ASSESSMENT OF WATER AVAILABILITY AND RIVER HEALTH IN THE MARSHYANGDI WATERSHED, NEPAL

A THESIS SUBMITTED TO THE

CENTRAL DEPARTMENT OF ENVIRONMENTAL SCIENCE

INSTITUTE OF SCIENCE AND TECHNOLOGY

TRIBHUVAN UNIVERSITY

NEPAL

FOR THE AWARD OF

DOCTOR OF PHILOSOPHY

IN ENVIRONMENTAL SCIENCE

BY

REETA SINGH

AUGUST 2022

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DECLARATION

Thesis entitled **"Assessment of Water Availability and River Health in the Marshyangdi Watershed, Nepal"** is being submitted to the Central Department of Environmental Science, Institute of Science and Technology (IOST), Tribhuvan University, Nepal for the award of the degree of Doctor of Philosophy (Ph.D.) is a research work carried out by me under the supervision of Prof. Dr. Sadhana Pradhanang Kayastha, Central Department of Environmental Science, Tribhuvan University and co-supervised by Prof. Dr. Vishnu Prasad Pandey, Department of Civil Engineering, Institute of Engineering (IOE), Tribhuvan University, Nepal.

This research is original and has not been submitted earlier in part or full in this or any other form to any university or institute, here or elsewhere, for the award of any degree.

………………………………

Reeta Singh

RECOMMENDATION

This is to recommend that **Ms. Reeta Singh** has carried out research entitled **"Assessment of Water Availability and River Health in the Marshyangdi Watershed, Nepal"** for the award of Doctor of Philosophy (Ph.D.) in **Environmental Science** under our supervision. To our knowledge, this work has not been submitted for any other degree.

She has fulfilled all the requirements laid down by the Institute of Science and Technology (IOST), Tribhuvan University, Kirtipur for the submission of the thesis for the award of a Ph.D. degree.

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AUGUST 2022

LETTER OF APPROVAL

Date: 08/22/2022

On the recommendation of **Prof. Dr. Sadhana Pradhanang Kayastha** and **co-supervisor Dr. Vishnu Prasad Pandey,** this Ph.D. thesis was submitted by **Ms. Reeta Singh**, entitled **"Assessment of Water Availability and River Health in the Marshyangdi Watershed, Nepal"** is forwarded by Central Department Research Committee (CDRC) to the Dean, IOST, T.U.

……………………………………….

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Reeta Singh
August 2022

ABSTRACT

Understanding water availability is essential for water resource development and management, as well as devising river health interventions. Climate change/variability impacts the hydrology of a river system which subsequently affects human and ecological health by altering the structure and function of the aquatic ecosystem. This study, therefore, aims to assess water availability and river health under current and future climate scenarios in the Marshyangdi Watershed, central Nepal, which has a huge potential for water infrastructure development. The specific objectives are i) to assess historical trends in the climatic variables, ii) to project future climate, iii) to evaluate the impacts of projected changes (climatic) on streamflow, and iv) to assess river health under current and future climatic conditions.

Historical (1983-2013) and future (near-future: 2014-2033; mid-future: 2034-2053) trends in the climatic extremes were computed using RClimDex and hydrologic extremes using the Indicators of Hydrologic Alteration (IHA) tool. Bias-corrected projected future climate for the near and mid future under moderate (RCP 4.5) and pessimistic (RCP 8.5) scenarios was developed based on multiple regional climate models. Further, trends in extreme indices were estimated using the Mann-Kendall test and Sens's slope estimator. A hydrological model was set up in the Soil and Water Assessment Tool (SWAT). It was calibrated and validated at multiple hydrological stations. Simulated hydrological time series was used to assess water availability under current and future conditions. Similarly, river health conditions under current, as well as future scenarios, were evaluated based on a customized indicator-based framework.

The annual maximum temperature was observed with a significant increasing trend over the historical period at all the stations whereas temperature-related extremes showed both increasing and decreasing trends (e.g., warm spell duration index, warm days, and summer days are increasing whereas cold spell duration index, cool days, and warm nights are decreasing). Further, trends in precipitation extremes such as the number of heavy and very heavy precipitation days and maximum 1-day precipitation were decreasing along with the average annual precipitation amount in the entire watershed, indicating drier and hotter conditions over the historical period in the watershed.

The climate in the Marshyangdi Watershed was projected to be hotter and wetter in the future. Among the stations, maximum climatic variation was observed at the Chame Station (Index: 816), with average annual precipitation projected to increase by 10% under RCP8.5 for mid-future, and maximum temperature increase at the rate of 0.06^{o}C/year. Maximum temperature and temperature-related extreme indices (hot nights and warm days) have been projected to have an increasing trend for both scenarios. Similarly, average annual precipitation has been also projected to increase at all the stations in the future for both RCPs but further decreases in consecutive dry days at most stations indicate wetter conditions in the future.

Climate change is anticipated to increase hydrological alterations from low (in the current) to high (in the future) as revealed by the IHA tool. Annual average water availability increased, varying across seasons, and seasonal trends followed the annual trends. The average annual volume of water in the Marshyangdi Watershed was estimated to be 9,335 Million Cubic Meters (MCM), which will increase by 15% in the near future and 11% in the mid-future under RCP8.5 scenarios. Statistically, at a 5% level of significance, current river health showed moderate condition (67% of the sites) and it is projected to remain the same condition in the future, for both near and mid-future under both RCPs (4.5 and 8.5) scenarios but with varying degrees.

Keywords: Climate Change, Indicators of Hydrologic Alteration, Marshyangdi Watershed, River Health, SWAT

LIST OF ACRONYMS AND ABBREVIATIONS

95PPUs	Ninety-Five Percent Predictive Uncertainties
ACCESS	Australian Community Climate and Earth-System Simulator
AQEM	Integrated Assessment System for the Ecological Quality of Streams and Rivers throughout Europe using Benthic Macroinvertebrates
AR5	Fifth Assessment Report
ASSESS-HKH	Assessment System to Evaluate the Ecological Status of Rivers in the Hindu Kush-Himalaya
AUC	Area under Curve
BA	Baseline
BI	Biotic Index
BOD	Biological Oxygen Demand
CBS	Central Bureau of Statistics
CD	Coefficient of Dispersion
CC	Climate Change
CMIP	Coupled Model Inter-comparison Project
CNRM	Centre National De Recherche Meteorologiques
CPA	Change Point Analysis
COD	Chemical Oxygen Demand
DEM	Digital Elevation Model
DHM	Department of Hydrology and Meteorology
DO	Dissolved Oxygen
DOED	Department of Electricity Development
ETCCDI	Expert Team on Climate Change Detection and Indices
EPT	Ephemeroptera, Plecoptera, Trichoptera
FHA	Freshwater Health Index
FHI	Flow Health Index
GCM	Global Circulation Model
GON	Government of Nepal
GRS-Bios	Ganga River System Biotic Score
GHS	Greater Himalayan Sequence
HRU	Hydrological Response Unit

MAR	Mean Annual Runoff
masl	Mean Average Sea Level
MEWRE	Ministry of Water Resources and Energy
MF	Mid Future
MOFE	Ministry of Forests and Environment
MPI	Max Plank Institute Earth System Model at Base Resolution
NCVST	Nepal Climate Vulnerability Study Team
NF	Near Future
NEPBIOS	Nepalese Biotic Score
NPC	National Planning Commission
NSE	Nash–Sutcliffe Efficiency
OAT	One parameter at a time (OAT)
PBIAS	Percentage Bias
Pre-CP	Pre-Impact
Post-CP	Post-Impact
RBPs	Rapid Bioassessment Protocols
RCP	Representative Concentration Pathways
RHA	River Health Assessment
RHI	River Health Index
RIVPACS	River Invertebrate Prediction and Classification System
RVA	Range of Variability Approach
SDM	Species Distribution Model
SDG	Sustainable Development Goals
SOTER	Soil Terrain Database Programme
SRTM	Shuttle Radar Topography Mission
SWAT	Soil and Water Assessment Tool
THS	Tethyan Himalayan Sequence
USEPA	United States Environmental Protection Agency
UNESCO	United Nations Educational Scientific and Cultural Organization
WECS	Water and Energy Commission Secretariat
WFD	Water Framework Directive
WQI	Water Quality Index
WMO	World Meteorological Organization

LIST OF SYMBOLS

%	Percentage
mm	Millimeter
r	Correlation coefficient
R^2	Coefficient of determination
SNOcov	Daily melt factor (mm day-1°C-1)
SNOi	Water content (mm) on day i
SNOmlt	Daily snowmelt amount (mm)
SWo	Initial soil water content
SWt	Final soil water content (mm)
Tmax	Daily maximum air temperature (°C)
Tmin	Daily minimum temperature (°C)
Tsno	Daily snowpack temperature (°C)
Wseep	Amount of water entering the vadose zone from soil profile on day

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CHAPTER 1
INTRODUCTION

1.1 Background

Freshwater resources are essential for ecological sustainability and socio-economic development in river basins (Wang *et al.,* 2021). Healthy rivers are the basis of life. A river is generally considered healthy if it can resist disturbances and have a higher resilient capacity to the natural and anthropogenic stressors, thereby providing sustainable ecological services to the society. River health includes two aspects i) the river's physical state including biota, water quality, and availability, and ii) river social service functions that support societal needs and livelihood (Huaibin & Jianping, 2014; Pinto & Maheshwari, 2014). However, in today's industrialized world, river systems have lost their natural integrity. Globally, river ecosystems are widely considered for their conservation due to various services provided by them (drinking, agriculture, and industry, sustenance of biodiversity, electricity generation, transportation, and recreational activities) (Leigh *et al.,* 2012). Climate-induced changes in hydrology, when combined with human activities, alter spatial-temporal variability in river hydrology affecting water availability (Haddleland *et al.,* 2014; Knouft & Ficklin, 2017; Konapala *et al.,* 2020; Oki & Kanae, 2006).

Understanding how climate change affects water resources is essential because it translates how it affects other related sectors (Stahl *et al.,* 2010). It is impacted by changes in precipitation and temperature, thus affecting water quality, and flow patterns (WECS, 2011). CC may result change in the quality of water resources (Delpla et al. 2009, Wang et al. 2015), which may ultimately impact adversely to the river health.

Thus, water availability on earth needs to be documented (measured and simulated) on finer temporal and spatial scales to ensure its availability for various instream (hydropower, recreational, fisheries) and outstream uses (irrigation, domestic, municipal, industrial). Several studies have determined climate uncertainty impacts on water availability at global, regional, and local scales (Abbaspour *et al.,* 2009; Aryal *et al.,* 2018; Pandey *et al.,* 2019; Shea *et al.,* 2014).

Hydrological models are important in determining the availability of water resources considering a change in climate with realistic estimates of water output and availability in a basin, as well as understanding its implications (Mapes & Pricope, 2020; Thapa *et al.*, 2017; Zhu & Ringler, 2012). They are useful for effective watershed planning, especially with widely available high spatial and temporal resolution data, because they are quick and inexpensive compared to obtaining physical measurements consisting of large spatial and temporal hydrologic processes (Mapes & Pricope, 2020; Ndomba *et al.*, 2008).

Climate change (CC) is the result of changes in climatic conditions that modify the composition of the atmosphere. It is accelerating at an alarming rate around the world, with significant implications for water availability and quality (IPCC, 2007; IPCC, 2014). Climate change alters river discharge due to the changes in annual runoff and, seasonal and interannual runoff regimes resulting significant impact on water resources (IPCC, 2014; Shrestha *et al.*, 2016b). Thus, CC also induces extreme weather events which cause a significant negative impact on society and creates challe nges in coping with a changing climate (CCSP, 2008; WMO, 2020). Extreme climatic phenomena such as heat waves, hot days, floods, droughts, and a decline in the number of colder days are predicted to exacerbate in the coming decades due to high unpredictability in hydrological and climatic events (IPCC, 2013; Perkins *et al.*, 2012). This will pose major challenges to agriculture production, biological resources, and ecosystem services (Shrestha *et al.*, 2017). A warmer temperature condition brings greater precipitation around the globe, including in Nepal. The majority of the models predict a wet and warm future (2040–2059), with temperatures ranging from 2 to 3ºC (Agrawala *et al.*,2003; MoFE, 2019). For instance, Baidya et al. (2008) detected an increase in temperature and precipitation patterns across Nepal. The findings suggest that a substantial number of weather-related extreme occurrences will occur in the future. Similarly, an increasing temperature trend and high variability in precipitation indices were observed at upper catchment areas of the Kali Gandaki River Basin at higher altitudes (Manandhar *et al.*, 2012). Such an increase in trend was also observed in the climatic extreme in recent years (Bastakoti *et al.*, 2016). Shrestha et al. (2017) determined rising patterns of extreme climate patterns and occurrences in the Koshi River Watershed, but no long-term change in rainfall patterns. The Chamelia Watershed of the Mahakali River Basin in western Nepal is likewise projecting a warmer and wetter future (Pandey *et al.*, 2019).

Thus, understanding historical climate and projecting future scenarios in climatic variables, in terms of magnitude, trend, and significance, is important for planning climate-resilient development. Furthermore, understanding the hydrologic effects of projected climate change is vital (Devkota & Gyawali, 2015) to ensure irreversible consequences for people, species, and ecosystems, as well as sustainable water resource use and management, ensuring human security and river health (IPCC, 2013).

1.2 Rationale

Water is one of the principle natural resources that support the economy of our country. But due to the ongoing changes in climate the country's water sector is witnessing as one of the most affected sectors (WECS, 2011). Climate change scenario for Nepal shows a continuous warming trend with average mean temperature increase of 1.2°C and 3°C by 2050 and 2100 respectively. The IPCC's Fifth Assessment Report reveal that temperatures are rising and in most South Asian countries, they will continue to rise (IPCC, 2013; Shrestha *et al.*, 2021) thus increasing the water demand and reducing the country's adaptive capability causing an additional challenge. As, the water resources are inextricably linked with climate, climate change challenges the existing water resources management practices by adding an additional uncertainty causing serious implications on them (Bates *et al.*, 2008). Therefore, it is undeniable that climate change will cause the negative impacts on freshwater systems by altering the river flow regimes (Doll and Zhang, 2010). As water availability and accessibility are necessary for maintaining a healthy ecosystem (Eum *et al.*, 2016) and for human and socio-economic development hence, projecting climate will aid in developing, managing, and protecting this resource which is critical to the country's economic future.

