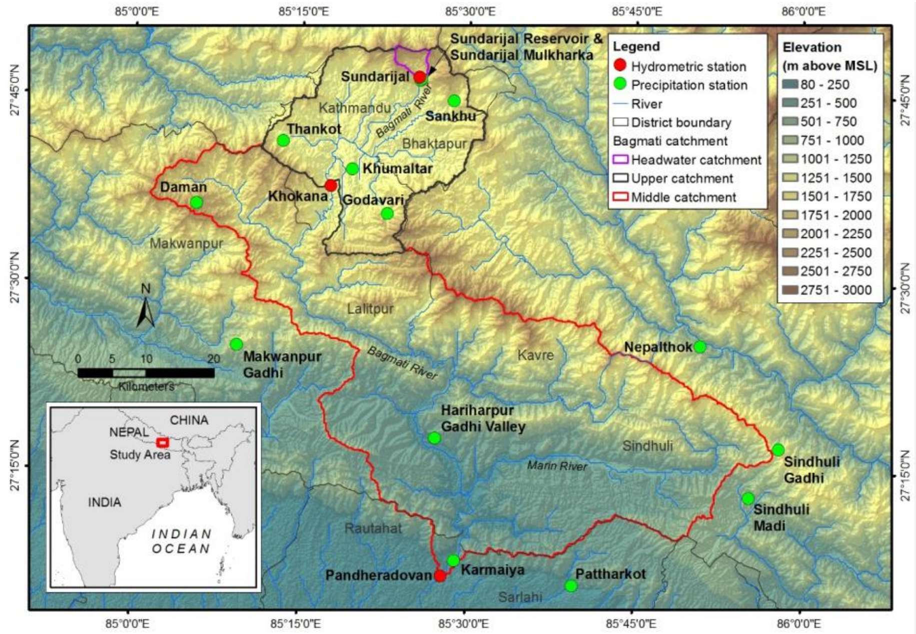

Figure 1. The Bagmati catchment and location of hydro-meteorological stations (elevation data source: SRTM).

The climate in the southern parts of the middle Bagmati catchment that includes lower hills and valleys (below 1000 m) is sub-tropical. The mid-elevation mountain ranges and valleys (1000–2000 m) have a warm temperate climate whilst the higher mountain parts experience a cold temperate climate [52–54]. On average, minimum temperatures within the catchment range from 0–12 °C in winter and 9–24 °C in summer, whilst maximum temperatures can be between 9 and 27 °C in winter and 21 and 39 °C in summer [31].

Precipitation, mostly in the form of rainfall, is the main source of water input to the catchment and no rivers are snow fed. The Indian summer monsoon delivers more than 80% of annual rainfall between June and September [48,55]. Westerly systems originating from the Mediterranean region bring some winter and spring precipitation between November and March [54]. River discharge in the region is related to rainfall pattern, peaking in July–August and reaching a low between January and April.

The lower parts of the Kathmandu valley are generally covered by agriculture and urban land uses. Based on district level census data [56], the permanent population of Bagmati catchment was 2.7 million in 2011. However, at least 30% more people are estimated to live in the Kathmandu valley temporarily [30,57] and the total population was estimated to be over 4 million [58]. Outside the Kathmandu valley, agricultural activities not only take place on valley bottoms and lowlands, but also on the mountain slopes that would otherwise be covered by forest and shrubs.

2.2. Remote Sensing Data

Landsat images between 1975 and 2015 were used to map historical LULC changes at a 10-year interval. Most of the Landsat images available from May to August have high cloud cover. And since agricultural area can be best separated from other vegetated areas when there are less crops, images from the dry season (November to April) were chosen. Due to the unavailability of suitable images around 1985, an image from 1988 was used. Table 1 shows the list of Landsat images used in the study.

Table 1. Landsat images used for mapping the land use/land cover (LULC) of the catchment.

Satellite-Sensor	Date of image	Path/Row
Landsat 2–Multi Spectral Scanner (MSS)	12 November 1975	151/041
Landsat 5–Thematic Mapper (TM)	3 April 1988	141/041
Landsat 5-TM	7 April 1995	141/041
Landsat 5-TM	2 April 2005 & 31 January 2006	141/041
Landsat 8–Operational Land Imager (OLI)	24 January 2015 & 12 February 2016	141/041

Landsat Multi Spectral Scanner (MSS) images have spatial resolutions of 60 m, unlike the 30 m of Thematic Mapper (TM) and Operational Land Imager (OLI) images. The TM and OLI sensors also have additional spectral bands. Studies have shown that Landsat images taken from MSS, TM and OLI sensors are comparable in terms of their spectral attributes [59,60] and have been used appropriately to map long-term LULC changes (e.g., [61–64]). Since the LULC is only classified into broad categories, the use of these images is considered appropriate for this study. SRTM V4 elevation data [51] were used to delineate the river catchment boundaries.

2.3. Hydro-Meteorological Gauge Records

Due to limitations of resources, meteorological stations are not well distributed in the mountainous areas of Nepal [52]. Nevertheless, in-situ records that are available remain valuable, since alternative sources such as remote sensing data may not have long historical coverage and their coarse spatial resolution may not be appropriate for studying small catchments. Daily precipitation records of 13 rain gauge stations and daily average discharges of three river gauge stations (obtained from the Department of Hydrology and Meteorology Nepal) are, therefore, the primary sources of data for this study. Since most of the stations have records from the early 1970s, this study focuses on variation in rainfall and river discharge between 1970 and 2017.

2.4. Land Use/Land Cover (LULC) Mapping

Landsat images were classified using maximum likelihood rule based supervised classification using the ERDAS Imagine (2016) image processing software. Data collected during field visits in 2016 and 2017 and information available from higher resolution images such as from Google Earth Pro was also used to assist the classification process.

LULC classifications for the study were kept to broad categories that were mappable consistently using historical Landsat images. Areas showing the characteristics of a forest, including tree cover and no other primary use [37], were mapped as forest. Apart from obvious shrub lands, areas which were not evidently distinguishable as agriculture or forest and showing mixed characteristics are also classified as shrubs. The shrub area in the region can, in fact, be considered as depleted forest or mixed vegetated land adjacent to agricultural areas [37]. Urban areas were classified as either built-up or mix of settlements that included some vegetated area, such as agriculture or trees. Smaller towns and human settlements that are generally a mixture of agriculture, sparse trees and some houses could not be distinguished consistently with Landsat images, so were not classified separately as urban areas. The results were filtered by merging classified areas that were smaller than three (five) pixels of image area for 1975 (1988–2015) with surrounding LULC classes. The accuracy of the LULC classifications were tested using 400 stratified random sites that were categorized based on Landsat and other higher resolution historical images available in Google Earth Pro. The accuracy statistics were calculated by comparing correct (actual) LULC and the classified LULC results at the random sites. The Kappa coefficients for the LULC classifications were between 0.89 and 0.91 and the overall accuracy of the results for each mapping period was over 85%.

2.5. Processing of Hydro-Meteorological Time Series Data

The daily precipitation and river discharge time series were tested for homogeneity using the RHtestsV4 package, in the R environment [65]. This was done to detect any "non-natural" variations introduced by gradual or abrupt changes in data collection and processing components [66,67]. Inhomogeneous daily time series data were homogenized by applying mean-based adjustments with respect to change-points detection results.

Data gaps in the daily time series were filled with 5-year daily averages [68] based on the daily records for two earlier and two later years for the same station. Annual rainfall time series were then created from the gap filled homogeneous daily series through arithmetic averaging. Regional average rainfall series for sub-catchments and the entire catchment were created based on inverse distance weighting (IDW) results of annual time series data. In general, geostatistical interpolation methods such as kriging are expected to provide a better estimation of rainfall distribution [69–71], while deterministic methods such as IDW, can also provide appropriate results [72,73]. Preliminary comparison of kriging and IDW results showed that IDW produced consistently appropriate interpolation of available data for this study. In the absence of dense measurement stations, the results will have some uncertainty [74] but the IDW technique has also been used in similar studies [71,75,76]. And since the focus of this study was on analyzing long-term variability using observations from the same set of locations, interpolation of rainfall using IDW was considered reasonable for this study.

2.6. Mann–Kendall Trend Test and Sen's Slope

The Mann–Kendall (MK) test is a widely used non-parametric test to determine the existence of a significant monotonic trend in various climatic variables. Such methods use ranks of data rather than actual values, which reduces the impact of outliers in the time series [77]. Furthermore, the MK test is also suitable for data such as rainfall series that are not normally distributed [77]. In this study, regional annual average rainfall, estimated surface runoff and annual average river discharge time series were tested with MK test to understand the presence of significant long-term trends. Statistically significant, monotonic trends in 95% confidence intervals were considered significant in this study.

The Sen's slope estimator is based on a linear model to estimate the rate of change and is a commonly used technique in analyzing hydro-meteorological data [78–80]. In this study, Sen's slope and its percentage in relation to the intercept value were used to represent the magnitude of change in rainfall, estimated surface runoff and river discharge.

2.7. Decadal Departure from Long-Term Mean

Apart from a long-term monotonic trend, climatic and hydrological time series can also have important long-term periodic variations. Decadal variation in regional average rainfall and river discharge were analyzed in relation to the long-term mean [81] for the period of 1970–2017. The departure of decadal average series were standardized by calculating standard scores. Positive (negative) departures from the mean that were larger than the order of one standard deviation were considered in this study to be substantially higher (lower).