Further for the proper management of water resources and to adequately evaluate its impacts, hydrological modeling of river basins is essential which provides a framework to investigate these relationships (Leavesley, 1994). The imbalance between the availability of water resources and demand due to climate anomalies is currently exacerbated and could become worse in the future. In addition, there exist several gaps in knowledge in terms of observations, and research needs concerning the projection of climate on water availability, quality, and flow patterns (WECS, 2011) which affects ecological integrity of a healthy ecosystems. For sustainable management of freshwater resources both the "quantity" (availability) and "quality" (river health) of water need to be quantified (Moog *et al.*, 2018). Such assessment will help to improve environmental aspects, thus supporting aquatic species and maintaining the water quality. Studies on the implications of climatic variability on river health are few thus urgently required (Zhao *et al.*, 2018) and are crucial for Himalayan snow-fed rivers (Viviroli *et al.*, 2007; Immerzeel *et al.*, 2013). This study, therefore, attempts to fulfill the gap by assessing the impact of climate change on river health and water resources availability using various multimodels and tools in as snow-fed-Himalayan River Marshyangdi. This watershed has at least 3,251.8 MW capacity for electricity yield (Jha, 2010). Three hydroelectric schemes currently in operation are 50 MW Upper MarshyangdiA,70 MW Middle Marshyangdi, and 69 MW Marshyangdi, and other 47 hydropower projects are in the various phases of operation in the watershed (DOED, 2020). Hence, assessing and preserving these Himalayan rivers, where the rate of warming is rapid, about three folds higher than the global average (Kulkarni *et al.*, 2013; Shrestha & Aryal, 2011), is a prerequisite for sustaining regional biodiversity and livelihood downstream (Khadka & Pathak, 2016).

1.3 Objectives

The general objective of this study is to assess water availability and river health under current and the future climatic scenarios in the Marshyangdi Watershed, Nepal.

The specific objectives are:

- To assess historical trends in climatic variables.
- To project future climate scenarios in the study area.
- To evaluate the impacts of projected changes (climatic) on streamflow.
- To assess river health under current and future conditions.

1.4 Limitations

This research has been carried out with the following limitations:

- The uncertainties associated with the selection of climate models and scenarios is due to the data and model-related limitations.
- Other confounding factors affecting river health like urbanization, landuse, population growth etc. are not considered in this study.
- Habitat assessment have been kept constant for predicting future river health
- Analysis of biological condition for current and future scenarios is based on identification of macroinvertebrates up to family level only.

CHAPTER 2
LITERATURE REVIEW

2.1 Historical and Future Climatic Trends in Nepal and its Implications

Gradual increase in temperature is evident at both global and regional context causing a significant impact on cryospheric processes and the hydrology of headwater catchments in the Himalayas (Cruz *et al.,* 2009; Immerzeel *et al.,* 2009).

In Nepal, based on observations of temperature from 1977-to 1994 shows a general warming trend of 0.06°C (Shrestha *et al.*, 1999). Such increasing trends in temperature have been reported by other researchers also at different periods of different magnitudes (APN, 2005; Baidya *et al.*, 2008; CDKN, 2016; Marahatta *et al.*, 2009; WWF, 2005). Temperature increases were found to be significantly higher at higher elevations in the northern half of the country compared to lower elevations in the southern part of the country (Agrawala *et al.,* 2003; Baidya *et al.,* 2008; Marahatta *et al.,* 2009). In annual and seasonal maximum temperatures positive trends are observed (0.056°C/year) and similar trend was observed in annual minimum temperature (0.002°C/year),but seasonal positive annual trend in minimum temperature was observed only in monsoon season. However, no significant trend has been observed in precipitation in any season (DHM, 2017).

In this context projection of climate is becoming important in all sectors which deal with weather, water, and climate as the concerns related to climate change implications are increasing (Persson *et al.,* 2007). Both maximum and minimum temperatures in South and Southeast Asian River basins would be around 1°C higher at the end of the century under the higher greenhouse gas (GHG) concentration emission scenario (RCP 8.5) than under the lower GHG concentration emission scenario (RCP4.5) (Shrestha *et al.,* 2021). According to Knutti & Sedlácek (2013), the global average temperature will rise by more than 1°C in a low-emission scenario and more than 4°C in a worstcase scenario. Climate models also predict increased precipitation variability in most regions due to global warming (Sun *et al.,* 2012).

The findings for Nepal, based on dozens of general circulation models (GCMs) reveal a considerable and consistent increase in projected temperatures among all the climate models for the years 2030, 2050, and 2100. Various models agreed on a consistent warming trend with a mean temperature rising by 1.2°C and 3°C, respectively in 2050 and 2100 (Agrawala *et al.*, 2003). In another study, Global Climate Models (GCMs) projected that country would become hotter, with more frequent heatwaves and less frost, with mean temperatures rising by 0.5 to 2.0ºC by 2030 and 1.7ºC to 4.5ºC by 2060 (NCVST, 2009).

However, while models predict an overall increase in annual precipitation, Nepal's anticipated mean annual precipitation shows no obvious trend in terms of both increases and decreases (NCVST, 2009). Recent studies have shown a likely increase in average annual mean temperature by 0.9–1.1^{o}C and 1.3–1.8^{o}C in the medium-term period and long-term periods, respectively. On the other side, with rising precipitation patterns, average annual precipitation is expected to rise by 2–6% in the medium term and by 8–12% in the long run (MOFE, 2019). In Nepal's Koshi Basin, the majority of GCMs (25 ensembles) predicted an increase in precipitation for all future periods (Agrawal *et al.*, 2014).

The projected future warmer and drier climate could have a wide range of impacts, especially at higher altitudes thus affecting water quality and supply (Clark *et al.*, 2010; Whitehead *et al.*, 2009). Due to increases in annual as well as the projected trend of climate change riverine ecosystem would be adversely affected. The situation is particularly serious for Himalayan snow-fed rivers, which are prone to be easily impacted by glacier melt dynamics, with flow controlled in a major part by glacier and snowmelt respectively (Bajracharya *et al.*, 2018; Lutz *et al.*, 2014; Viviroli *et al.*, 2007). Shrestha et al. (2021) also stated that the presence of glacier lakes in the Himalayan basins of South Asia could have a significant impact, resulting in Glacier Lake Outburst Floods (GLOFs). Due to an increase in snow and glacier melt, rising temperatures have a significant impact on river discharge in glacierized basins (Bhattarai & Regmi, 2015). According to Khadka and Pathak (2016), the Marshyangdi Watershed is at risk of geo-disaster due to projected temperature and precipitation increases under three RCP scenarios (2.5, 6.5, and Coupled Model Inter-comparison Project 8.5

The degree of fluctuation and uncertainty in the climate change process is measured by climatic variability (Pelletier & Turcotte, 1999) which triggers the climatic extreme events. A changing climate alters the frequency, severity, spatial extent, length, and timing of severe events which occur concurrently with other more severe events (Seneviratne *et al.*, 2012). Even if human-caused climate change did not exist, there would be an occurrence of a broad range of natural weather and climatic extreme (Sen eviratne *et al.*, 2012). Extreme weather events are rare stochastic events that happen as a result of climate change and are classified as (a) simple climate statistics extremes, such as extremely cold or extremely hot temperatures; (b) more complex event-driven extremes, such as droughts and floods, which don't always happen every year in a given location (Hales *et al.*, 2003). Extreme weather events have significant impacts on soci eties, ecosystems, and environments (Moberg & Jones 2005; Toreti & Desiato, 2008).

Depending on the degree of temperature rise, unprecedented and frequent heat extremes, reduction in crop production, and water availability are prevalent in South Asia (World Bank, 2012). On a global scale heat, waves are projected to grow in many (but not all) places, whereas abnormally cold days and nights are expected to diminish on a worldwide scale (Seneviratne *et al.*, 2012). Simultaneously, cool days and cool nights are decreasing in the South Asian Association for Regional Cooperation (SARRC) region, while warm days and warm nights are expected to increase (Islam *et al.*, 2009).

In Nepal, climate change is projected to increase the frequency of extreme rainfall intensities and the unpredictability of rainfall patterns. In addition, the possibility of prolonged dry periods, mass and volume of glaciers loss, and temperature rise are also expected from its uncertainties. In Nepal, such declining patterns in cool days and cool nights have been observed predicting that Nepal's climate would become much warmer and wetter in the future (MoFE, 2019). Such climate patterns are predicted with a significant impact on water supplies and agriculture-dependent livelihoods across the country (ADB, 2010; Devkota, 2014; Shrestha *et al.*, 2016a).

In Nepal extremely hot days are expected to rise by 55 percent by the 2060s and 70 percent by the 2090s, based on GCM predictions concerning the baseline period of 1970-1999. Similarly, extremely hot nights during the same period are estimated to rise to 77% and 93% in the 2060 and 2090s, respectively (NCVST, 2009). A general increasing trend has been observed in the temperature extremes of Nepal with increasing trends in warm days and nights but with less frequency of cool days and cool nights (Baidya *et al.*, 2008). For the precipitation extremes, it has been observed an increasing trend in total and heavy precipitation events at many places. Similarly, Karki *et al*. (2017) also reported an extension of dry spells due to significant positive increases in the consecutive dry day (CDD) and significant negative patterns in the number of wet (rainy) days across the nation. According to MOFE (2019), the frequency of heavy precipitation events will increase while the number of wet days will decrease, resulting in increased water-related hazards in the future. Furthermore, different precipitation extreme indices intensified over different sections of the country reflect the flood, landslide, and drought hazards (Karki *et al.,* 2017).

2.1.1 Global Climate Models

Climate models are a simple representation of a complex world that use information from multiple disciplines such as atmospheric science, geology, biochemistry, and ecology (Stocker, 2011). There are many climate models developed to date amongst them, Global Climate Model is a mathematical model that uses a mathematical equation of atmosphere, ocean, and sea to explain the global earth's climate and forecast the future concerning temperature, precipitation, air pressure, and wind speed (IPCC, 2013). Global climate models project a wide range of climate change indicators, reflecting that the models' uncertainty adds to the overall uncertainty while evaluating climate change implications (Chen *et al.,* 2017). There are different kinds of GCMs and each of them has its strategy and scheme suitable to conduct climate change assessments for different purposes (Viner, 998). However, due to poor resolution, the predictions have not been able to accurately represent the larger spatial scale climate scenarios at different scales. Hence downscaling techniques allow getting variables in smaller scales from larger spatial scales (Brekke *et al.,* 2009). The downscaling can be performed using statistical and dynamic downscaling using different regression predictions, artificial neural network approaches, regional climate models, and analog procedures. Downscaling procedures are also usually utilized to correlate the coarse-resolution outputs with finer-scale catchment scales on climate impact studies and hydrological simulations and empirical linkages between observed large-scale atmospheric parameters obtain from observation and predicted analyzed variables. Regional climate models (RCMs) perform the dynamic downscaling procedure and are better at simulation and prediction of extreme and predicting extreme climatic events. For example, changes in extreme weather, such as significant rainfall occurrences, are predicted to have a greater impact compared to temporal (annual or seasonal) means. RCMs are far better at simulating extremes than GCMs in such circumstances. Several researchers have used RCMs in climate projection and impacts of climate change studies (Bhattarai *et al.,* 2018; Fang *et al.,* 2015; Kulkarni *et al.,* 2013; Khadka *et al.,* 2016; Pandey *et al.,* 2019).

2.1.2 Bias correction

Following downscaling, appropriate bias correction techniques were performed to minimize the mismatch of scale in the downscaled data. Generally, bias correction can be done by either transformation or non-transformation methods. A statistical function removes biases in the transformation approach, whereas in the non-transformation technique, biases are calculated openly and the model is rectified by changing those biases. Some of the transformation methods are the power transformation method, quantile mapping, and regression and mean bias removal, and multiplicative shift. Local intensity scaling is categorized under the non-transformation method. The advantages and disadvantages of the bias correction method (Table 2.1).

Table 2.1: Summary of bias correction methods

Method	Variable	Advantage /Disadvantage
Linear scaling	Precipitation Temperature	+ corrects mean + variability of corrected data is more consistent with actual data - standard deviation, wet day frequencies, and intensities are not corrected - same correction factor is used for all the events
Delta-change	Precipitation Temperature	+ corrects mean - standard deviation wet day frequencies, & intensities are not corrected - all events change by the same amount
Quantile mapping	Precipitation Temperature	+ corrects mean + corrects standard deviation, wet day frequencies, and intensities + events adjusted non-linearly + variability of corrected data is more consistent with actual data
Power transformation	Precipitation	+ corrects mean and standard deviation + events adjusted non-linearly + variability of corrected data is more consistent with actual data - cannot completely adjust wet-day frequencies and intensities
Variance scaling	Temperature	+ corrects mean and standard deviation + variability of corrected data is more consistent with actual data - same correction factor is used for all the events
Local intensity scaling	Precipitation	+ corrects mean, wet-day frequencies, and intensities + variability of corrected data is more consistent with actual data - standard deviation is not corrected - same correction factor is used for all the events

Source: Teutschbein & Seibert, (2013)

2.1.3 Climate scenarios

Estimating future greenhouse gas concentrations provides a wide understanding of the climate and its impact on future climate change. The Representative Concentration Pathways (RCPs) are based on Integrated Assessment Modelling, which uses a variety of climate models to estimate the implications of climatic systems. The radiative forcing is the four greenhouse gas concentration trajectories, not the emission scenario (Moss *et al.,* 2010).

The climate change scenarios which include the future emission and concentration of GHGs and other factors that bring a change in the climate are quite important for climate change projection (IPCC, 2013). The RCPs were chosen primarily for their emissions, as well as the outcomes of their related concentration and net radiative forcing, which all represent the cumulative estimate of human GHG emissions from all sources in Watts per square (IPCC, 2014). The majority of Nepalese literature has indicated that the medium (RCP4.5) and high (RCP8.5) RCP scenarios elucidate more information for climate projections (Babel *et al.,* 2014; Bajracharya *et al.,* 2018). RCP4.5 scenarios define a climate stability path to 4.5 W/m^2 without overshoot, whereas RCP8.5 scenarios define a rising radiative forcing pathway to 8.5 W/m^2 by 2100 (Moss *et al.,* 2010).

2.2 Water Resources Availability and River Health

As freshwater resources are limited on the surface of the earth, it is essential to check and quantify water resources to assure an aquatic environment has adequate water to function effectively. More importantly for the development of various infrastructures e.g., hydropower, accurate and timely prediction of the streamflow is essential. Nepal stands good position in freshwater resource availability, with mean water availability of about 225 billion m^3 per annum (BCM) (WECS, 2011). Even though only roughly 15 BCM per year of water is now utilized, this represents a massive capacity resource for hydroelectric generation, irrigating agriculture lands, residential water supply, and industrial purposes. A substantial amount of water is accessible in the aquifers, estimated to be 8.8 BCM annually (WECS, 2011), which might be managed to meet the need for irrigation purposes and domestic supply of water.

Climate change is altering the natural runoff of watersheds in various parts of the world (Haddleland *et al.,* 2014; Milly *et al.,* 2008) due to changes in seasonal and annual mean precipitation and evaporation thus influencing water availability and impacting society and the ecosystem (Konapala *et al.,* 2020). Water availability is also affected due to the glacier retreat process induced by climate change (Wang *et al.,* 2021). As a result, determining the availability of water in a hydrologic system is crucial for controlling and maintaining healthy ecological and socioeconomic circumstances (Eum *et al.*, 2016). Furthermore, projecting future water supply is necessary for long-term water resource planning (Bajracharya *et al.*, 2018; Najafi *et al.*, 2012; Wagener *et al.*, 2010). The ecosystem's health will be critical for socio-economic and human growth when there is insufficient quantity and quality of water (UNESCO-WWAP, 2015). Similarly, Palmer et al. (2009) stated that climate change could exacerbate already existing hazards, disrupting biological communities with strong ecological links. Although various studies on river health have been conducted, there have been few studies on the implications of climate change on river health, which are urgently needed (Battin *et al.*, 2016; Zhao *et al.*, 2018).

2.2.1 Hydrological models for study of impact of climate change

Climate change impacts hydrologic processes and sub-surface water level, water quality, and streamflow due to variations in precipitation, evaporation, and soil moisture content.

Thus, hydrologic models are important tools for hydrologists and planners to plan for sustainable development of the water resources systems as they can inform water management decisions addressing several societal demands, e.g., effects of altered land use, the impact of climate change, protection of riverine ecology (Reed *et al.*, 2006; Seibert & van Meerveld, 2016). Various hydrological tools have been used around the world to better understand flow dynamics, runoff generation, and water resource management, for example, the Variable Infiltration Capacity model (VIC) (Eum *et al.*, 2016; Liang, 1994; Nijssen *et al.*, 1997), the Hydrological Simulation Program-FORTRAN (HSPF) (Bicknell *et al.*, 1997; Johanson *et al.*, 1980), Cold Regions Hydrological Model Platform (CRHM) (Pomeroy *et al.*, 2007; Zhou *et al.*, 2011), DeNitrification DeComposition DayCet (DNDC) and the Pasture Simulation model (PaSim) (Wang *et al.*, 2021), Soil Water Assessment Tool (SWAT) (Arnold *et al.*, 1998, 2012), Snowmelt runoff model (SRM), SPHY, GR4, TOPMODEL (Beven & Freer, 2001), HBV (Bhatta *et al.*, 2019; Lindström *et al.*, 1997; Remondi, 2018), etc. These models are distributed or semi-distributed, accounting for structural and spatial changes, stochasticity or spatial-temporal applications in all variables and parameters, and have been widely employed for optimal water resource management and planning, minimizing any negative impact on the ecosystem (Pechlivanidis *et al.,* 2011; Singh *et al.,* 2002; Wang *et al.,* 2021).

i. Metric (Empirical) Models

The major features of this model are that it is mainly empirical, defining the system response from available data based on inputs and outputs without considering the physical hydrological processes causing changes (Bourdin *et al.,* 2012; Wheater *et al.,* 1993). The empirical models consist of statistical and soft computing methods. The statistical methods comprise time series Box-Jenkins's models and regressions. Similarly, computing methods usually work following the principles of Artificial Neural Networks (ANN) (Dawson *et al.,* 2006; Jain *et al.,* 2004; Lange, 1999) and Data-Based Mechanistic (DBM) modeling (Ratto *et al.,* 2007; Young, 2003). Sherman introduced the unit hydrograph (UH) theory as the first metric model (1932). However, data-driven empirical hydrological models, on the other hand, have the drawback of being only relevant under the same conditions as when they were first built (Bourdin *et al.,* 2012).

ii. Conceptual Models

Conceptual models are simple models that contain physical processes and data not available in the empirical systems. It is achieved by using semi-empirical rules to simplify the mathematical representation of individual physical processes. Though they are simple they are not inferior to physical models due to their computational speed and robustness. Wheater et al. (1993), define conceptual models as those that meet two criteria: first, describing the model's structure before the beginning of any model, and second, all parameters of models cannot be physically interpreted.

The Stanford Watershed Model (SWM), the first conceptual model, replicates the entire hydrological cycle (Crawford & Linsley, 1966). The SWM evolved greatly since its inception and simulates a wide continuum of hydrological processes (Brun & Band, 2000).

iii. Physics-Based Models

In these models, the hydrological phenomenon (like evapotranspiration, overflow) is represented by governing equations of motion. Physics-based models, in theory, can provide a continuous runoff response for simulated data without the requirement for calibration, allowing for a powerful compilation of major idealized processes (Beven, 2001). The physics underlying this model structure is mainly based on research in lab or small-scale in-situ field experiments, therefore the nature of study influences these models, for example, ParFlow (Maxwell *et al.*, 2016), Modflow (Harbaugh *et al.*, 2000), and HydroGeoSphere (Harbaugh *et al.*, 2000) (Aquanty, 2016).

iv. Hybrid Models

Hybrid models are created to integrate the benefits of both data-driven and conceptual models. They are usually included as a rudimentary routing component and simple conceptual loss functions (e.g., soil moisture monitoring program to provide effective rainfall). Hybrid models use metric models' unique parameterization and can characterize observational data in statistical terms, as well as other previous knowledge, to validate assumptions regarding the structure of component hydrological stores (Pechlivanidis *et al.*, 2011) for example, SWAT (Arnold *et al.*, 1993). Other classification systems given by (Pechlivanidis *et al.*, 2011; Wheater *et al.*, 1993) are also widely used.

v. Lumped and Distributed Models

In this model, the watershed is taken as a unified entity, with model parameters describing the average across the watershed (Beven, 2001). A lumped model is a set of differential or experimental algebraic equations that ignores the catchment system's spatial variability processes, inputs, boundary conditions, or geometric aspects of the catchment (Singh, 1995). Distributed models on the other hand provide projections that spread in space, with state variables that reflect local averages by discretizing the watershed into numerous components and solving the governing equations for the model parameters which are related to each element (Beven, 2001; Singh & Frevert, 2006). Distributed models can account for some spatial heterogeneity in processes, inputs, boundary conditions, and watershed characteristics to some extent.

Similarly, semi-distributed models, on the other hand, are intermediate complex models that depict geographical variability by employing a set of lumped models to discretize a watershed into sub-units (Bourdin *et al.,* 2012). The watershed is divided into small sub-watersheds, elevation bands, or hydrologically homogenous units. The division helps to eliminate the requirement for average parameter values across spatially heterogeneous areas, which requires less information and computational work compared to completely scattered approaches (Orellana *et al.,* 2008). These models take into account the height of the watershed which is critical in determining runoff in mountainous areas. Bergstrom (1976) and Moore (1993) introduced the Hydrologiska Byrans Vattenbalansavdelning (HBV) model and its derivatives.

vi. Deterministic and Stochastic Models

Deterministic models' outputs are determined by known correlations between states and data. These models generate a single output from a simulation using a single set of input data and parameter variables, and if the parameter values are kept constant, a given input will always yield the same output (Pechlivanidis *et al.,* 2011). It is also known as the process-based model because the conservations of mass, momentum, and energy are reflected as a sequence of partial differential equations or water budget balances (Chen *et al.,* 2021; Singh *et al.,* 2002). Stochastic models are created by selecting input parameters based on statistical regressions of monitoring or experimental data represented by statistical distributions.

vii. Time Scale-based Classification

Rainfall-runoff models are of two types namely continuous simulation models and event-based models. Continuous simulations often consider a time series of rainfall, which may include multiple storm events, whereas event-based models consider only one storm event.

viii. Space Scale-based Classification

This classification, rather than conceptual, is arbitrary. It assumes homogeneity on scales at which processes are reliably averaged (Wagener *et al.,* 2007; Young *et al.,* 2006). The Soil and Water Assessment Tool (SWAT) is related to the study of watersheds and integrated management of water resources to predict basin hydrology under various conditions of climatic extremities (Arnold *et al.*, 2012; Gassman *et al.*, 2007; Mishra *et al.*,2018; Tamm *et al.*,2016). SWAT is a semi-distributed model that uses process-based equations to simulate various hydrologic processes. It is most popular in the public domain due to its low cost and ease of setup (Jain *et al.*, 2017). Similarly, in Nepal, (Bharati *et al.*, 2014, 2016; Dahal *et al*., 2016; Mishra *et al.*, 2018; Marahatta *et al.*, 2021; Pandey *et al.*, 2018, 2019; Shrestha *et al.* (2017) used this conventional approach for watersheds of various spatial scales to assess the impacts of climate change on streamflow.

The SWAT model divides each sub-basin up to 10 elevation zones by accounting for the orographic impacts on precipitation, temperature, and solar radiation (Neitsch *et al.*, 2001). Each elevation zone's snow accumulation, sublimation, and melt are calculated, and a weighted average is calculated subbasin-by-subbasin. Snowmelt depth in similar elevation bands is considered to be similar in all sub-basins. Though SWAT is an effective tool for watershed management, there are many unknowns about conceptual factors, physical parameters, drainage region, elevation range, and HRUs (Shi *et al.*, 2011). The input data, which may directly affect the output, the structure of the model, which was constructed based on assumptions and simplifications, and the model parameters are the three main sources of uncertainty in hydrological modeling (Beven *et al.*, 2001; Bourdin *et al.*, 2012; Xue *et al.*, 2014; Zhao *et al.*, 2018). As a result, comprehensive calibration, validation, and uncertainty investigations are necessary to achieve the best model performance. Many studies have examined model parameter uncertainties, but few have examined model structure uncertainties, such as the number of subbasins, hydrological response units (HRUs), and elevation bands (Narsimlu *et al.*, 2015; Singh *et al.*, 2014). For minimizing calibration time and confusion in the model's physical structure, evaluating model performance under multiple circumstances is critical (Bhatta *et al.*, 2019). One of the SWAT model's flaws (Krysanova & Arnold, 2008) is the lack of lateral fluxes, which means that water, fertilizer, and pollutant transit between HRUs within a subbasin will not occur (Bryant *et al.*, 2006). As a result, water flows, including snowmelt water, are calibrated using monitoring data rather than the closures of water balance equations (Wang *et al.*, 2021).

2.3 Understanding River Health

Ecosystem and river health concepts have gained prominence in the field of aquatic ecology (Costanza *et al.*, 1992; Rapport, 1989 Rapport *et al.*, 1998, Boulton, 1999; Scrimgeour & Wicklum, 1996). However, ecologists disagree over what constitutes "ecosystem health" (Haskell *et al.*, 1992; Karr, 1993; Rapport *et al.*,1998) or "river health" (Boulton, 1999; Norris &Thoms, 1999). The majority of river health definitions do not come into consideration human or societal values, as well as biophysical variables (Boulton, 1999; Pinto & Maheshwari, 2014; Roux & Everett, 1994; Rapport, 1998). The river health condition correlates positively with the integrity of biological systems (Boulton, 1999). Frey (1977) describing river health as the capacity of ecosystems to maintain a balanced and integrated community that supports community assemblages that are comparable to reference natural habitats of the area. Different scientists and researcher's defined river health in different ways. Some researcher like Norris & Thomas (1999) put forward their view by stating that rivers would be healthy with the sustenance of even a single species of fish, but not considered healthy if any of the fish utilized for recreation activities declines.

Similarly, according to Costanza et al. (1992) ecological health of an ecosystem is intimately tied with the concept of sustainability, which is considered a detail, multi-dimension, and potential measure of ecosystem resistance, resilience, and vigor. Karr et al. (1986) defined it as any stable biological system which has the capacity for self-repair to preserve its perturbation thus requiring minimal external support for its management. The health of an ecosystem can be categorized into three, viz. system integrity, environmental impairments caused by stress, and counteractive capacity, all of which are influenced by social and cultural values (Rapport, 1989).

Later on, in 1970, the term river health was legalized under the Clean Water Act (USEPA, 1972) in the United States (US). Under this act, a river was considered healthy if it meets the physical, chemical, and biological integrity. Then, during the 1990s, countries like Australia, and South Africa implemented National River Health Plan (Huaibin & Jianping, 2014). However, the key factors for the river's health were considered as adequate and clean flow (Changming & Xiaoyan, 2009). A healthy river can be visualized as a river having balanced ecosystem dynamics, high resistance, and resilience capability to different forms of disturbances, which maintains sustainable social values (Storer *et al.*, 2011).