2.8. Association of River Discharge with Rainfall and LULC Changes

The Natural Resources Conservation Service's curve number (CN) method [82] was used to estimate surface runoff from the sub-catchments, for the purpose of analyzing the impact of LULC and daily rainfall changes. This method calculates direct surface runoff based on precipitation, maximum soil retention and initial abstractions. Maximum soil retention can be estimated based on curve number that is determined by LULC and hydrological soil group [82]. Current LULC results and hydrological soil groups based on Food and Agriculture Organization (FAO) soil data [83] were used to identify soil curve numbers, as adopted by Mishra et al. [84]. Initial abstractions can be approximated in relation to maximum soil retention estimated as above. An initial abstraction ratio of 0.05 (i.e., initial abstraction = 0.05 × maximum soil retention), as suggested by Woodward et al. [82] and Hawkins et al. [85], was used in this study. LULC coverages of 1975, 1988, 1995, 2005 and 2015 were used to estimate LULC proportion for other years during 1970–2017 assuming linear changes in LULC. Weighted runoff for sub-catchments were then estimated using percentages of the area with specific LULC-hydrologic soil groups. Apart from changes in rainfall and LULC, river discharge depends on many other factors, such as soil moisture, evaporation, evapotranspiration, etc. However, we focused on the impact of rainfall and LULC changes only, and more comprehensive modelling was not within the scope of the study.

Pearson's correlation coefficients were calculated to check the association between the rainfall, estimated surface runoff and observed river discharge series. Cross correlations were also analyzed to see any lagged association. Percentages of annual rainfall, estimated surface runoff and observed river discharge series with respect to their long-term means were also compared to visualize the associations between them. Multiple regression analysis was performed to quantify the influence of major LULC changes and rainfall (predictors) on river discharge. For the purpose of comparing the relative contributions of the predictor variables, the importance for each of the variables were calculated as the ratios of change in R^2 (when the variable of interest is not considered) to the overall R^2 (when all predictor variables are considered) [86,87].

3. Results

3.1. Land Use/Land Cover (LULC) Change

Figure 2 shows LULC of the Bagmati catchment from 1975 to 2015. In general, mountainous parts of the catchment are covered by forest, shrubs, agriculture or a mixture of trees and agriculture, while the valleys are generally cultivated or used for settlement/urban purposes. The land use types representing mixed human settlements and urban areas both increased consistently during the study period (1975–2015) at the expense of agricultural lands. However, most of these urban expansions were concentrated in Kathmandu valley.

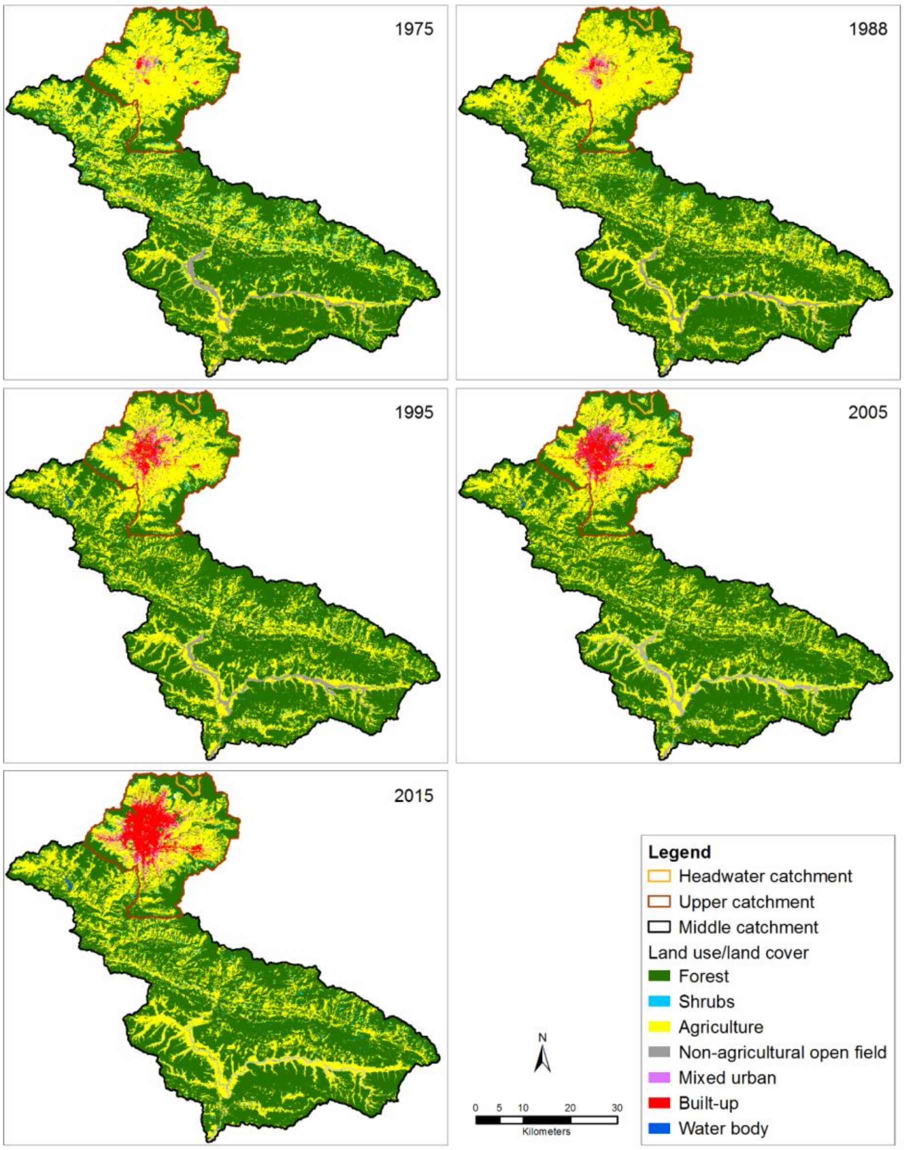

Figure 2. Land use/land cover in the Bagmati catchment—1975, 1988, 1995, 2005 and 2015.

Since most of the rivers and other water bodies in the catchment were too small to be consistently classified with Landsat images and their changes were negligible, no further analysis was done to compare changes in water surfaces. On average, shrubs and non-agricultural open fields were found to cover only 1.6% and 2.2% of the total area, respectively. Since the changes in these land cover were also not significant, further analysis was not performed.

Based on the most recent (2015) results, forest covers 62% of the entire catchment, while around 30% of the land is used for agriculture (Table 2). In the upper catchment forest and agricultural land cover 36% and 38% of the area, respectively, while 24% of the land is mixed urban or built-up (Table 3). In the middle catchment, forest covers 69% of the area and 28% of the land is used for agriculture (Table 4).

Table 2. LULC in the entire Bagmati catchment between 1975 and 2015 (areas shown in km^2).

LULC	1975	1988	1995	2005	2015	Average (1975–2015)
Forest	1688 (59.8%)	1682 (59.7%)	1721 (61.1%)	1753 (62.2%)	1757 (62.3%)	1720 (61.0%)
Agriculture	975 (34.6%)	1013 (35.9%)	923 (32.7%)	873 (31.0%)	842 (29.9%)	925 (32.8%)
Mixed urban	9 (0.3%)	15 (0.5%)	29 (1.0%)	32 (1.1%)	41 (1.5%)	25 (0.9%)
Built-up	5 (0.2%)	8 (0.3%)	35 (1.2%)	57 (2.0%)	100 (3.5%)	41 (1.5%)
Others	144 (5.1%)	101 (3.6%)	111 (3.9%)	104 (3.7%)	78 (2.8%)	108 (3.8%)

Note: values within parenthesis represent percentages of the LULC area in relation to the total area.

Table 3. LULC in the upper Bagmati catchment between 1975 and 2015 (areas shown in km^2).

LULC	1975	1988	1995	2005	2015	Average (1975–2015)
Forest	207 (35.1%)	197 (33.3%)	206 (34.9%)	215 (36.4%)	213 (36.1%)	208 (35.3%)
Agriculture	357 (60.6%)	366 (61.9%)	306 (51.9%)	275 (46.5%)	223 (37.8%)	305 (51.7%)
Mixed urban	9 (1.5%)	15 (2.5%)	29 (4.9%)	32 (5.4%)	41 (6.9%)	25 (4.2%)
Built-up	5 (0.8%)	8 (1.4%)	35 (5.9%)	57 (9.6%)	100 (16.9%)	41 (6.9%)
Others	11 (1.9%)	5 (0.8%)	14 (2.4%)	12 (2.0%)	13 (2.2%)	11 (1.9%)

Note: values within parenthesis represent percentages of the LULC area in relation to the total area. LULC areas within headwater Bagmati catchment are not included in this table.

Table 4. LULC in the middle Bagmati catchment between 1975 and 2015 (areas shown in km^2).

LULC	1975	1988	1995	2005	2015	Average (1975–2015)
Forest	1467 (66.2%)	1473 (66.5%)	1501 (67.8%)	1525 (68.8%)	1531 (69.2%)	1499 (67.7%)
Agriculture	617 (27.9%)	645 (29.1%)	616 (27.8%)	597 (27.0%)	617 (27.9%)	618 (27.9%)
Others	131 (5.9%)	96 (4.3%)	97 (4.4%)	93 (4.2%)	64 (2.9%)	96 (4.3%)

Note: values within parenthesis represent percentages of the LULC area in relation to the total area. Areas of mixed urban and built-up land were negligible (e.g., <1%), so are not listed separately.

The results of LULC analysis (Figure 2, Table 2) show that forest cover in the entire catchment increased by 4.1% over the 1975–2015 period. Agricultural area in the catchment decreased by 13.7% over the same period, even though it increased by 38 km^2 between 1975 and 1988. Less than 5% (8%) of total area covered by built-up category in 2015 were built-up in 1975 (1988). The results show that mixed urban land use covered a larger area compared to built-up areas in 1975 and 1988, but the growth rate of built-up area overtook that of mixed urban land from 1995.

Analysis of LULC change in the upper and middle Bagmati catchment shows some contrasting results. In the upper catchment (Table 3), built-up area has expanded consistently, especially after 1988 from the core of Kathmandu, Lalitpur and Bhaktapur city towards the outer parts of the valley. It increased to 35 km^2 in 1995, and it has increased by around 60% every decade since then. Mixed urban areas have also increased significantly in the upper catchment. The decrease of 134 km^2 in agricultural area and 127 km^2 increase in combined area of mixed urban and built-up areas between

1975 and 2015 shows that most of the LULC changes related to urbanization are concentrated within Kathmandu valley, the upper part of the Bagmati catchment.

In the middle catchment (Table 4), the forest area increased by 4.4% (64 km^2) between 1975 and 2015, while the increase was only 2.6% in the upper catchment. Apart from slightly higher coverage in 1988, there was no significant change in the percentage of agricultural area in the middle catchment.

The overall difference (1975–2015) in forest cover in the headwater area upstream of Sundarijal station, was less than 2% and the fluctuation remained within 2.25% of the average (Table 5). However, considering the actual area of the changes in relation to accuracy of LULC classification, these changes were considered to not be of a significant scale.

Table 5. LULC in the headwater Bagmati catchment between 1975 and 2015 (areas shown in km^2).

LULC	1975	1988	1995	2005	2015	Average (1975–2015)
Forest	13.6 (88.9%)	13.2 (85.2%)	13 (84.4%)	13.2 (86.3%)	13.4 (87%)	13.3 (86.4%)
Agriculture	1.6 (10.5%)	2 (12.9%)	1.6 (10.4%)	1.5 (9.8%)	1.7 (11.0%)	1.7 (11.0%)
Others	0.1 (0.7%)	0.3 (1.9%)	0.8 (5.2%)	0.6 (3.9%)	0.3 (1.9%)	0.4 (2.6%)

Note: values within parenthesis represent percentages of the LULC area in relation to the total area. Areas of mixed urban and built-up land were negligible (e.g., <1%), so are not listed separately.

3.2. Rainfall Variability

Time series of regional annual average rainfall derived from IDW interpolation, and their long-term trends in the Bagmati catchment and its sub-catchments, are shown in Figure 3. The results show that annual average rainfall in the Bagmati catchment was decreasing by 0.20% per year. Variability in the average rainfall of the middle catchment is very similar to that of the entire catchment and the MK test showed that the long-term trends in both cases were not statistically significant. Rainfall in the headwater catchment was also decreasing non-significantly by 0.19% per year, while a higher decrease of 0.36% per year in the upper catchment was statistically significant, at 95%.

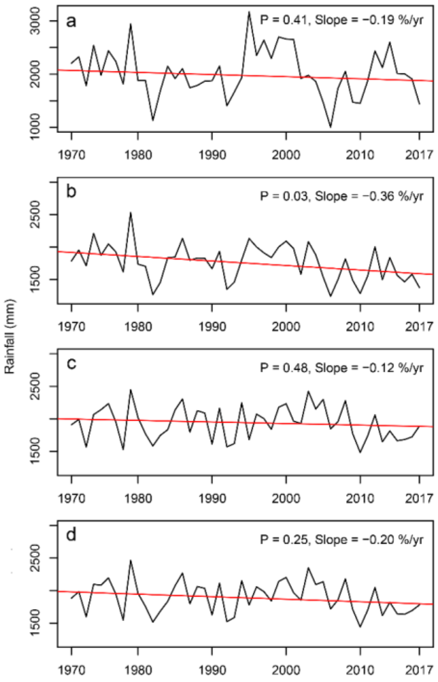

Figure 3. Long-term trend in annual average rainfall of (**a**) headwater, (**b**) upper, (**c**) middle and (**d**) entire Bagmati catchments.

Decadal analysis of rainfall departures from the long-term mean (Figure 4) shows that regional average rainfall in the catchment was higher to substantially higher than the long-term mean during the 1970s. On the other hand, rainfall after 2010 was substantially lower in all parts of the catchment except the headwater catchment. Patterns of decadal average rainfall in middle and entire catchment were very similar, with minor departures from long-term mean and the departure after 2010 being substantial in both cases. Decadal departure of rainfall in headwater catchment highly fluctuated, while the departure in the upper catchment showed generally decreasing rainfall during 1970–2017.

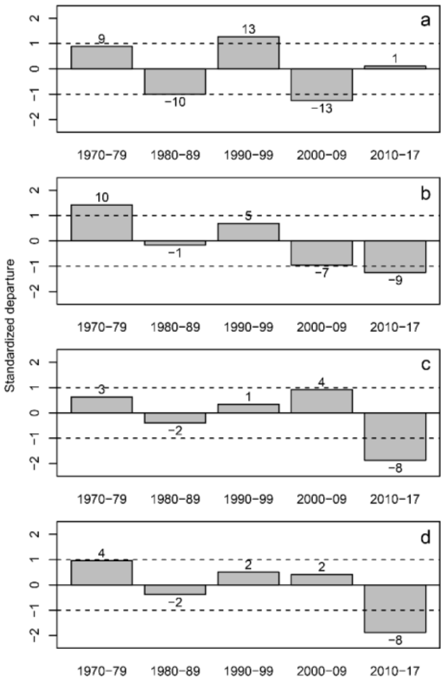

Figure 4. Decadal departure of rainfall in (**a**) headwater, (**b**) upper, (**c**) middle and (**d**) entire Bagmati catchments. Note: labels associated to the bars represent percentage of departure in relation to long-term mean.

3.3. River Discharge Variability

Average annual river discharge from the entire Bagmati catchment and its sub-catchments together with their long-term trends are shown in Figure 5. Based on the 1970–2017 records at Karmaiya/Pandheradovan station that represent the river discharge from the entire Bagmati catchment, annual river discharge was decreasing significantly by 0.61% per year. River discharge measured at Sundarijal also showed a decreasing trend of 0.32% per year in headwater catchment, but the trend was statistically non-significant. Observations at Khokana station during 1992–2016 show that river discharge from the upper catchment was decreasing significantly by 2.05% per year.

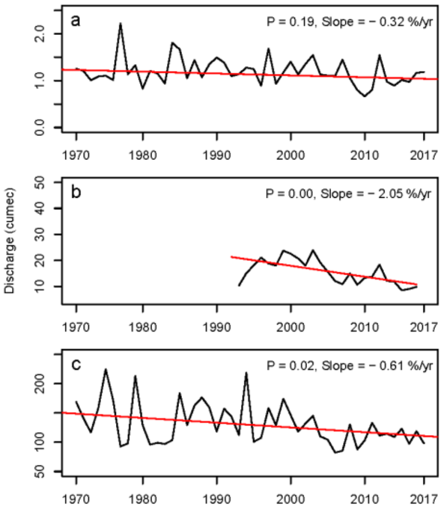

Figure 5. Long-term trend in annual average discharge of (**a**) headwater, (**b**) upper and (**c**) entire Bagmati catchments.

Figure 6 shows decadal departures of river discharge at Sundarijal, Khokana and Pandheradovan station in relation to their long-term means. The discharge from the entire catchment in the 1970s was substantially higher (by 16%), while the decadal discharge after 2000 was substantially lower by around 15% compared to the long-term mean. It is noticeable that river discharge from upper catchment has decreased consistently between 1992 and 2017 with substantially higher discharge in the 1990s; discharge after 2010 was substantially lower. The departures of discharge from the headwater and the entire catchment are comparable, considering higher discharge before 2000 and lower discharge after 2000.

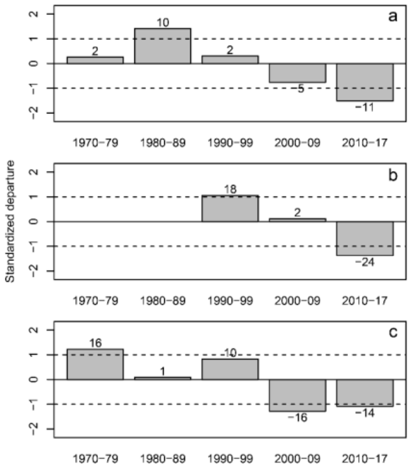

Figure 6. Decadal departure of river discharge from (**a**) headwater, (**b**) upper and (**c**) entire Bagmati catchments. Note: labels associated to the bars represent percentage of departure in relation to long-term mean.

3.4. Influence of Rainfall and LULC Change on River Discharge

The association of (observed) river discharge with rainfall and estimated surface runoff, derived from rainfall and LULC changes using the CN method, are shown in Figure 7. The values represent annual distribution of rainfall, estimated surface runoff and the observed river discharge as percentages of their long-term means in the headwater, upper and entire Bagmati catchments. Patterns of estimated surface runoff and annual discharge from upper and entire catchments are highly influenced by the amount of rainfall even though the ratio of fluctuations were relatively different for some years.