Ecological vigor and resilience have been used to characterize the components of river health (Rapport *et al.*, 1989). The latter highlights the importance of ecosystem capacity to restore the structure and function of ecosystems for ensuring ecological sustainability (Sheldon & Leigh, 2012). River health can be properly determined by studying the environmental factors which affect aquatic biotas, like habitat conditions, flow dynamics, energy availability, land-water, and biotic interactions (Norris & Thoms, 1999). The goal of a river health assessment (RHA) is to determine the rivers under poor conditions, by identifying their degrading causes. In doing so it helps to prioritize river restoration and management actions successfully (Speed *et al.*, 2012; Sheldon & Leigh, 2012).

2.3.1 Components of River Health

The distribution of aquatic organisms is influenced and regulated by several factors like velocity, temperature, altitude, season, total suspended solids, the substratum, and vegetation. Thus, these physical, chemical or biological indicators of river health that respond favorably or adversely to a given amount of disturbance are thought to indicate changes in river health (Boulton, 1999; Sheldon & Leigh, 2012). These indicators must not only be realistic and ecologically based, but also sensitive to environmental perturbations across different ecological areas (Harris & Silveira, 1999; Boulton, 1999). In most of the studies, indicators are used to define river health, and their results are matched using statistical approaches from descriptive summaries and multimeric to predictive and multivariate approaches (Boulton, 1999). For the holistic management of rivers, Cairns et al. (1993) advocated the construction of an indicator system based on three categories of indicators: compliance, diagnostic, and early warning indicators.

For a decade, monitoring of water quality is considered a standard practice in almost all nations. However, in many regions of the world, the fundamental scientific components of sustainable water management are still poorly understood. As a result, measurements of water quality serve as both disturbance gradients and indicators of river health (Leigh *et al.*, 2012). The assemblages of stream fauna and flora are influenced by water quality, with high-quality streams having the highest species composition, richness, and diversity. However, because many aquatic insects are pollutant intolerant, they are rarely seen in polluted environments, reducing species diversity.

Biological aspects are one of the robust indicators of river health since they combine the independent and interacting effects of a variety of stresses (Cairns *et al.*, 1993). There are many biological organisms used to represent river health (fish, plankton, algae, macroinvertebrate, macrophytes). But the benthic macroinvertebrates are widely used biological indicators (Chen *et al.,* 2019; Karr & Chu, 1999; Nieto *et al.,* 2017; Rosenberg & Resh, 1993). The biotic requirements are thought to reflect the hydro morphological condition (WFD, 2000), which aids in the achievement of "good ecological status". Macroinvertebrates being ubiquitous, have a long life and due to their sedentary habits, they will represent the site-specific ecological conditions (Cook, 1976; Cairns *et al.,* 1993; Chen *et al.*, 2019).

Similarly, riparian vegetation, which grows at the intersection of a stream's bank and the surrounding land, is impervious and serves as a helpful indicator of ecological change (Benjankar *et al.,* 2012; Nilsson & Berggren, 2000). Riparian vegetation performs several important roles for aquatic ecosystems, including evapotranspiration, which helps to moderate water and ambient air temperatures, and shade, which reduces solar energy input. It also serves as a filter between land and water, a conduit for dispersing migratory species. The vegetation also acts as a food source for a variety of animals (Naiman & Decamps, 1997). Changes in riparian vegetation directly affect river conditions hence biomonitoring programs must include it among other indicators, like habitat integrity, fish, and macroinvertebrates (Scherman *et al*., 2004).

The physical habitat is crucial to determine because without a proper 'living environment,' a species is unable to survive in that area (Maddock, 1999). A river's morphological characteristics are formed by eight variables of the channel, viz. width, depth, velocity, discharge, slope, material roughness, sediment load, and size (USEPA, 1983). River's overall habitat composition and its physical characteristics could alter affecting the availability of suitable habitats for aquatic species due to the changes in the above parameters (USEPA, 1983). Further variation in these parameters causes spatial and temporal heterogeneity in hydraulic conditions (Ried & Thoms, 2008). If the physical environment of the stream is degraded, it affects the biological condition

(Brookes & Shields, 1996; Plafkin *et al.,* 1989). Thus, understanding the nature of the parameters described above is crucial for proper river design and implementation.

There is a remarkable association between each of the parameters making each parameter important for physical assessment. For example, the depth and velocity of flow, are influenced by the channel's slope and roughness, both of which determine turbulence. In turn, turbulence impacts waste and tributary stream mixing rates, reaeration, sedimentation, or scour of particles, associated biological growths, and purification activities. Thus, rather than focusing on one aspect, a more comprehensive study of the physical environment is required (USEPA, 1983).

Similarly, the stream substrates which are a product of underlying geology and climatic conditions of the watershed are affected by various catchment features and processes. Slope and land use are common catchment features, and weathering, erosion, sedimentation, and biological factors connote the processes. In addition, a substrate is also a crucial component affecting the abundance and distribution of aquatic biota (Jowett, 2003; Schroder *et al.,* 2013). Sediments, in general, play a vital role in habitat diversification and composition, as well as habitat quality, particularly for the development of habitat characteristics in the long and short term. Sediments also contribute to the formation of habitat (boulders) and morphological features (gavel at gravel bars which define a river's hydraulic patterns) (Hauer *et al.,* 2014). Benthic macroinvertebrates have evolved to resist difficult conditions like uncommon catastrophic events e.g., floods and ice jams, which result in sediment transport. Increased fine sediment, on the other hand, has major effects on benthic macroinvertebrates in lotic systems, threatening biodiversity and thus leading to critical ecological degradation. But in "supply-limited" rivers, a coarser bed surface can reduce macroinvertebrate taxa diversity that needs fine sediments as a habitat (Leitner *et al.,* 2015).

Flow regime has a major influence on stream ecosystems, such as stream morphology, species diversity, food web structure, and structure of aquatic community (Bunn & Arthington, 2002; Jowett & Duncan, 1990; Laini *et al.,* 2019; Speed *et al.,* 2012). The pattern of the flow regime is explained mainly by unique flow amplitude, time, period, frequency, and change in rate, which have profound impacts on shaping aquatic ecosystems (USEPA, 2015). However, alterations in flow may act as a type of perturbation, but a mild change in hydrological functions increases biodiversity in river systems (Bunn & Arthington, 2002). Many species live on regular or seasonal river flow variations for completing their life cycles, and the aquatic organisms have evolved adaptation mechanisms to cope with habitat alterations from natural flow regimes (Poff *et al.,* 1997). The majority of the published study found adverse ecological consequences in terms of a variety of flow changes (Poff & Zimmerman, 2010). Water current (velocity) substantially controlled the variety of substrates and the quantity of food accessible for aquatic macroinvertebrates. Macroinvertebrates are largely dependent on it for their feeding purposes as well as for their respiratory requirement. It is one of the key determinants of species presence and abundance, as well as the overall organization of the animal population in lotic water (USEPA, 1983).

Besides anthropogenic activities, climate change in combination with stressors like pollution, habitat loss, invasive species, and flow alteration also affects aquatic organisms impacting river health (Dudgeon *et al.,* 2006). The unpredictable flow regime possesses an impact on the growth of aquatic and amphibian plants, recession in agriculture productivity, and quality of water. It has a major influence on stream ecosystems, such as stream morphology, species diversity, food web structure, and the structure of aquatic communities (Jowett & Duncan, 1990). Flow variability of various regimes are important for the sustenance of healthy rivers, for instance, high flows of various frequencies are important for the maintenance of the channel, riparian vegetation, and bird breeding sites. Similarly, moderate flows are essential for organic matter cycling and support fish movement. The low flows, on the other hand, are useful for algal treatment, and water quality improvement to support aquatic life and habitat connectivity (Kashaigili, 2013).

2.3.2 Approaches for River Health Assessment

Rivers provide a healthy ecosystem as well as essential hydrologic functions to communities. River health is under attack worldwide, hence studies of river ecological status are necessary to detect rivers in poor health. The state of a river's ecology can be determined by comparing it to a set of reference values and identifying threats so that appropriate restoration and protection measures can be devised (Barbour *et al.,* 2000; Speed *et al.,* 2012).

In 1972 nationwide mandate was proposed through Clean Water Act in the United States. The act has set one of the goals to restore and maintain water for chemical, physical and biological properties. To put that directive into reality, Karr (1981) established an Index of Biotic Integrity (IBI). This index identifies the situation of aquatic ecosystems using a variety of indicators, which encompasses quantifiable biotic community traits comparable to reference site conditions. The index includes themes such as biological diversity, functional features, exotic species, ecosystem vigor, and population dynamics.

Previously, research on river health assessment (RHA) solely depends on traditional water quality indices that incorporate physicochemical aspects of water (Barbour *et al.*, 2000; Kim *et al.,* 2013). However, it has various flaws, including the fact that it only offers information on water quality at a specific spatial unit (during sampling time) rather than historical information on it, and it cannot detect stressors that occur over time at various scales (Furse *et al.*, 2006; Subramanian & Sivaramakrishnan, 2007) it was used in combination with biological aspects. In addition, each river's reach has its own set of biological and ecological traits, as well as a wide range of stresses and consequences (Moog *et al.,* 2018). Physical-chemical monitoring alone will not be sufficient to document aquatic ecosystem health. Due to these constraints, river health has been monitored directly utilizing indicators such as aquatic biotic conditions or bio-assessments. Biomonitoring tools provide some historical insights into the water quality in combination with physicochemical parameters (Cook 1976; Karr & Chu 1999; Resh & Rosenberg, 1993; Subramanian & Sivaramakrishnan, 2007).

Biomonitoring methods consider many ecosystem components, including biological and physical indicators (Scherman *et al.,* 2004). Macroinvertebrates, fish, and riparian vegetation are biological indicators. Similarly, channel geomorphology, water quality, and flow regime are physical indicators. It will also evaluate the catchment characteristics during field assessments. Monitoring biological, biochemical, and physicochemical parameters have long been the most effective method of identifying the effects of human activity on aquatic ecosystems (Verdonschot, 2000).

Forbes (1887), who established the biological community idea, pioneered biomonitoring research in the United States. Kolkwitz & Marsson (1902) investigated contaminated rivers near Berlin in the early 1900s and elaborated on community assemblages in distinct zones with high organic levels.

Based on that saprobic system, they invented the concept of "biological indicators of pollution" which is in use across Central and Eastern European countries, currently, the saprobic system is included in Austria's multi-metric indices (Ofenbock *et al.,* 2010), Czech Republic (Kokes *et al.,* 2006), and Germany (Meier *et al.,* 2006). The saprobe index gives information about the degree of water pollution (Kolkwitz & Marsson, 1902). The different saprogenic stages are related to certain indicator organisms like bacteria, fungi, algae, amoeba, mussels, worms, insect larvae, or fishes. The stages range from polysaprobic (very highly polluted), a-mesosaprobic (highly polluted), b-mesosaprobic (medium polluted), to oligosaprobic (rather clean and clear water) (Muller *et al.,* 2013).

Rapid Bioassessment (RBPs) is one of the most commonly used biomonitoring approaches (Barbour *et al.,* 1999). RBPs have been implemented as mandatory methods for assessing wadeable streams in the United States of America (Barbour *et al.,* 1999) and in Austria (Moog *et al.,* 1999) to infer data about running water quality. There are mainly three different types of RBPs available each with thorough procedure descriptions namely, streams-fish, periphyton, and macroinvertebrate surveys respectively. Among these three RBPs, the macroinvertebrate survey was the most popular because it required less equipment and specialist understanding. RBPs are also recommended by the EPA as they deliver quick and accurate results and are cost-effective, time-saving, and minimally intrusive (Barbour *et al.,* 1999). Besides RBP other biomonitoring approaches have been used widely: Diversity approaches, Biotic indices, Multimeric approaches, and Multivariate techniques.

i. Diversity Approaches

This method considers species richness, abundance, and evenness as components of community structure. Non-stressed populations are assumed to have a lot of variety and an equitable share of individuals within species. When disturbances and pollution loads (organic enrichments) grow, sensitive taxa perish and tolerance taxa proliferate (Czerniawska-Kusza, 2005). In general, Shannon Wiener Index (Wilhm & Dorris, 1968), Simpson index (Pinder *et al.,* 1987), and Margalef Index (Wilhm & Dorris,

1968) are commonly used diversity measures (Metcalfe, 1989). The diversity approach is a more appropriate method for comparing disturbed sites with undisturbed sites or reference sites (Metcalfe, 1989).

ii. Biotic Indices (BI)

Biotic indices are the most often used indices that integrate quantitative characteristics of species diversity with each taxon's ecological sensitivity data (Czerniawska-Kusza, 2005; Ollis, 2005). The disappearance of sensitive taxa and the decrease in the number of taxa with an increase in pollution level are the two basic principles considered in any biotic indices (Czerniawska-Kusza, 2005). Around the same period in 1950, the first indexes were introduced in the US and Europe (Beck, 1954; Pantle & Buck, 1955). In general, pollution-tolerant taxa (e.g., Chironomidae, Physidae) outnumber sensitive taxa (e.g., mayflies, stoneflies, and caddisflies) in streams and rivers that are enriched with organic matter (Metcalfe, 1989). Numerous biotic indices have been developed based on macroinvertebrates. Some of the widely used methods are listed below in chronological order.

Beck's BI was first originally developed biotic index, designed for streams in Florida (USA), and Beck is credited with coining the phrase 'biotic index' (Beck, 1954; Pantle & Buck, 195; Washington, 1984). Trent River Authority in England then developed Trent Biotic Index (TBI) (Woodiwiss, 1964), and it is attributed to the invention of modern biotic indicators (e.g., Metcalfe, 1989; Reynoldson & Metcalfe-Smith, 1992). As TBI has been proven to be insensitive to changes in water quality in its application (e.g., Balloch *et al.,* 1976; Friedrich *et al.,* 1996; Pinder *et al.,* 1987; Tolkamp, 1984) an upgraded version of the index called the Expanded TBI or Extended Biotic Index (EBI) (Rico *et al.,* 1992; Woodiwiss, 1978) was developed with a maximum attainable value of 15 (Hawkes, 1982; Metcalfe, 1989; Washington, 1984). Based on the TBI, different biotic indices such as Chandler’s biotic index were devised for upland rivers (Chandler, 1970). Then it was renamed the Average Chandler Biotic Score (Jones, 1973; Balloch *et al.,* 1976) because of the low rating for undisturbed headwater locations (Johnson *et al.,* 1993).

Similarly, Chutter's Biotic Index (CBI) was invented in 1972 to provide a measure of organic contamination in South African streams and rivers. Then, in the 1990s a CBI adaption was devised to assess biological contamination in streams of the Wisconsin Region of North America based on Hilsenhoff's Biotic Index (HBI) (Davis, 1995; Hilsenhoff, 1977, 1987). The Biological Monitoring Working Party (BMWP) score technique was employed for the lotic system in the United Kingdom between 1978/1979, 1980, and 1983 (Armitage *et al.,* 1983; Tolkamp, 1984), which was first developed in 1978 and updated in 1979 (Hawkes, 1997), and is based on the CBS system. Modified versions of BMWP Score System were used in different countries with a different name e.g., Iberian IBMWP in Spain, SASS in South Africa, SIGNAL in Australia and MCI in New Zealand and NEPBIOS/ASPT (Sharma, 1996) for Nepal. After that, in 1983 (De Pauw & Vanhooren, 1983), the Belgian Biotic Index (BBI) was established, which combines the TBI's sample process and the IB's scoring system, but scores both lotic and lentic habitats.

The Macroinvertebrate Community Index (MCI), following the BMWP approach and similar to CBI and HBI, was developed in 1985 for monitoring water quality in New Zealand streams (Stark, 1985). By enhancing and adapting the BMWP System, the South African Scoring System (SASS) (Chutter, 1998) using macroinvertebrates assemblage was created for many years in South Africa for assessing rivers. It is intended to be a low-cost and rapid way of detecting water quality contamination (Chutter, 1998).

Similarly, the Stream Invertebrate Grade Number, SIGNAL Biotic Index (Chessman, 1995; 2003), and Danish Stream Fauna Index (DSFI) (Skriver *et al.,* 2000) were devised for monitoring water quality. The DSFI was an updated version of previous indices using macroinvertebrates utilized for the biological assessment of lotic systems namely the Viborg Index (Andersen *et al.,* 1984), and a successive modification known as the Danish Fauna Index (DFI). Finally, Balkan Biotic Index (BNBI) was devised the monitoring the water quality of rivers (Simic & Simic, 1999). The BNBI, which is based on the CBS, necessitates a macroinvertebrate abundance estimate.

iii. Multimetric Approaches

It is a more advanced and complex approach, as it assesses environmental deterioration using numerous quantitative features of a biological assemblage (Karr *et al.,* 1986). The Multimetric method consists of a group of variables that represent different components of an ecosystem thereby providing reliable information about the effects of stressors on aquatic ecosystems (Korte *et al.,* 2010). This approach analyzes biological data using simple univariate statistics and is based on the assumption that undisturbed biological systems have distinct structural and functional characteristics. The first multimetric index to assess the river's biological condition was the Index of Biotic Integrity which relied on fish assemblages (Karr, 1981). Later several multimetric indices have been developed for benthic macroinvertebrates in different regions of the globe (Barbour *et al.,*1996; Dahl & Johnson, 2004; Kerans & Karr 1994; Korte *et al.,* 2010; Ohio EPA, 1987; Plafkin *et al.,*1989). Benthic macroinvertebrates-based multimetric indices are widely applied in the biomonitoring of rivers across the United States (Barbour *et al.,* 2000). Subsequently, the Index of biotic integrity has been applied to different biota, vascular plants, algae as well as terrestrial and freshwater ecosystems (Bradford *et al*., 1998; Guilfoyle *et al*., 2009; Fore *et al.*, 1996; Kane *et al.*, 2009; Mack, 2007).

iv. Predictive Models (Multivariate)

The link between macroinvertebrate assemblages and ecological characteristics of sampling locations is used in multivariate or model-based prediction approaches (Metcalfe-Smith, 1994; Reynoldson & Metcalfe-Smith, 1992). The multivariate method uses similarity distances, often grouping using classification, direct and indirect multivariate approaches (Sandin *et al.*, 2001). The model suggests which organisms ought to be present at a "target" location considering environmental variables. If the aquatic species identified at the test location are identical to the expected, the study location is considered a "reference condition" (Moog *et al.,* 2018). However, if the observed biota at the test location differs from the predicted, the study site is considered "disturbed". River Invertebrate Prediction and Classification System (RIVPACS) is the initial and most widely used predictive model for flowing water ecosystems in the United Kingdom (Wright *et al.,* 1984) since 1990. Comparable systems have been developed throughout several nations considering mathematical concepts of RIVPACS. The Benthic Assessment of Sediment (BEAST) was designed in Canada during the mid-1990s (Reynoldson *et al.*, 1995).

AUSRIVAS (Australian River Assessment Scheme) was designed by the federal government in 1994 to assess the biological condition of Australian rivers (AUSRIVAS, 2005; Simpson *et al.,* 1997). Based on RIVPACS, other predictive models have been introduced. Swedish SWEPAC (Johnson & Sandin, 2001), Czech Republic PERLA (Kokes *et al.,* 2006), and the Luxembourgian model (Ferreol *et al.,* 2008; Moss *et al.,* 1987; Wright *et al.,* 1984) are some widely used predictive models. Similarly, for Spanish Mediterranean watercourses, a new predictive tool, MEDPACS (Mediterranean Prediction and Classification System) was introduced and implemented for assessing the aquatic macroinvertebrates (Posquet *et al.*, 2009). This model uses the Ecological Quality Ratio (EQR) based on two published biotic indices (IBMWP and IASPT) and is based on the RIVPACS/AUSRIVAS predictive technique (Posquet *et al.,* 2009).

Further, the prediction of species can be also done using species distribution models (SDM) which is one of the popular tools to predict habitat suitability (Elith *et al*., 2011; Franklin, 2009). SDM is based on niche theory, which examines the major factors influencing species distribution and predicts the species' likely distribution relying on species occurrence and environmental variables data. To collect data on ecosystems, biological surveys are done by keeping the record of the occurrence of species at respective locations and using different regression methods (common are generalized linear and non-linear models) (Elith *et al.,* 2011).

Among SDM, maximum entropy (MaxEnt) models have been a prominent approach for predicting species distribution since 2004 (Phillips *et al.*, 2006) due to their capacity to cope efficiently with scanty, randomly sampled data with modest location deflections (Kramer-Schadt *et al.,* 2013). The key assumption of MaxEnt, on the other hand, is that the whole region of interest has been thoroughly surveyed, and the models are built from occurrence records of a specific species (Kramer-Schadt *et al.,* 2013). This information is available commonly in digital format. Once the biodiversity-environment relationship is assessed, future distribution due to climate change could be easily predicted spatially and temporally by extending the model onto available environmental layers (Elith *et al.,* 2011).

However, there are three general requirements for properly implementing a multivariate prediction system, which is as follows:

i. A complete understanding of the species catalog and structure of the target biota, as well as its regional and periodic distribution under reference conditions.
ii. A thorough comprehension of the reference conditions' requirements.
iii. Models that can accurately anticipate living organisms for a specific site or stream, despite natural environmental variables that vary.

v. Integrated Approach

Europe's Water Framework Directive (WFD) sets a common legislative framework for water management in 2000. The WFD's main mission was to enhance the ecological integrity of all European waterways. Water chemistry, hydromorphology, algae, macrophytes, phytoplankton, benthic invertebrates, and fish are used by the EU to evaluate the ecological conditions of the rivers using an integrated approach based on the regulation annexes II and V. Water bodies are categorized into five categories based on their ecological states: extremely good, good, moderate, poor, and bad (European Commission, 2000).

An integrated assessment, compares habitat characteristics, water quality, and biological indicators with reference sites for the evaluation of river health (Barbour *et al.*,1999). The integrated biological assessment approach aims to analyze the effects of anthropogenic influences on environmental assets across several spatial and temporal dimensions, then transform the findings into actionable management strategies (Verdonschot, 2000). An integrated technique-specific stressor could be identified with their immediate response to environmental parameters or stressors. Using an integrated measure of ecosystem status has the advantage that any flaws in the indicator capacity of any one parameter will not invalidate the whole assessment (Cairns *et al.*, 1993). Thus, an integrated framework is essential for the long-term management of river basins (Davids *et al.*, 2018; Zhao *et al.*, 2018). Integrated RHA approaches are being widely adopted and supported throughout the world. For example, Water Framework Directive (WFD) which is implemented in 25 countries across Europe, the Ecosystem Monitoring and Assessment Program (EMAP) in the United States, the Australia China Environment Development Program (ACEDP) in China, and the River Health Program (RHP) in South Africa (Storer *et al.*, 2011) and Ecosystem Health Monitoring

Programme (EHMP), 1999 for estuaries and marine ecosystems (Bunn *et al.,* 2010; Smith & Grice, 2005).

vi. Biomonitoring in Nepal

In Nepal, the concept of the biological index for surface water quality assessment was introduced based on the Extended Biotic Index (DISVI, 1988). After a decade, Sharma (1996) introduced the Nepalese biotic score (NEPBIOS), the first region-specific score-based technique for measuring saprobic water quality in Nepalese rivers, an adaption based on score/average score per taxon (BMWP/ASPT) system.

Then some modifications were done on NEPBIOS which give various indices like BRSbios (Pradhan, 1998), GRSbios (Nesemann, 2007), and HKHbios (Ofenböck *et al.,* 2008) and NEPBIOS-Extended (Sharma, 2009). Similarly, the HKH biotic score (ASSESS-HKH) was developed in 2008 as part of a European Union-funded research project (contract number: INCO-CT-2005 003659) for the monitoring of river conditions in the Hindukush Himalaya region (Ofenbock *et al.*, 2008). Existing score-based approaches NEPBIOS, (Sharma & Moog 1996), GRSbios (Nesemann *et al.,* 2007), and new data from 390 multi-habitat-samples were used to create HKHbios. The HKHbios is similar to the British BMWP (Armitage *et al.*, 1983), in which species found at a location are utilized as indicators for river health, primarily at the family and genus level. Then finally Shah et al. (2012) proved new biotic indices GRSbios as one of the best indices and others include NEPBIOS-Extended, HKHbios, NEPBIOS, and BRSbios. They concluded that GRSbios is one of the promising biomonitoring tools across the different geographic regions of Nepal.

There are several studies on water quality assessment in different rivers of Nepal such as Seti River Basin, Pokhara (Shrestha *et al.,* 2009), Saptakoshi (Sharma, 1999), Bagmati River Basin (Moog & Sharma, 1996; Mehta & Kushwaha, 2016; Pradhan, 1998; Shah *et al.,* 2013), selected rivers of Karnali Basins (Sharma,1996), water quality status of various streams (Brewin & Ormerod 1994; Rundle *et al.,*1993; Suren, 1994; Shah *et al.,* 2008). Assessment of river water quality had been done by using different indicators like macroinvertebrates and physicochemical parameters (Davids *et al.,* 2018; Feld *et al.,* 2011; Rana & Chettri, 2015; Shrestha *et al.,* 2008; Shah *et al.,* 2012; Sharma *et al.,* 2015), using macroinvertebrates only (Brewin *et al.,* 1996; Brewin *et al.,* 2000; Brewin & Ormerod, 1994; Korte *et al.,* 2010; Pradhan, 1998; Shah *et al.,* 2013, Sharma & Moog, 2005) assessment using fish, diatoms, macroinvertebrates as well as physicochemical parameters (Ormerod *et al.,* 1994), assessment using fish and physicochemical parameters (Edds, 1993; Jha *et al.,* 2007; Pokharel *et al.,* 2018; Sharma *et al.,* 2005).

2.4 Drivers of River Health Deterioration

2.4.1 Natural impact on riverine ecosystem

Climate change causes pressing impacts on biological diversity and localized ecosystem functions. It causes significant changes in the freshwater environment since its thermal and hydrological regimes are interrelated (Pletterbauer *et al.*, 2018). A riverine ecosystem with a restricted species dispersal capacity is fragile to climate change (Woodward *et al.*, 2010). Ambient temperature to ectothermic aquatic animals has both direct and indirect effects. The biological repercussions of projected climate change in freshwater ecosystems, on the other hand, will be heavily influenced by the rate and magnitude of change caused by climatic forcing (Pletterbauer *et al.*, 2018).

2.4.2 Anthropogenic impact on riverine ecosystem

Water resource developmental activities have caused unexpected impacts on riverine ecosystems, with the majority of these impacts due to variations in the hydrological components (Rosenberg *et al.,* 2000; Zeiringer *et al.*, 2018). Large dams have already altered the majority of the world's major river basins (Nilsson *et al.*, 2005). Dams, whose construction history goes back more than 5000 years are a direct modifier of river flow (Schmutz & Moog, 2018). Humans have already used a major portion of the world's accessible surface water, with that percentage expected to rise to 70% by 2025 (Postel, 1998).

Modern dams have a variety of ecological effects (Poff & Hart, 2002), ranging from reduced velocity to alterations in the intensity and timing of the flow, often resulting in practically stagnant waters of varied sizes. Dams also obstruct the movement of fish and other aquatic organisms, including the flow of nutrients. Dams and reservoirs have resulted in some of the most severe cases of environmental problems in recent years (Haidvogl, 2018). Dams trap sediments as they move down a river, coarsening the streambed and reducing the amount of habitat accessible to aquatic organisms that reside in or use interstitial spaces (Chien, 1985; Loucks & Becks, 2017). Furthermore, rivers become fractured and lose their natural connectivity due to dam construction and flow regulation (Zeiringer *et al.,* 2018).

2.5 River Health Assessment and Management

Majority of national-level river health assessment procedures have been designed throughout the globe but those river health assessment procedures are inefficient in settings other than those for which they were designed(Pinto and Maheshwari ,2011). . This is owing to the uncertainty of numerous national scale evaluation approaches, the difficulty of locating "pristine" areas for comparison, and the inability to account for complex biological interactions amongst aquatic organisms (Pinto & Maheshwari, 2014).