Estimated surface runoff in headwater catchment is also related to annual rainfall although the river discharge has a slightly different pattern.

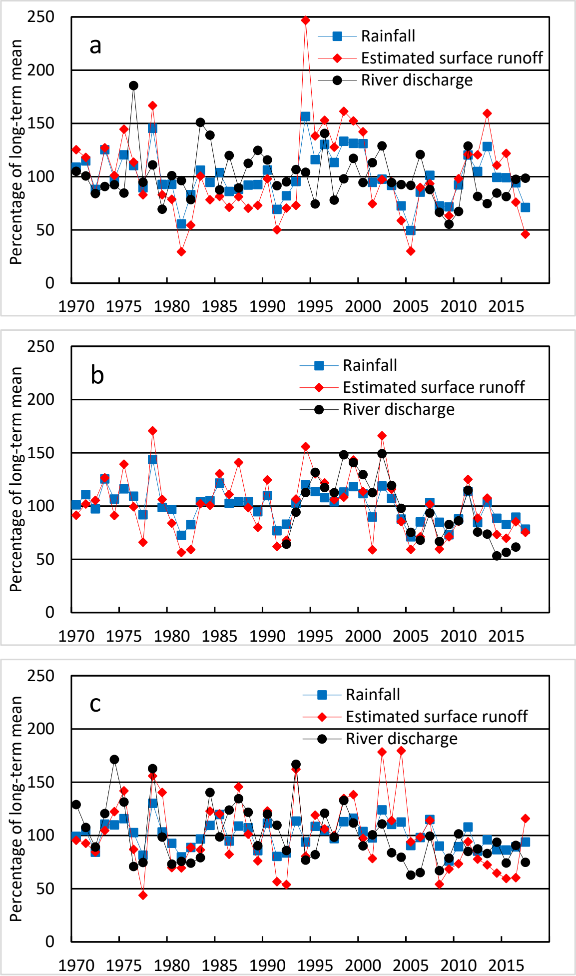

Figure 7. Relationships of annual river discharge with rainfall and estimated surface runoff (derived based on rainfall and LULC) for (**a**) headwater, (**b**) upper and (**c**) entire catchments. Note: values on y-axis represent percentages in relation to corresponding long-term means.

Table 6 shows the correlation results of river discharge with rainfall and estimated surface runoff in sub-catchments of the Bagmati River. There is a statistically significant, positive correlation (r = 0.58) between annual rainfall and discharge for the entire catchment. A statistically significant, strong, positive relationship (r = 0.79) exists between rainfall and river discharge in the upper catchment, while a statistically insignificant, weak relationship (r = 0.22) was found for headwater catchment. The association between estimated surface runoff and river discharge was also weak in the headwater catchment. On the other hand, river discharge from upper and entire catchment exhibited a statistically significant correlation with estimated surface runoff.

Table 6. Correlation of river discharge with rainfall and surface runoff estimated based on rainfall and LULC changes.

Catchment	Rainfall and River Discharge		Estimated Surface Runoff and River Discharge	
	R	P Value	R	P Value
Headwater catchment	0.22	0.13	0.10	0.48
Upper catchment	0.79	0.00	0.75	0.00
Entire catchment	0.58	0.00	0.54	0.00

Table 7 shows the results of multiple regression analysis, highlighting the contributions of rainfall and major LULC changes to the river discharge. The direct influence of rainfall change is statistically significant in all sub-catchments. In the upper catchment, the inverse influences of change in agricultural and urban areas were significant on river discharge but the direct contribution of rainfall change appears to be the most significant. In headwater and the entire catchment, the influences of LULC changes are not statistically significant.

Table 7. Multiple regression results showing contributions of rainfall and major LULC changes on river discharge.

Catchment	No. of Observation	Overall R Square	P Value	Predictor	P Value	Importance	Slope %
Headwater catchment	48	0.15	0.07	Forest	0.81	0.01	0.68
				Agriculture	0.11	0.35	1.01
				Rainfall	0.03	0.69	0.67
Upper catchment	25	0.75	0.00	Agriculture	0.03	0.09	−0.82
				Urban	0.02	0.11	−0.19
				Rainfall	0.00	0.32	0.09
Entire catchment	48	0.49	0.00	Forest	0.16	0.05	−1.30
				Agriculture	0.35	0.02	0.18
				Urban	0.10	0.07	0.08
				Rainfall	0.00	0.67	0.14

Note: "Importance" represents the ratio of change in R^2 (when the predictor variable of interest is not considered) to the overall R^2 (when all predictor variables are considered) [86,87]. "Slope %" indicates percentage of regression coefficient in relation to intercept value.

4. Discussion

4.1. Land Use/Land Cover Change

LULC results show that the forested area in the middle and entire Bagmati catchment increased by 4.1% between 1975 and 2005. However, overall forest coverage in Nepal decreased by 3.1% during 1975–2005 [88]. Shrubs/mixed land area in the catchment has not changed significantly, although DFRS data [37] suggest that the national coverage of shrub land, including deteriorated forest, doubled between 1986 and 1994. These dissimilarities highlight varying LULC changes in different parts of the country. Nevertheless, the increase in forest cover within the Bagmati catchment between 1988 and 2005 is consistent with FAO [23] findings, suggesting a 4% increase in forest cover of central Nepal during 1986–1994.

Current results further suggest that due to increasing human settlements, mixed urban land use takes place in agricultural areas of Kathmandu valley which eventually develops into built-up areas. Analysis showed a remarkable (513%) increase in combined area of mixed urban and built-up land use together with 38% decrease in agricultural area of upper catchment between 1988 and 2015. This is comparable with estimates of Ishtiaque et al. [40] showing a 412% increase in built-up area and 32% decrease in agricultural area within Kathmandu valley. However, the apparent differences could be related to differences in land use classification scheme and methods employed. Furthermore, our results are also similar to the 1978–2000 urban expansion of 450% estimated by Haack and Rafter [89]. The current estimate for 2015 is also comparable to the built-up area estimated by Kumar [90] within 2 km of Kathmandu metropolitan city. Population within the Bagmati catchment increased by almost 400% between 1971 and 2011 [56]. Furthermore, the urban population in Kathmandu valley, one of the fastest growing urban agglomerations in South Asia [91] has increased annually by 4% to 5.8% from 1970 to 2010 [92]. As pointed out by Pradhan [93], conversion of agricultural area to urban land in the upper catchment is consistent with the rapid population growth in Kathmandu valley.

4.2. *Rainfall Variability*

MK tests showed that the decrease in annual rainfall in the Bagmati catchment was not statistically significant; however, similar analysis of monthly rainfall suggests that June and July rainfall decreased significantly by 0.55% and 0.4% per year, respectively. Individual trends at 11 rainfall stations used in this study also suggested that most of them were receiving decreased rainfall with four of those stations (viz. Godavari, Pattharkot, Sindhuli Madi and Thankot) showing significantly decreasing trends [48]. However, significantly increasing rainfall at one of the stations (Makwanpur Gadhi) that represents a part of the middle catchment could also have moderated the negative change in the regional average for the entire catchment. Decadal departure patterns of the regional rainfall also support the trend results in all sub-catchments of the Bagmati River.

Current results for the period of 1970–2015 appear different to the findings of Shrestha and Sthapit [44], suggesting that average rainfall in the Bagmati catchment, including the lower Terai sub-catchment, was increasing significantly during 1981–2008. Decadal departure from the long-term mean (cf. Figure 5) as well as further trend analysis for the shorter period of 1981–2008 does show non-significantly increasing rainfall in the Bagmati catchment. However, considering multi-decadal variation present in the regional rainfall, this increase does not seem to represent the long-term change in rainfall over the catchment.

In contrast to the decreasing trend noticed in this study, Babel et al. [43] and Dahal et al. [94] predicted increasing rainfall for the 2020s and 2030s relative to the rainfall of the 1980s. These differences could be partly due to lower than long-term rainfalls in the 1980s which were used as baselines in both of those studies and the lower than average rainfalls after 2010. However, results of this study showing higher rainfall decrease in the upper catchment are consistent with the prediction by Babel et al. [43] that the upper catchment is set to receive lower rainfall compared to the middle one.

Previous studies have indicated that rainfall patterns in Nepal are somewhat linked to El Niño Southern Oscillation and Indian Ocean Dipole [68,95,96], but relationships are not consistent [95]. Shrestha and Kostaschuk [57] also suggested that influence of ENSO phases on the streamflow within Nepal vary from one region to another. However, examining the influence of these coupled ocean–atmosphere phenomenon on rainfall distribution is beyond the scope of this study.

4.3. *River Discharge Variability*

A decrease in annual river discharge from the Bagmati River in the 1970–2017 period was statistically significant. Trend analysis of all available data (1965–2017) for the Karmaiya/Pandheradovan station also confirmed that river discharge decreased significantly. Sharma and Shakya [28] also found that mean annual and monsoonal river discharge from the Bagmati catchment decreased significantly during the 1965–2000 period. Based on 1980–2009 records, Dhital et al. [45] found seasonal discharge of the Bagmati catchment decreasing in all seasons except pre-monsoon. Consistency of the current findings with the results based on different record periods confirms that river discharge from the catchment is truly decreasing in the long term. The analysis of decadal departure from long-term means showing substantially lower discharge after 2000 and higher discharge before 2000 also supports the long-term trend for the entire catchment.

Steadily decreasing decadal discharge from the upper catchment aligns well with trend result. Considering availability of records only from 1992, significantly decreasing discharge from the upper catchment is not directly comparable with the 1970–2017 results for the entire catchment. However, the most consistent and highest rate of rainfall decrease for 1970–2017 in the upper catchment and highest positive correlation between rainfall and river discharge indirectly suggest that the long-term rate of river discharge decrease would also be higher in the upper catchment compared to others.

Most of the river discharge, as recorded at Sundarijal station, especially during dry season, is diverted for hydropower and drinking water purposes. However, the long-term average of this discharge is less than 1% of the discharge at Pandheradovan, and the diversion started before the study period. Likewise, most of the discharge from the Kulekhani river catchment has been diverted to the Rapti basin for hydropower generation since 1982 [28,43]. This diverted discharge accounts for less than 3% of the annual discharge at the Pandheradovan station and is expected to remain unchanged in the future [43,94]. Further analysis by adding 3% discharge on observed discharge at Pandheradovan station from 1982 onwards showed that, this would not change the direction and/or significance of long-term trend results of this study. Hence, these diversion schemes were not considered in the analysis of temporal change in river discharge.

In contrast to the results reported here, Babel et al. [43] have predicted annual water availability for the 2020s in the Bagmati basin to increase by 1.04% and 6.29% relative to the 1980s under A2 and B2 scenarios respectively. Considering lower than long-term average rainfall (Section 4.3) and relatively lower discharge from the entire catchment in the 1980s, the increase for the 2020s may not be as high as they have estimated, if not actually a decrease instead, as suggested by the trend assessment of 1970–2017.

4.4. The Influences of Rainfall and LULC Changes on River Discharge

River discharge from the Bagmati catchment was shown to be significantly correlated with rainfall, even though the degree of association was different in the sub-catchments. Hannah et al. [35] also indicated that the relationship between precipitation and river discharge in the region varies from basin to basin depending on LULC.

Rainfall from the headwater catchment is decreasing non-significantly by 0.19% per year while river discharge is decreasing non-significantly by −0.29%. The MK test on estimated surface runoff in the headwater catchment showed a statistically non-significant decrease (−0.20%) which is very similar to the change in annual rainfall. The multiple regression results also suggested that the influence of LULC change in river discharge is negligible, and that influence of rainfall change is more important.

The Kathmandu valley area (downstream of Sundarijal and upstream of Khokana) is the most dynamic part of the Bagmati catchment. River discharge from the upper catchment during 1992–2017 has decreased by −2.05% per year even though the rate of rainfall decrease is only −0.83%. Despite an increase in urban area, which generally results in higher surface runoff [97,98], the MK test on 1992–2017 estimated that surface runoff for the upper catchment showed a significant decrease of −1.51%. Multiple regression analysis suggested that, compared to the influence of LULC changes, a decrease in rainfall is more influential on river discharge from the upper catchment. This finding is also supported by strong correlations between rainfall, river discharge and estimated surface runoff in the upper catchment.

In addition, part of the decrease in river discharge from the upper catchment may also be related to increased water demand. For example, many of the headwater streams in Kathmandu valley, especially during the dry season, are exploited for the purpose of drinking water. Further, the water table in the Kathmandu valley is reported to be lowering substantially due to low recharge and increased extraction of ground water driven by scarcity and low quality of surface water [29,50,57]. Some studies have also reported increasing temperatures in most parts of the catchment [45] which suggests higher rates of evaporation. Hence, urban expansion and pressure on water sources along with a rising temperature and decreasing rainfall seem to be related to the long-term decrease in river discharge from the upper catchment.

The rate of decrease for estimated surface runoff and river discharge are both higher than the rate of rainfall changes in the entire catchment. Apart from the urban growth in the upper catchment, the major LULC change in the middle catchment was an increase in forest cover by 4.4%. However, multiple regression results indicate that the influences of LULC changes on river discharge from the entire catchment are not significant and that changes in rainfall are the greatest contributing factor. Considering many tributaries in the middle catchment are unaffected by urban usage, decreasing rainfall along with increasing temperature [45] and higher evapotranspiration seemed to be influencing river discharge from the middle catchment. Therefore, river discharge decrease from Bagmati catchment can be attributed to decreasing rainfall, increasing temperature and differing influences of LULC in upper and middle catchments.

The correlation coefficient between annual rainfall in the headwater area of the Bagmati River and discharge at Sundarijal station was only 0.31. Further analysis of cross correlation (not shown here) suggested that annual rainfall does not have a lagged correlation with annual river discharge. However, cross correlation of monthly series showed a lagged correlation of one month between rainfall and discharge from headwater catchment. Considering high forest cover that reduces direct surface runoff, increases ground water retention and causes a higher density of natural springs, the lagged correlation in the headwater catchment is reasonable. On the other hand, no lagged correlation in either annual or monthly series suggests that immediate surface runoff of rainfall is highly influential on river discharge from the upper catchment, and secondly, that of the middle catchment. These results can be related to the combined proportion of urban and agricultural land in the upper and middle catchments.

5. Conclusions

Long-term changes in rainfall and river discharge of the Bagmati River catchment were analyzed with Mann–Kendall trend tests and decadal departures from the long-term mean using historical records between 1970 and 2017. Changes in LULC were also analyzed based on classification of Landsat images. Further, the impacts of rainfall and LULC changes on river discharge were examined using correlation and multiple regression analysis, and their relationship to surface runoff was estimated based on the curve number method.

River discharge from the Bagmati catchment is decreasing significantly even though decrease in rainfall was statistically non-significant. However, the decreasing trends of regional average rainfall and river discharge from the upper catchment are both significant and even depicted a higher rate of change compared to the entire catchment. Decadal departure of rainfall showed that the rainfall in all sub-catchments was generally higher than long-term average in the 1970s, while it was substantially lower after 2010 except in the headwater catchment. At the same time, river discharge from the headwater and entire catchment after 2000 was substantially lower, while discharge before 2000 was higher.

Most of the expansion in urban land use which occurred by gradual conversion of agricultural area to mixed urban area that further develops to built-up area is consistent with rapid population growth in the Kathmandu valley in the upper catchment, especially after 1988. In fact, the percentage of urban area in the upper catchment increased from 3.9 in 1988 to 23.8 in 2015. Another main LULC change in the Bagmati catchment was an over 4% increase in forest area with a higher rate in the middle catchment.

Multiple regression analysis showed that, despite a positive contribution from urban area increase, decreasing river discharge from upper catchment is largely dependent on changes in rainfall. Analysis of correlation in conjunction with LULC changes also suggested that river discharge is highly dependent on rainfall in urban area, and the correlation is weaker when the extent of human activities, especially urbanization, is limited. Changes in estimated surface runoff based on rainfall and LULC change also shows a higher rate of decrease in urban area. This is coupled with an increased use of water from headwater streams and groundwater in the upper catchment for use as drinking water. As a main conclusion, based on these findings, both regional climate change and local human activities seem to put increased pressure on water availability in the upper Bagmati catchment. In contrast, with no substantial urban growth, river discharges from the headwater and the entire catchments are decreasing at smaller rates compared to the upper catchment. This, together with results of multiple regression suggest that the headwater and middle catchments are mostly influenced by changes in climatic factors. These findings also point to the need for more detail hydrological modelling of river discharge in relation to topography, soil characteristics, climatic variables, LULC change and water extraction which would be beneficial for drawing more concrete conclusions.

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REFERENCE STATEMENT

APPENDIX C – SUPLEMENTARY RESULTS

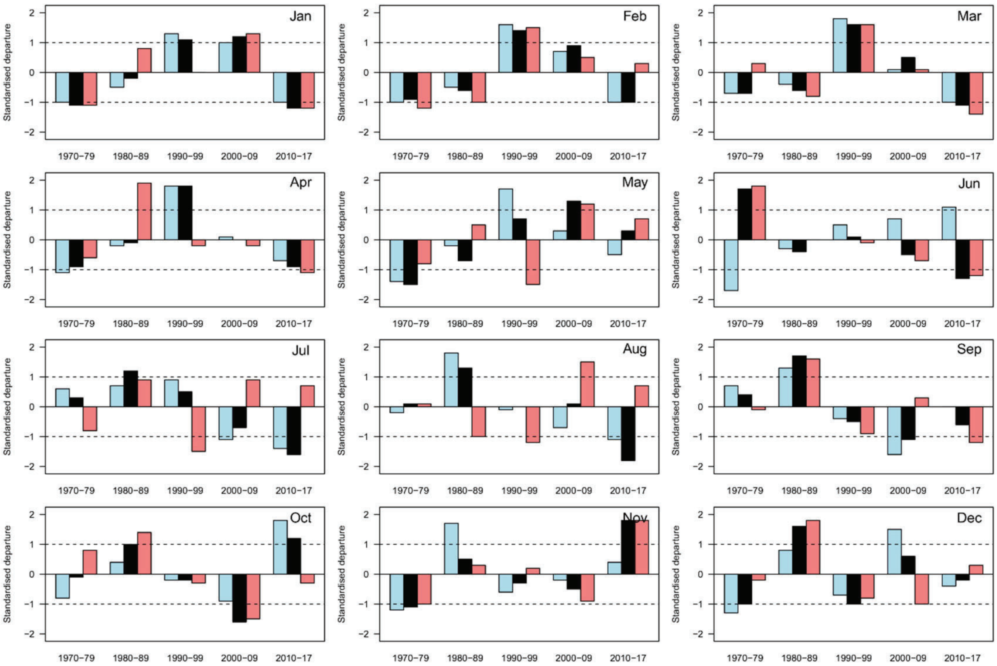

Figure 1 Monthly departure of minimum (light blue), average (black) and maximum discharge (light red) from headwater Bagmati Sub-catchment