To date, numerous river health assessment approaches have been presented for reaching successful river management goals with the help of various indicators like water quality, biological organisms, riparian condition, and substrate composition (Brown *et al.,* 1970; ISC, 2006; Sheldon & Leigh 2012). However, individual or combined physicochemical approaches or bio-assessment are insufficient for a comprehensive RHA (Pinto & Maheshwari, 2014). As a result, a global river health assessment is necessary, which is currently lacking as a result of significant geographical variations, watershed characteristics, and specialist species assigned to the watershed. In this context, one of the simplest approaches to addressing the geographical and temporal complexity associated with river health assessment is to establish a framework, a hypothetical or analytical construction for simplifying a complex phenomenon, which can be used as a guide for developing relevant tools based on geographic characteristics and specific knowledge (Pinto & Maheshwari, 2014). It is very much useful for integrated ecological assessment (Storer *et al.,* 2011; Verdonschot, 2000). Thus, the framework will aid in assessing, guiding, and informing the city's efforts to support and sustain the river's overall health. Naiman et al. (1992) also advocated for striking a balance between environmental, financial, and social goals to address issues such as intergovernmental cooperation and the coordination of geographically and temporally autonomous human use changes.

The Water Framework Directive (WFD) and the Freshwater Health Assessment are two widely acknowledged frameworks for the assessment of surface and groundwater resources (FHA) (FHA, 2013; WFD, 2000). WFD was implemented in 2000 to have all surface and groundwater resources in Europe in a "good status" by 2015. The FHA uses four biophysical factors to assess the state of water resources, including flowing water, characteristics of water quality, fish diversity, and benthic aquatic organisms (Pinto & Maheshwari, 2014). Even though nations such as Australia have adapted well-established river health assessment frameworks from the UK to match local conditions (AUSRIVAS from RIVPACS and SIGNAL from ASPT), users of such frameworks typically neglect to update them beyond their first inception (Krogh *et al.,* 2008; Sheldon & Leigh, 2012). Similarly, while several state and national assessments were established, no single approach was employed over an extended time (ISC, 2006; Peter *et al.,* 2008).

Various countries created and accepted frameworks to assess river health, encompassing biological, physical, hydrological, social, chemical, and other variables, as indicated in (Annex I). But basically, all the proposed frameworks for river health assessment should have these traits (Pinto & Maheshwari, 2014).

i. Gain a social and environmental understanding of the river system
ii. Create predictive tools based on important river health indicators and
iii. Use the tools to provide timely advice on river health management

2.6 River Health Management in Practice

2.6.1 International Legislations

Internationally and in European countries, there is a growing awareness of the need to legally protect the limited quantity and quality of freshwater resources. In this context, the worldwide and European Legislative Framework for river ecosystem management is led by an integrated water resources management strategy, which has a significant impact on national water legislation (Hold, 2018). There are more than 3600 bilateral and multilateral international agreements focused on water-related concerns in Transboundary Rivers, lakes, and seas (United Nations, 2016; Vinogradov *et al.,* 2003). Water being a limited and perishable resource, the majority of agreements were made between AD 805 and 1984 (United Nations Food and Agriculture Organization, 1984;

United Nations Environment Programme, 2002). The UN Convention on the Protection and Use of Transboundary Watercourses and International Lakes (UNECE, 1997), as well as the UN Convention on the Law of Non-Navigational Uses of International Watercourses (United Nations, 1997), are the well-known legal acts that strengthen freshwater governance and promote equitable and long-term transboundary watercourse sharing. However, the Water Framework Directive for integrated water resources management, which is relied on a watershed management strategy, is the most significant regulation for river ecosystem management in European countries (Hold, 2018). The WFD (European Commission, 2000) is a governance framework, adopted in 2020, for all waters that avoids further degradation by preserving and enhancing the aquatic ecosystems in the European Union (EU).

2.6.2 National Laws

Water Resource Act 1992 (MEWRE/GoN) is an Umbrella Act to protect the water resources of Nepal. However, all water-related legislation either for drinking water, sanitation, irrigation, and hydropower of them have provisions for preventing and controlling water pollution. National Drinking Water Quality Standards, 2062 and National Drinking Water Quality Standards Implementation Guidelines, 2062 have provided the maximum and minimum concentrations of various parameters of the drinking water quality as well as the approach and basis for the water quality testing, monitoring, and surveillance for water system designers, operators and service providers respectively. Similarly, National Water Plan (2005), aims at universal coverage of safe drinking water and sanitation by 2017 which is also compatible in line with the Tenth Plan. In this 21st century, the Government of Nepal as published in the Nepal Gazette has only focused on these aspects rather than any long-term plans for river health management. Even though the Environmental Protection Rules were amended in 2077, there are still gaps in provisions related to the management of rivers.

i. Establishment of the required quality standard for water resources for varied applications.
ii. Setting a limit on the amount of pollution that can be tolerated in water resources.
iii. Not causing any significant detrimental environmental impact.

With the long history of the Department of Soil Conservation and Watershed Management (DSCWM) establishment, in 1974, there is still no clear plan or vision to protect aquatic ecosystem integrity, nor any framework or indicator-based plan to conserve river health. Nepal, a signatory to the United Nations' 2030 Sustainable Development Agenda in 2015, aims to conserve and restore water-related ecosystems under SDGs-6, but the target of 6.6 by 2020 has yet to be met, and indicators have yet to be developed as there is inadequate institutional framework and mechanisms to implement the policies (NPC, 2015; NPC, 2017).

CHAPTER 3
MATERIALS AND METHODS

3.1 Description of Study Area

The Marshyangdi Watershed, a sub-basin of the Gandaki River Basin, is one of Nepal's major river systems. It has an area of 4,748 square km and is located between the latitudes of 27°50'42" N and 28° 54'11" N, and the longitudes of 83°47'24" E and 84°48'04" E (Fig. 3.1). From the headwaters north of the Annapurna range to the crossing with the Trisuli River, the Marshyangdi River flows about 150 km. Headwaters of the river originates from the Tethyan Sedimentary Series (TSS), but it passes through the Greater Himalayan Sequence (GHS; also known as the High Himalaya Crystalline Series, HHCS) on its journey southeast before turning south and cutting through the Lesser Himalayan Sequence (LHS) (Evans *et al.*, 2001). Glacier meltwater adds to the water volume of streams in this catchment area since part of the TSS is covered by glaciers. The GHS is made up of sedimentary and granitic rocks that have been metamorphosed from amphibolite to granulite facies (Wolff-Benish *et al.*, 2009).

This watershed's altitude varies from 274 to 8,042 m above mean sea level (masl), representing bioclimatic zones ranging from subtropical (1,000 – 2,000 m) to alpine (4000-5000 m) (Shrestha, 2008). The majority of the watershed has a slope of more than 45% and is covered in snow and glaciers, i.e., the land is between 4,000 -6,000 m above sea level. In the watershed, the climate ranges from tropical in the lower belt to polar frost in the higher elevations (Karki *et al.*, 2016). This basin has a mean slope of 29.4 degrees. The average maximum and minimum temperatures for the year are 27°C in June and -6°C in January. Based on the four districts within the watershed, the population coverage is 0.77 million people (CBS, 2019). Grassland, barren land and agricultural land are the most common land use/cover patterns in the watershed (ICIMOD, 2010). This place is part of the main Annapurna Trekking route from Besisahar, which helps to support the local economy in the study region. This river is an important source of hydropower besides water adventure sports like rafting and kayaking and have great cultural values. The Marshyangdi River is a dendritic perennial river that originates at the junction of the Khangsar and Jharsang mountain rivers. Then river heads east. Manang District before heading south through Lamjung District, passing through Gorkha and Tanahu districts. Finally, in Mugling, it joins the Trishuli River as a major tributary of the Saptagandaki River.

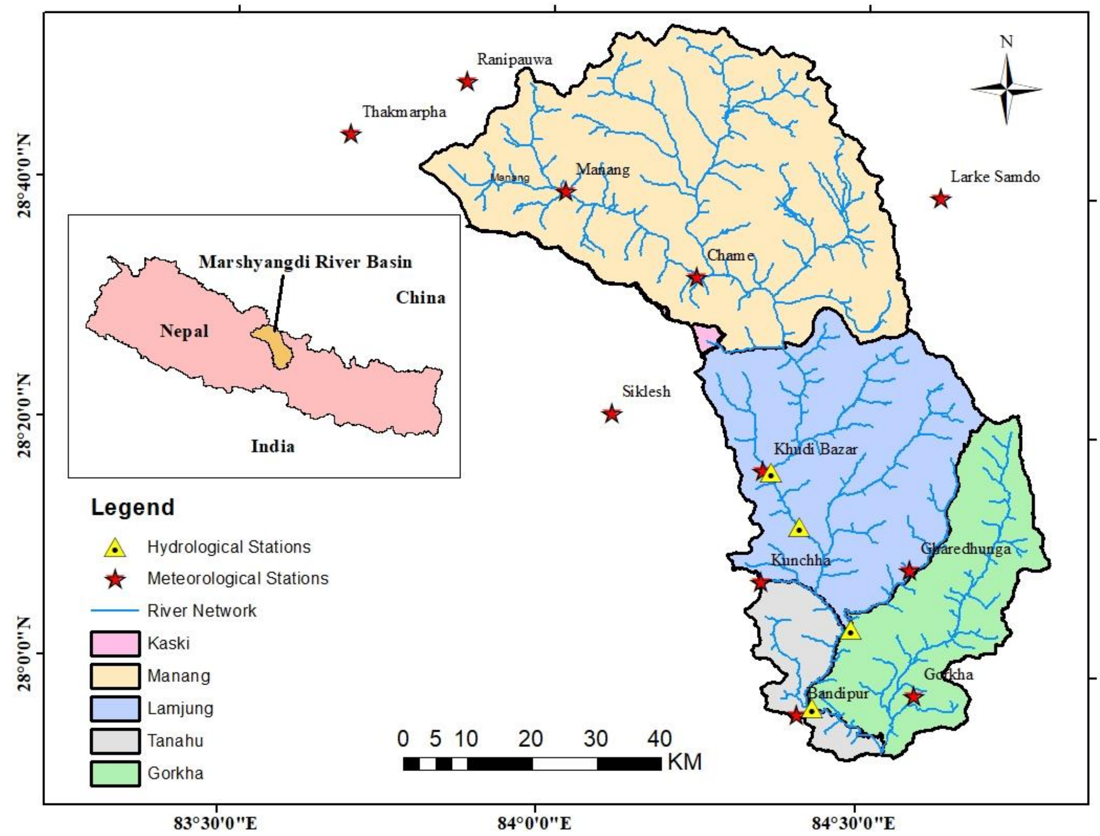

Figure 3.1: Location and topographical details of Marshyangdi Watershed in Nepal

3.2 Methodological Framework

An overall methodological framework as depicted in Fig. 3.2 connects all of the four objectives of this study. It starts with the preparation of historical time series of climatic data at selected stations, projection of future climate, selection of suitable indices determining hydro-climatic extremes, and evaluating the trends of those hydro-climatic and extreme indices. Then the direction, magnitude, and amount of trends in hydro-climatic variables were analyzed. Finally, SWAT hydrological model was set up, calibrated, and validated. Furthermore, the framework depicts additional concise methods for measuring river health under present and future scenarios.

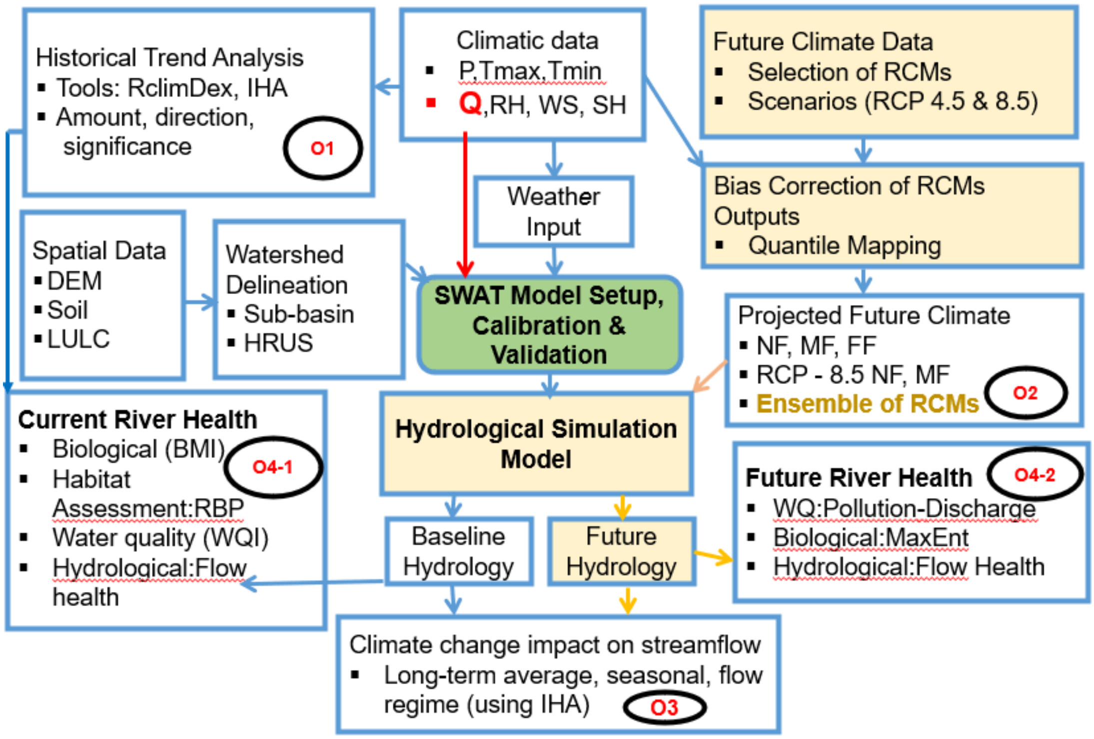

Figure 3.2: Methodological framework

3.3 Trends in Climatic Variables

3.3.1 Data quality assessment

Time series for daily observed temperature (Tmax and Tmin), precipitation, and river discharge were collected from four climatic stations, eleven meteorological stations, and four hydrological stations of the Department of Hydrology and Meteorology, Nepal (Fig. 3.3). Then suitable data length was selected after data quality assessment, which included analysis of missing values and exploratory data analysis (Table 3.1).