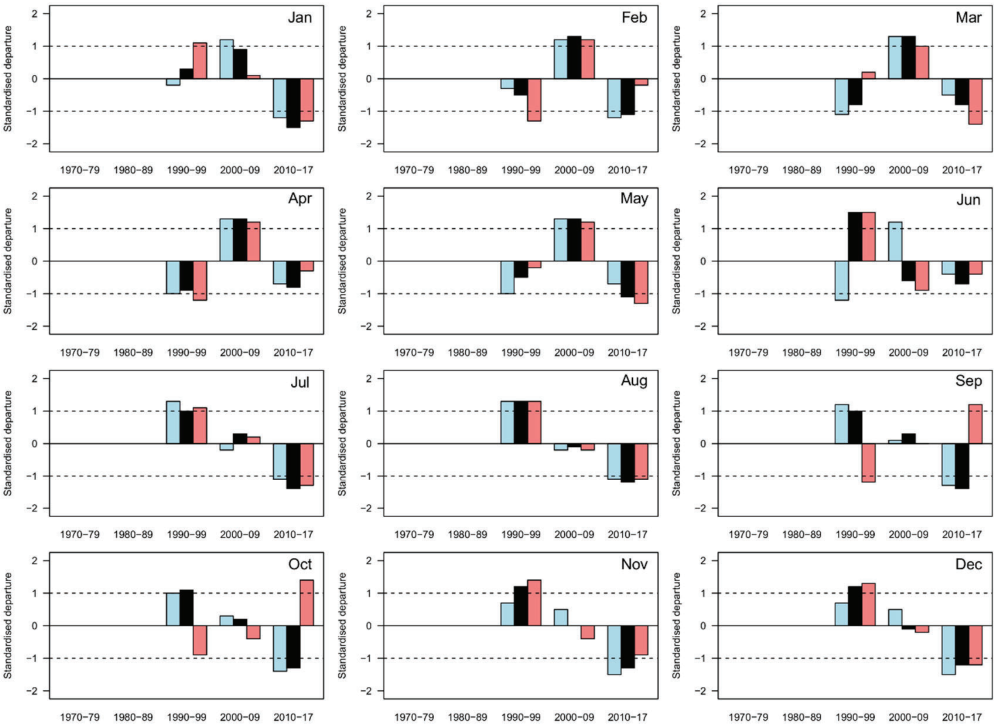

Figure 2 Monthly departure of minimum (light blue), average (black) and maximum discharge (light red) from upper Bagmati catchment

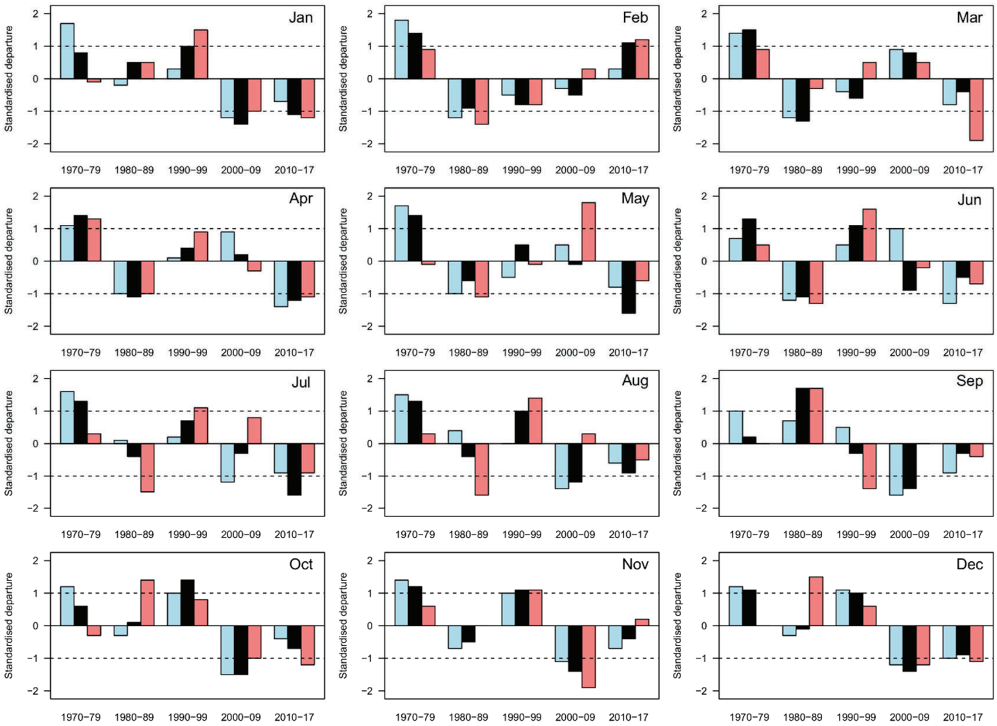

Figure 3 Monthly departure of minimum (light blue), average (black) and maximum discharge (light red) from entire Bagmati catchment

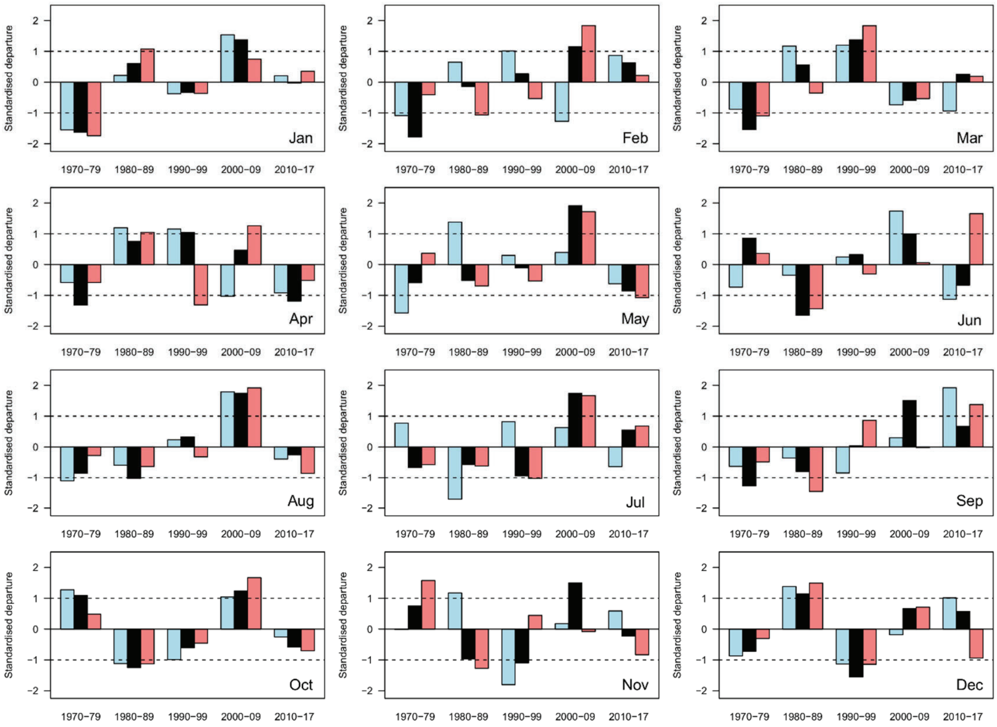

Figure 4 Monthly departure of minimum (light blue), average (black) and maximum discharge (light red) from Chepe sub-catchment

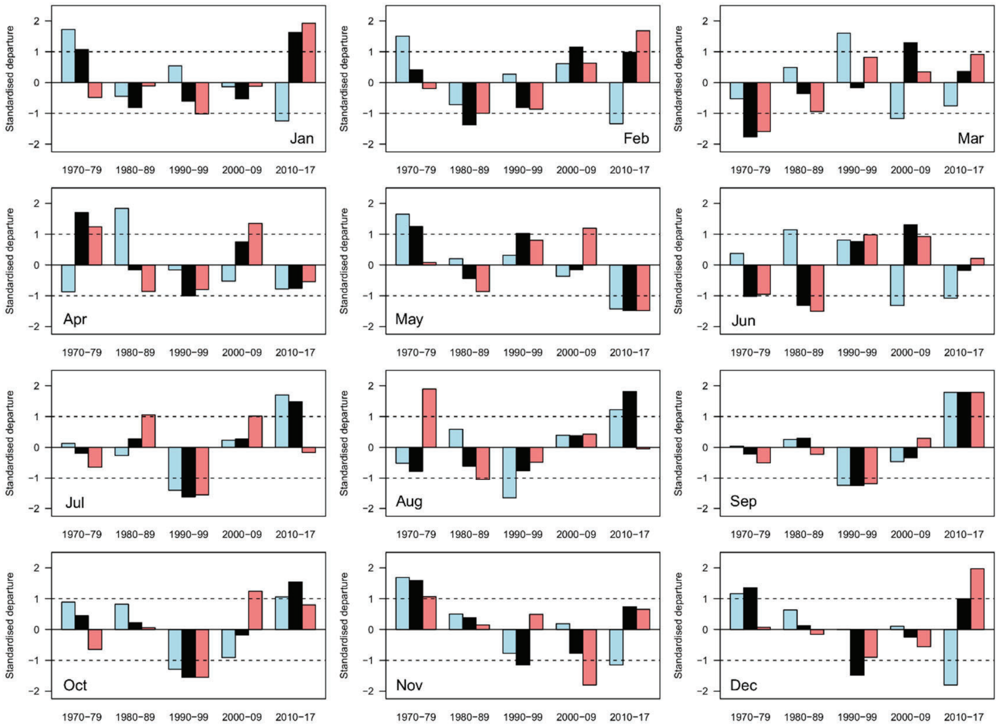

Figure 5 Monthly departure of minimum (light blue), average (black) and maximum discharge (light red) from entire Marsyangdi catchment

Table 1 Correlation of monthly precipitation with temperature and river discharge in Bagmati sub-catchments. Note: underlined r and *p* value represent moderately significant correlation (at 90% CI) and underlined bold values represent significant correlation (at 95% CI).

		Headwater		**Upper**		**Entire**	
	Month	**r**	***p***	**r**	***p***	**r**	***p***
Precipitation - T_{max}	Jan	0.13	0.39	-0.11	0.46	-0.29	0.10
	Feb	-0.18	0.23	-0.18	0.23	-0.28	0.12
	Mar	-0.23	0.12	**-0.45**	**0.00**	**-0.57**	**0.00**
	Apr	**-0.47**	**0.00**	**-0.66**	**0.00**	**-0.68**	**0.00**
	May	-0.04	0.79	-0.21	0.15	**-0.36**	**0.04**
	Jun	**-0.35**	**0.02**	**-0.50**	**0.00**	**-0.44**	**0.01**
	Jul	-0.19	0.20	**-0.42**	**0.00**	-0.34	0.05
	Aug	-0.07	0.65	-0.17	0.25	**-0.52**	**0.00**
	Sep	-0.14	0.34	**-0.42**	**0.00**	**-0.48**	**0.00**
	Oct	**-0.31**	**0.03**	**-0.36**	**0.01**	**-0.46**	**0.01**
	Nov	-0.26	0.08	-0.17	0.26	-0.07	0.69
	Dec	**-0.33**	**0.02**	**-0.37**	**0.01**	**-0.66**	**0.00**
Precipitation - T_{min}	Jan	0.20	0.18	0.11	0.45	-0.03	0.86
	Feb	-0.02	0.89	0.08	0.61	0.09	0.62
	Mar	-0.13	0.39	-0.12	0.43	-0.11	0.54
	Apr	-0.28	0.06	-0.28	0.05	-0.17	0.35
	May	0.27	0.07	0.25	0.09	0.16	0.36
	Jun	-0.01	0.94	0.07	0.65	-0.04	0.83
	Jul	-0.12	0.43	-0.28	0.06	**-0.37**	**0.03**
	Aug	0.05	0.76	0.05	0.76	0.00	1.00
	Sep	0.01	0.95	-0.19	0.21	-0.33	0.06
	Oct	-0.07	0.66	-0.05	0.73	0.06	0.73
	Nov	-0.04	0.78	-0.01	0.97	0.18	0.31
	Dec	0.01	0.92	-0.03	0.86	0.04	0.82
Precipitation - river discharge	Jan	**0.34**	**0.02**	**0.53**	**0.01**	**0.32**	**0.03**
	Feb	0.08	0.59	0.38	0.06	**0.41**	**0.00**
	Mar	-0.03	0.86	0.25	0.22	**0.38**	**0.01**
	Apr	0.11	0.44	**0.67**	**0.00**	**0.55**	**0.00**
	May	**0.34**	**0.02**	**0.71**	**0.00**	**0.46**	**0.00**
	Jun	**0.41**	**0.00**	**0.83**	**0.00**	**0.77**	**0.00**
	Jul	**0.38**	**0.01**	**0.76**	**0.00**	**0.80**	**0.00**
	Aug	0.04	0.81	**0.83**	**0.00**	**0.71**	**0.00**
	Sep	**0.32**	**0.03**	**0.76**	**0.00**	**0.62**	**0.00**
	Oct	0.26	0.08	0.13	0.53	**0.61**	**0.00**
	Nov	-0.15	0.33	0.34	0.10	0.00	0.98
	Dec	0.05	0.72	**0.60**	**0.00**	0.25	0.09

Table 2 Correlation of monthly temperature with river discharge in Bagmati sub-catchments. Note: underlined r and *p* value represent moderately significant correlation (at 90% CI) and underlined bold values represent significant correlation (at 95% CI).

		Headwater		**Upper**		**Entire**	
	Month	**r**	***p***	**r**	***p***	**r**	***p***
T_{max} – river discharge	Jan	0.00	1.00	-0.30	0.14	-0.32	0.07
	Feb	0.01	0.96	-0.16	0.44	-0.12	0.51
	Mar	-0.01	0.92	-0.12	0.57	**-0.45**	**0.01**
	Apr	-0.08	0.59	**-0.55**	**0.00**	**-0.56**	**0.00**
	May	0.01	0.96	**-0.43**	**0.03**	**-0.39**	**0.02**
	Jun	**-0.43**	**0.00**	**-0.55**	**0.00**	**-0.45**	**0.01**
	Jul	**-0.36**	**0.01**	-0.35	0.08	**-0.37**	**0.03**
	Aug	-0.26	0.07	**-0.63**	**0.00**	**-0.66**	**0.00**
	Sep	**-0.37**	**0.01**	**-0.47**	**0.02**	**-0.7**	**0.00**
	Oct	0.07	0.63	-0.27	0.18	**-0.47**	**0.01**
	Nov	-0.01	0.96	-0.07	0.75	0.00	0.99
	Dec	-0.07	0.65	**-0.44**	**0.03**	**-0.38**	**0.03**
T_{min} – river discharge	Jan	0.00	0.98	-0.22	0.28	-0.08	0.64
	Feb	0.10	0.51	-0.03	0.88	0.21	0.25
	Mar	0.12	0.41	-0.04	0.85	-0.11	0.54
	Apr	-0.21	0.16	**-0.42**	**0.03**	-0.31	0.08
	May	0.14	0.34	0.12	0.56	0.06	0.74
	Jun	-0.08	0.60	-0.02	0.93	-0.15	0.39
	Jul	-0.15	0.33	-0.26	0.2	-0.33	0.06
	Aug	-0.13	0.39	**-0.48**	**0.01**	-0.27	0.12
	Sep	-0.18	0.22	-0.06	0.76	**-0.72**	**0.00**
	Oct	0.13	0.39	0.11	0.60	-0.23	0.19
	Nov	-0.13	0.39	0.14	0.50	-0.06	0.74
	Dec	-0.07	0.63	-0.18	0.40	-0.27	0.12

Table 3 Correlation of monthly precipitation with temperature and river discharge in Marsyangdi sub-catchments. Note: underlined r and *p* value represent moderately significant correlation (at 90% CI) and underlined bold values represent significant correlation (at 95% CI).

		Chepe		**Upper**		**Entire**	
	Month	**r**	***p***	**r**	***p***	**r**	***p***
Precipitation - T_{max}	Jan	**-0.35**	**0.01**	**-0.53**	**0.00**	**-0.51**	**0.00**
	Feb	**-0.43**	**0.00**	**-0.48**	**0.00**	**-0.50**	**0.00**
	Mar	**-0.65**	**0.00**	**-0.56**	**0.00**	**-0.59**	**0.00**
	Apr	**-0.44**	**0.00**	-0.14	0.41	-0.16	0.32
	May	-0.19	0.20	**0.37**	**0.02**	**0.31**	**0.05**
	Jun	-0.26	0.07	0.03	0.85	-0.04	0.83
	Jul	**-0.37**	**0.01**	-0.21	0.20	-0.20	0.21
	Aug	-0.29	0.05	-0.02	0.90	-0.17	0.30
	Sep	0.10	0.49	-0.13	0.41	-0.22	0.17
	Oct	**-0.35**	**0.02**	-0.28	0.08	**-0.35**	**0.03**
	Nov	**-0.38**	**0.01**	-0.24	0.13	-0.27	0.09
	Dec	**-0.47**	**0.00**	**-0.42**	**0.01**	**-0.45**	**0.00**
Precipitation - T_{min}	Jan	0.03	0.86	0.17	0.29	0.14	0.38
	Feb	-0.26	0.07	**-0.41**	**0.01**	**-0.42**	**0.01**
	Mar	**-0.38**	**0.01**	**-0.47**	**0.00**	**-0.48**	**0.00**
	Apr	0.06	0.69	-0.17	0.31	-0.12	0.45
	May	0.15	0.31	**0.35**	**0.03**	**0.36**	**0.02**
	Jun	0.19	0.19	0.24	0.14	0.21	0.19
	Jul	-0.14	0.36	0.27	0.10	0.20	0.22
	Aug	0.19	0.19	**0.37**	**0.02**	0.25	0.12
	Sep	0.24	0.10	0.28	0.08	0.16	0.34
	Oct	-0.02	0.90	0.13	0.44	0.08	0.65
	Nov	0.14	0.35	-0.03	0.84	-0.01	0.96
	Dec	-0.20	0.17	-0.18	0.27	-0.20	0.22
Precipitation - river discharge	Jan	0.17	0.25	0.48	0.05	**0.31**	**0.04**
	Feb	0.10	0.49	**0.49**	**0.04**	0.02	0.90
	Mar	**0.67**	**0.00**	0.24	0.34	0.16	0.30
	Apr	**0.34**	**0.02**	0.10	0.70	0.01	0.95
	May	**0.45**	**0.00**	0.39	0.11	**0.47**	**0.00**
	Jun	**0.80**	**0.00**	**0.69**	**0.00**	**0.76**	**0.00**
	Jul	**0.51**	**0.00**	0.30	0.22	**0.61**	**0.00**
	Aug	**0.68**	**0.00**	0.36	0.14	**0.59**	**0.00**
	Sep	**0.55**	**0.00**	**0.66**	**0.00**	**0.57**	**0.00**
	Oct	**0.47**	**0.00**	0.16	0.52	**0.44**	**0.00**
	Nov	0.28	0.06	0.03	0.91	-0.01	0.97
	Dec	0.28	0.06	0.09	0.74	0.12	0.44

Table 4 Correlation of monthly temperature with river discharge in Marsyangdi sub-catchments. Note: underlined r and *p* value represent moderately significant correlation (at 90% CI) and underlined bold values represent significant correlation (at 95% CI).