Table 3.1: Description of the hydro-meteorological stations considered in this study

Index	Station	Data	Data Length	Latitude (°N)	Longitude (°E)	Altitude (m)	District
604	Thakmarpha	P, T, RH, W, SR	1983-2013	83.68	28.73	2655	Mustang
608	Ranipauwa	P, T	1983-2013	83.86	28.81	3671	Lamjung
802	Khudi Bazar	P, RH	1983-2013	84.34	28.28	838	Gorkha
806	Larke Sambdo	P	1983-2013	84.61	28.66	3650	Lamjung
807	Kunchha	P	1983-2013	84.34	28.12	820	Tanahu
808	Bandipur	P, T	1983-2013	84.40	27.94	991	Gorkha
809	Gorkha	P, T, RH	1983-2013	84.58	27.97	724	Manang
816	Chame	P, T, RH	1990-2011	84.23	28.55	2680	Tanahu
820	Manang Bhot	P	1983-2013	84.02	28.66	3556	Manang
823	Gharedhunga	P	1983-2013	84.58	28.14	1088	Lamjung
824	Siklesh	P	1983-2013	84.10	28.35	1996	Kaski
804	Pokhara Airport	T	1987-2017	84.00	28.13	827	Kaski
439.3	Khudi Bazar	Q	1983-1995	84.35	28.28	990	KhudiBazar
439.35	Bhakundebesi	Q	2000-2015	84.40	28.20	610	Bhakundebesi
439.7	Bimalnagar	Q	1987-2015	84.43	27.95	354	Bimalnagar

Note: P, Precipitation; T, Temperature; Q, Discharge

Source: DHM, Nepal

For the trend analysis in climatic and hydrological extremes, the Mann-Kendall test was performed and its amount was calculated using Sen's Slope method in R software (R core team). Mann–Kendall (MK) is a widely used non-parametric rank-based technique for detecting monotonic trends in hydro-climatic data series (air temperature, precipitation, and streamflow) (Kendall, 1975; Mann, 1945).

3.3.2 Calculation of extreme indices

Annual trends in climatic extreme indices were calculated employing RClimDex (1.0) at multiple locations utilizing daily data of precipitation and temperature with varying lengths (Table 3.1), and results were tabulated based on the following 5 categories (Alexander *et al.,* 2006). Rclimdex is a R-based Tool for calculating extreme climate indices for monitoring and detecting climate change. These climatic indices are usually closely related to possible consequences, making them more illustrative to users than simple climatic means, which can be addressed with a set of appropriate indices expressing the climatic variables' extremes (Toreti *et al.,* 2008).

i. Absolute extreme indices (Intensity): Absolute indices represent maximum or minimum values within a season or year. They include maximum daily maximum temperature (TXx), maximum daily minimum temperature (TNx), minimum daily maximum temperature (TXn), minimum daily minimum temperature (TNn), maximum 1-day precipitation amount (RX1day), and maximum 5-day precipitation amount (RX5day).
ii. Percentile-based (non-fixed) threshold indices (Tank *et al.,* 2003): It encompasses the occurrence of cool nights (TN10p), warm nights (TN90p), cold days (TX10p), warm days (TX90p), very wet days (R95p), and extremely wet days (R95p) (R99p). Temperature percentile indices sample the coldest and warmest deciles for both maximum and minimum temperatures, allowing us to assess how extremes are changing. The precipitation indices in this category describe the amount of rain that falls between the 95th and 99th percentiles (R95p and R99p), respectively.
iii. Absolute-based (fixed) threshold indices (Frequency): The number of days on which a temperature or precipitation value falls above or below a fixed threshold is defined by threshold indices, which include the annual occurrence of frost days (FD), the annual occurrence of summer days (SU), the annual occurrence of tropical nights (TR), the number of heavy precipitation days > 10 mm (R10), and the number of very heavy precipitation days > 20 mm (R20) (R20).
iv. Duration-based indices: They are defined as periods of extreme wet and dry periods' warmth, and cold (Kiktev *et al.,* 2003). They include cold spell duration indicator (CSDI), warm spell duration indicator (WSDI), consecutive dry days (CDD), and consecutive wet days (CWD).

Some of the other indices available are annual precipitation total (PRCPTOT), diurnal temperature range (DTR), simple daily intensity index (SDII), extreme temperature range (ETR), and annual contribution from very wet days (R95pT). They don't fall into any of the categories above, yet changes in them could have substantial societal consequences.

Data quality control (QC) was performed using the RClimDex to identify a problem in data processing, such as inaccuracies in manual keying (Alexander *et al.,* 2006). The following processes are performed by the QC module of the RClimDex (1.0) software: (1) converts all missing values (now coded as -99.9) to an internal format recognized by the software (i.e., NA, not available); (2) converts all illogical values to not available (NA). Those values include: (a) daily precipitation amounts less than zero and (b) daily maximum temperature less than daily minimum temperature. QC also discovered outliers in daily maximum and minimum temperatures, which are daily values that fall outside of a user-defined range. When compiling data for RClimDex, months with missing values of more than 10 days were considered as missing months and categorized accordingly. Outliers in daily maximum and minimum temperatures were defined as values that were outside of three standard deviations (SD) of the mean (i.e., [mean ± 3*SD]) (Vincent *et al.,* 2005; Zhang & Yang, 2004). Similarly, the upper and lower daily maximum temperature criteria are 25° and 0°C, respectively, while the daily precipitation threshold is 25 mm. The 27 indices relating to daily temperature and precipitation created by an Expert Team on Climate Change Detection and Indices (ETCCDI) were used in this investigation (WMO, 2009). In this study, 23 indices (13 temperature linked; 10 precipitations linked) were chosen from a total of 27 for studying climatic extremes, as indicated in Table 3.2. The magnitude, direction, and significance of the trends were calculated following Zhang & Yang (2004).

Table 3.2: Definitions of extreme climatic indices

S. N	ID	Indicator name	Definitions	Unit
1	SU25	Summer days	Annual count when TX (daily maximum) >25ºC	Days
2	TR20	Tropical nights	Annual count when TN (daily minimum) >20ºC	Days
3	TXx	Max Tmax	Monthly maximum value of daily maximum temp	ºC
4	TNx	Max Tmin	Monthly maximum value of daily minimum temp	ºC
5	TXn	Min Tmax	Monthly minimum value of daily maximum temp	ºC
6	TNn	Min Tmin	Monthly minimum value of daily minimum temp	ºC
7	TN10p	Cool nights	Percentage of days when TN<10th percentile Days	Days
8	TX10p	Cool days	Percentage of days when TX<10th percentile Days	Days
9	TN90p	Warm nights	Percentage of days when TN>90th percentile	Days
10	TX90p	Warm days	Percentage of days when TX>90th percentile	Days
11	WSDI	Warm spell duration indicator	Annual count of days with at least 6 consecutive days when TX>90th percentile	Days
12	CSDI	Cold spell duration indicator	Annual count of days with at least 6 consecutive days when TN>90th percentile	Days
13	DTR	Diurnal temperature range	Monthly mean difference between TX and TN	ºC
14	RX1day	Max 1-day precipitation amount	Monthly maximum 1-day precipitation	mm
15	RX5day	Max 5-day precipitation amount	Monthly maximum consecutive 5-day precipitation	mm
16	SDII	Simple daily intensity index	Annual total precipitation divided by the number of wet days in the year	mm/day
17	R10	Number of heavy precipitation days	Annual count of days when PRCP>=10mm	Days

18	R20	Number of very heavy precipitation days	Annual count of days when PRCP>=20mm	Days
19	CDD	Consecutive dry days	Maximum number of consecutive days with RR<1mm Days	Days
20	CWD	Consecutive wet days	Maximum number of consecutive days with RR>=1mm Days	Days
21	R95p	Very wet days	Annual total PRCP when RR>95th percentile	mm
22	R99p	Extremely wet days	Annual total PRCP when RR>99th percentile	mm
23	PRCPTOT	Annual total wet-day precipitation	Annual total PRCP in wet days (RR>=1mm) mm	mm

Source: Zhang and Yang, (2004)

3.4 Future Climate Projection

Climate for the future has been projected following the outputs of the Coupled Model Inter-comparison Project - Phase 5 (CMIP5). CMIP5 is a collaborative modeling, coordinated by the World Climate Research Programme (WCRP), which employs diverse climate forcings. Projections of future climate were performed at Thakmarpha (Index: 604), Khudi Bazar (Index: 802), Gorkha (Index: 809), and Chame (Index: 816), all of which provide long-term temperature and precipitation data. In the dataset, missing values were adjusted by filling the gaps with long-term average daily values for each of the variables. Then, from the South Asia CORDEX data portal, three different Regional Climate Models (RCMs) with $0.5^{o} \times 0.5^{o}$ horizontal resolution, ACCESS-1, CNRM-CM5, and MPI–ESM-LR, were downscaled and divided into two periods, near-future (2014-2033) and mid-future (2034-2053), to predict future climate scenario (Table 3.3). Only future periods up to the mid-century were analyzed with the study's focus on river health and water infrastructure development. The RCMs used in this study were chosen based on previous research reviews (Annex 2) and its characteristic is briefly presented in Table 3.3. RCM outputs are usually only accessible for RCP4.5 and 8.5, with RCP 2.6 being provided on rare occasions. As a result, RCP 4.5 was chosen as a medium stabilizing scenario in this study, with a stabilization without overshoot pathway leading to 4.5 W/m^2 (~650 ppm CO_2) at stabilization after 2100 and RCP 8.5 has been chosen as a very high emission scenario, which refers to rising radiative forcing pathways leading to 8.5W/m^2 (~1370 ppm CO_2) by 2100. To remove the systematic bias in the downscaled data, a quantile mapping bias correction approach was applied to all raw daily temperature and precipitation time series before calculating the extreme climatic indices with RClimDex, as detailed in section 3.3.2. The analysis of future climate extreme indices was based on ensemble time series data, which helps to reduce projection uncertainty.

Table 3.3: Summary of RCMs

RCM	RCM Description	Forcing GCM	Affiliated Institute	Resolution
ACCESS 1 CNRM - CM5	Commonwealth Scientific and Industrial Research Organisation (CSIRO), Conformal-Cubic Atmospheric Model (CCAM; McGregor and Dix, 2001)	ACCESS 1.0 CNRM-CM5 CCSM4 GFDLCM3 MPI-ESMLR NorESM-M (McGregor and Dix, 2001	CSIRO Marine and Atmospheric Research, Melbourne, Australia	0.5° × 0.5° horizontal resolution
MPI-ESMLR		(CCLM) MPIESM-LR (Giorgetta et al. 2013)		

3.5 Water Availability and Hydrological Extremes Assessment

3.5.1 Soil and Water Assessment Tool (SWAT)

SWAT is a physically-based hydrologic model (Neitsch *et al.*, 2011) with open-source and several add-ons for calibration and uncertainty assessment (Abbaspour *et al.*, 2007). SWAT can simulate surface and subsurface flow and nutrient cycling and transport, among others (Arnold *et al.*, 2011). A watershed can be discretized into sub-basins and hydrologic-response units (HRUs), depending upon land use and soil distribution, to represent spatial heterogeneity. Watershed model parameters in each HRU indicate a volume average of their variability across the unit, which is made up of homogeneous land use, management, soil attributes, slopes, and weather conditions (Srinivasan, 2012; Wang *et al.*, 2021). HRU water balance components control discharge at the outlet of a sub-basin. The sub-basins are connected via a river network and water movement is represented as routing.

SWAT uses soil, DEM, land use, and meteorological data as inputs. Variation in precipitation and temperature with altitude is represented using elevation bands and lapse rate.

SWAT is also suitable for simulating future discharge using GCM climate data. Once a model is calibrated and validated, future climate data can be incorporated into the model to project future discharge. Weather Generator files in SWAT help to fill in missing data. It is one of the most important advantages of using SWAT. If data is missing in certain stations, the presence of the Weather Generator file helps to overcome the missing data. Therefore, in the mountain region where data is inadequate Arc SWAT can be very effective use (Xu, 2015). The general equation for SWAT model is given below:

$$SW_t = SW_{0+} \sum Rday - Qsurf - Ea - Wseep - Qgw \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where SW_t is the final soil water content (mm), SW_0 is the initial soil water content and Rday, Qsurf, Ea, and Wseep are daily amounts of precipitation, runoff, evapotranspiration, percolation in mm respectively and Qgw is the amount of return flow to compute water balance at the HRU level.

3.5.2 Model inputs and set-up

Input data were collected from various sources, assessed their quality, and pre-processed to feed as input to the SWAT model. ArcSWAT 2012 was used as an interface to set up the model in Marshyangdi Watershed. DEM was used to derive the stream network and subbasins boundaries. For this, we selected a threshold drainage area of 500 ha. Monitoring points were added manually based on all the hydropower stations which are at various stages of development (in operation, planned, got license), and divided the watershed into 63 sub-basins and 469 HRUs. To define the HRUs, we derived a slope map from the DEM and separated them into 3 classes with breaks at 5%, 10%, 15%, and 20%. We used thresholds of 10%, 10%, and 10% for land use, slope, and soil, respectively. To simulate the process of snowmelt and orographic distribution of temperature and precipitation ten elevation bands with a 500 m interval were developed. For documenting glacier and snowmelt contribution to water availability all the input parameters related to snow (SFTMP, SMTMP, SMFMX, SMFMX, TIMP) were taken while calibrating and validating the model. As a result, the projected water availability in the current and future scenarios has not been underestimated or overestimated as revealed by acceptable statistical performance at the watershed's outlet. The weather conditions of those meteorological stations which do not exists above 4000m within the watershed were accurately represented by defining ten elevation bands at an altitude of 500m and by using the model's built-in weather generation tool. Further overall climatic condition of the watershed has been well represented by calibrating the model using parameters like temperature and precipitation lapse rate with good statistical performance.