		Chepe		**Upper**		**Entire**	
	Month	**r**	***p***	**r**	***p***	**r**	***p***
T_{max} – river discharge	Jan	-0.21	0.16	-0.18	0.50	0.08	0.63
	Feb	-0.04	0.80	-0.01	0.96	-0.05	0.77
	Mar	**-0.53**	**0.00**	0.30	0.23	-0.28	0.09
	Apr	**-0.39**	**0.01**	0.01	0.96	0.24	0.13
	May	-0.25	0.09	**0.57**	**0.01**	**0.51**	**0.00**
	Jun	**-0.44**	**0.00**	-0.36	0.14	-0.12	0.48
	Jul	-0.24	0.11	-0.20	0.42	**-0.39**	**0.01**
	Aug	**-0.36**	**0.01**	-0.27	0.28	**-0.51**	**0.00**
	Sep	-0.10	0.49	-0.31	0.21	-0.12	0.46
	Oct	-0.01	0.96	0.37	0.14	0.03	0.88
	Nov	0.09	0.54	0.27	0.28	0.17	0.30
	Dec	-0.14	0.36	-0.01	0.97	0.05	0.75
T_{min} – river discharge	Jan	**-0.42**	**0.00**	0.43	0.09	**0.43**	**0.01**
	Feb	-0.11	0.45	0.23	0.35	0.11	0.50
	Mar	**-0.44**	**0.00**	0.19	0.45	0.11	0.49
	Apr	-0.27	0.07	0.10	0.68	-0.02	0.89
	May	-0.05	0.73	**0.47**	**0.05**	0.25	0.12
	Jun	0.10	0.50	0.11	0.65	0.19	0.25
	Jul	-0.11	0.46	0.22	0.38	0.04	0.82
	Aug	-0.04	0.79	0.11	0.67	0.16	0.32
	Sep	0.00	0.98	0.08	0.77	0.09	0.59
	Oct	-0.13	0.39	0.34	0.17	0.10	0.55
	Nov	-0.10	0.48	0.39	0.11	0.05	0.76
	Dec	-0.23	0.12	0.21	0.40	0.24	0.14

Table 5. Correlation between precipitation and temperature below and above 2000 m elevation in Marsyangdi catchment. Note: underlined r and *p* value represent moderately significant correlation (at 90% CI) and underlined bold values represent significant correlation (at 95% CI).

		Above 2000 m		**Below 2000 m**	
	Month	**r**	***p***	**r**	***p***
Precipitation - T_{max}	Jan	**-0.52**	**0.00**	**-0.41**	**0.00**
	Feb	**-0.48**	**0.00**	**-0.42**	**0.00**
	Mar	**-0.55**	**0.00**	**-0.57**	**0.00**
	Apr	-0.11	0.48	**-0.57**	**0.00**
	May	**0.37**	**0.02**	**-0.37**	**0.01**
	Jun	0.04	0.82	**-0.43**	**0.00**
	Jul	-0.17	0.30	**-0.38**	**0.01**
	Aug	-0.06	0.69	-0.17	0.26
	Sep	-0.10	0.54	-0.15	0.31
	Oct	-0.28	0.08	**-0.31**	**0.03**
	Nov	-0.24	0.13	**-0.30**	**0.04**
	Dec	**-0.42**	**0.01**	**-0.32**	**0.03**
Precipitation - T_{min}	Jan	0.19	0.25	-0.14	0.34
	Feb	**-0.41**	**0.01**	-0.14	0.35
	Mar	**-0.46**	**0.00**	-0.21	0.15
	Apr	-0.16	0.33	-0.16	0.29
	May	**0.32**	**0.04**	0.22	0.13
	Jun	0.24	0.14	0.09	0.53
	Jul	0.28	0.08	-0.15	0.30
	Aug	**0.33**	**0.04**	0.05	0.72
	Sep	0.27	0.09	0.02	0.89
	Oct	0.13	0.43	-0.04	0.80
	Nov	-0.04	0.82	0.12	0.42
	Dec	-0.18	0.26	-0.02	0.92
T_{min} - T_{max}	Jan	0.28	0.09	**0.51**	**0.00**
	Feb	**0.74**	**0.00**	**0.75**	**0.00**
	Mar	**0.39**	**0.01**	**0.85**	**0.00**
	Apr	**0.41**	**0.01**	**0.69**	**0.00**
	May	0.21	0.20	**0.62**	**0.00**
	Jun	0.28	0.08	**0.46**	**0.00**
	Jul	**0.34**	**0.03**	**0.61**	**0.00**
	Aug	**0.34**	**0.03**	**0.55**	**0.00**
	Sep	**0.35**	**0.03**	**0.80**	**0.00**
	Oct	**0.45**	**0.00**	**0.67**	**0.00**
	Nov	0.24	0.13	0.28	0.05
	Dec	**0.33**	**0.04**	**0.62**	**0.00**

Table 6. Change in number of days without rain in Bagmati catchment. Note: underlined values indicate moderately significant trend (at 90% CI) and underlined bold values indicate significant trend (at 95% CI).

	Headwater Catchment			**Upper Catchment**			**Entire Catchment**		
	Intercept	**Slope**	***p***	**Intercept**	**Slope**	***p***	**Intercept**	**Slope**	***p***
Jan	26.29	0.03	0.27	26.23	0.03	0.34	26.00	0.00	0.87
Feb	22.50	0.00	0.69	21.00	0.00	0.57	20.69	-0.05	0.32
Mar	**24.60**	**-0.12**	**0.01**	**22.73**	**-0.13**	**0.01**	**23.50**	**-0.18**	**0.00**
Apr	13.00	0.00	0.87	13.50	0.00	0.73	14.11	-0.11	0.14
May	5.50	0.00	0.54	5.50	0.00	0.62	5.14	-0.06	0.11
Jun	1.00	0.00	0.85	1.00	0.00	0.32	**0.00**	**0.00**	**0.01**
Jul	0.00	0.00	0.73	0.00	0.00	0.52	0.00	0.00	1.00
Aug	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.02**	**0.00**	**0.00**	**0.01**
Sep	0.50	0.00	0.12	0.00	0.00	0.20	0.00	0.00	0.23
Oct	18.42	-0.08	0.15	16.74	-0.08	0.19	**15.67**	**-0.12**	**0.04**
Nov	28.00	0.00	0.30	26.53	0.03	0.19	26.50	0.00	0.49
Dec	29.00	0.00	0.17	28.50	0.00	0.24	28.00	0.00	0.57
Annual	172.14	-0.29	0.06	**168.83**	**-0.33**	**0.04**	**165.40**	**-0.63**	**0.00**

Table 7. Change in number of days without rain in Marsyangdi catchment. Note: underlined values indicate moderately significant trend (at 90% CI) and underlined bold values indicate significant trend (at 95% CI).

	Chepe Catchment			**Upper Catchment**			**Entire Catchment**		
	Intercept	**Slope**	***p***	**Intercept**	**Slope**	***p***	**Intercept**	**Slope**	***p***
Jan	18.42	0.03	0.58	16.00	0.00	0.99	15.50	0.00	0.87
Feb	14.60	-0.07	0.07	9.00	0.00	0.82	9.00	0.00	0.80
Mar	11.44	-0.13	0.11	**10.18**	**-0.13**	**0.02**	**10.09**	**-0.14**	**0.01**
Apr	**8.61**	**-0.10**	**0.03**	**6.06**	**-0.08**	**0.05**	**5.84**	**-0.08**	**0.03**
May	**4.96**	**-0.09**	**0.00**	**2.43**	**-0.05**	**0.00**	**2.31**	**-0.05**	**0.00**
Jun	0.00	0.00	0.13	0.00	0.00	0.07	0.00	0.00	0.06
Jul	0.00	0.00	0.15	0.00	0.00	0.15	0.00	0.00	0.15
Aug	0.00	0.00	0.11	0.00	0.00	0.16	0.00	0.00	0.16
Sep	**0.00**	**0.00**	**0.03**	0.00	0.00	0.05	0.00	0.00	0.06
Oct	13.00	0.00	0.58	12.29	-0.06	0.19	11.88	-0.06	0.17
Nov	22.85	0.08	0.13	18.20	0.11	0.08	18.45	0.10	0.07
Dec	26.26	0.00	0.98	22.62	0.01	0.94	22.09	0.02	0.87
Annual	109.49	0.09	0.63	101.37	-0.35	0.29	79.30	0.36	0.12