Then the model was fed with daily weather data. Surface runoff was evaluated using the SCS curve number technique, which estimates daily curve numbers as a function of soil moisture. Penman-Monteith method was used to calculate PET. Similarly, the flow in the channels was routed using a Muskingum method, a variable storage method.

The spatial dataset used for the SWAT model development is briefly explained below.

3.5.2.1 Digital Elevation Model (DEM)

To depict the topographic features of the Marshyangdi Watershed, it was retrieved from the Shuttle Radar Topography Mission (SRTM). DEM from SRTM has a coordinate system of WGS1984 and has a resolution of 90 m. As per the DEM, the elevation of the watershed ranges from 226-8,042 m (Fig. 3.3).

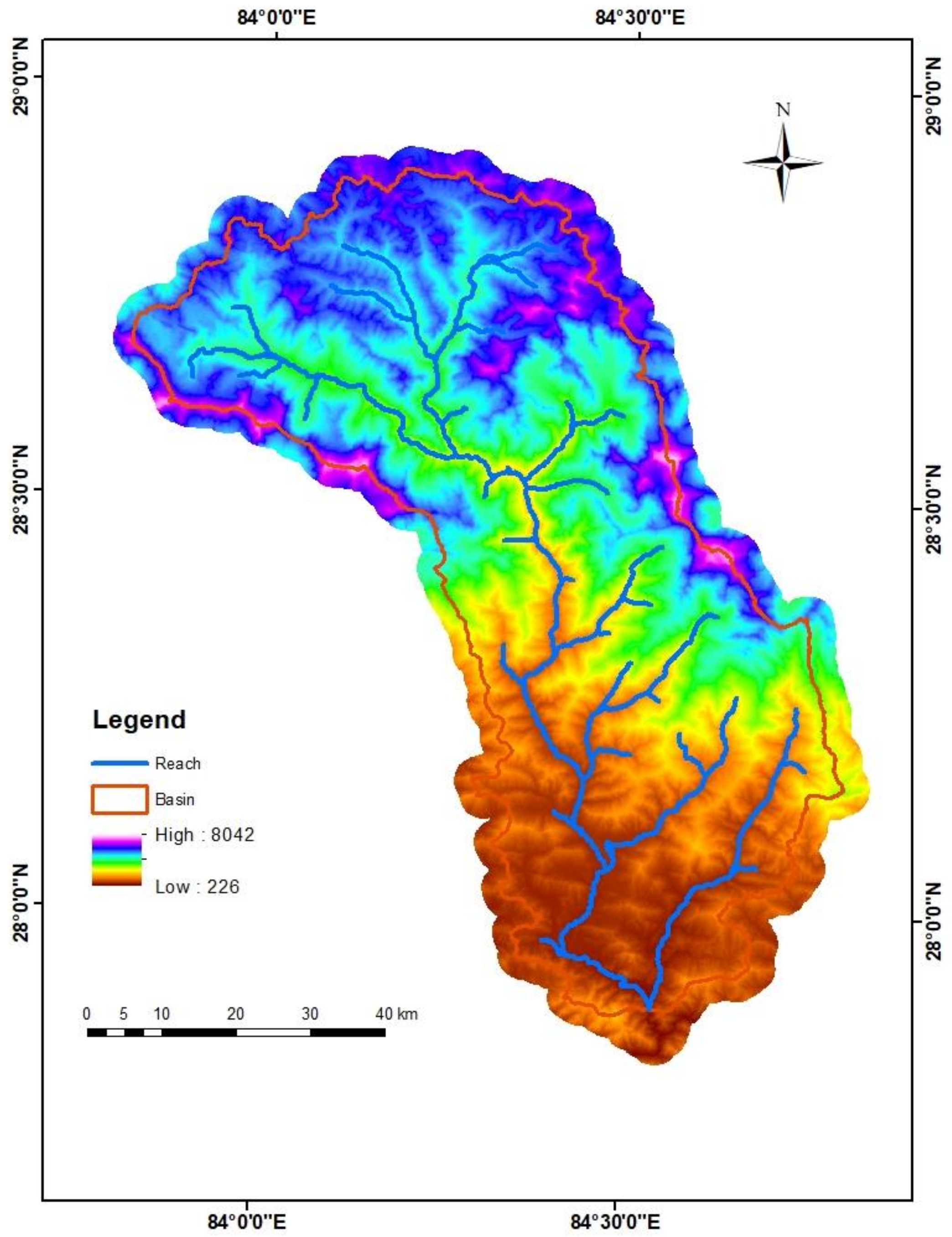

Figure 3.3: DEM map of Marshyangdi Watershed

3.5.2.2 Land Cover (LC)

Land use land cover data was retrieved from ICIMOD (2010). The classification showed that grassland covers the major proportion, followed by barren terrain and agricultural land, in the watershed. Grassland covers 17.41%, barren land covers

11.78% and agricultural land covers 11.28% with the remainder of shrubland, woodland, water bodies, snow and glaciers, and built-up areas (Fig. 3.4).

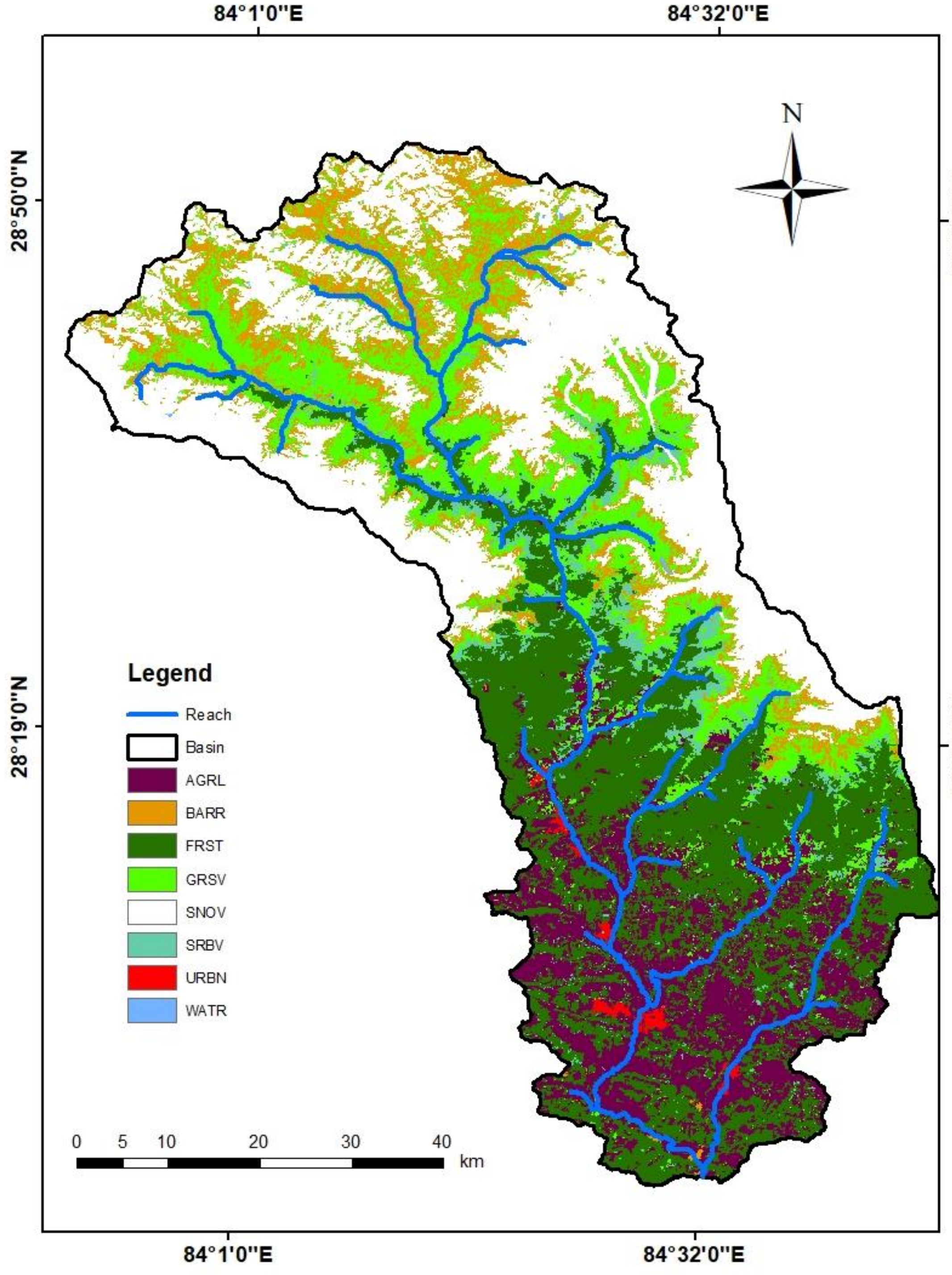

Figure 3.4: Land use map of Marshyangdi Watershed

3.5.2.3 Soil

Spatial distribution in soil within the watershed was obtained from the Soil and Terrain (SOTER) map (Dijkshoorn & Huning, 2009) and is presented in Fig. 3.5. In the basin Gelic Leptosol is dominant soil type covering 54.4% followed by Humic Cambisol (13.0%), Eutric Cambisol (12.0%), Eutric Regosol (9.2%), Chromic Cambisol (7.2%), Glacier (1.1%), and Gleyic Cambisol (2.1%) of the area.

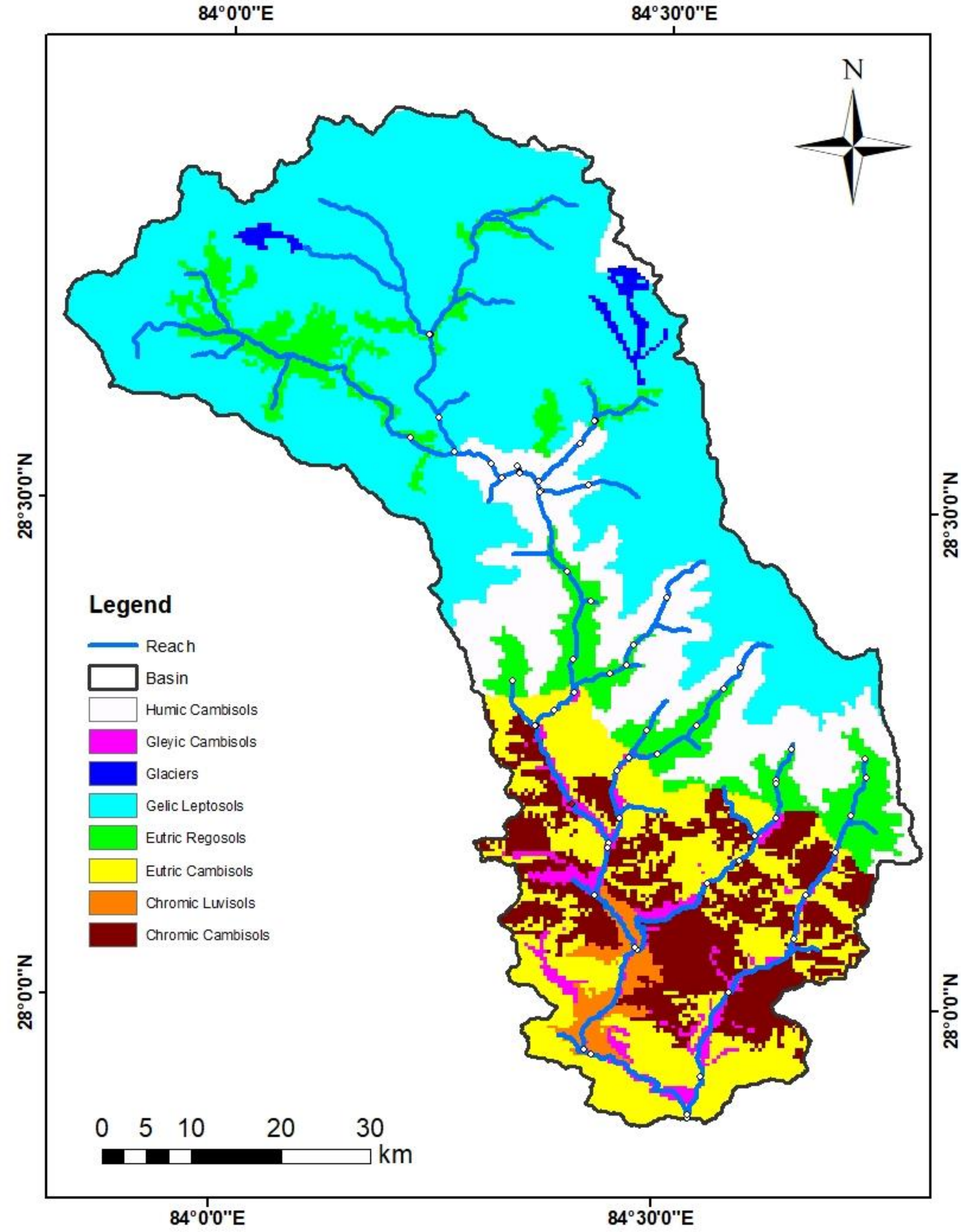

Figure 3.5: Soil map of Marshyangdi Watershed

3.5.2.4 Slope

Slope in the Marshyangdi Watershed was derived from DEM. Its spatial distribution is shown in Fig. 3.6. The slope of the Marshyangdi Watershed is categorized into three categories: 0-25%, 25-45%, and 45% above. The majority of the basin is above 45 percent slope and covers 2488 km^2 (60 percent) of the basin's total area. Similarly, a slope above 25% occupies 1037 km^2 area and 25% occupies 623 km^2 area.

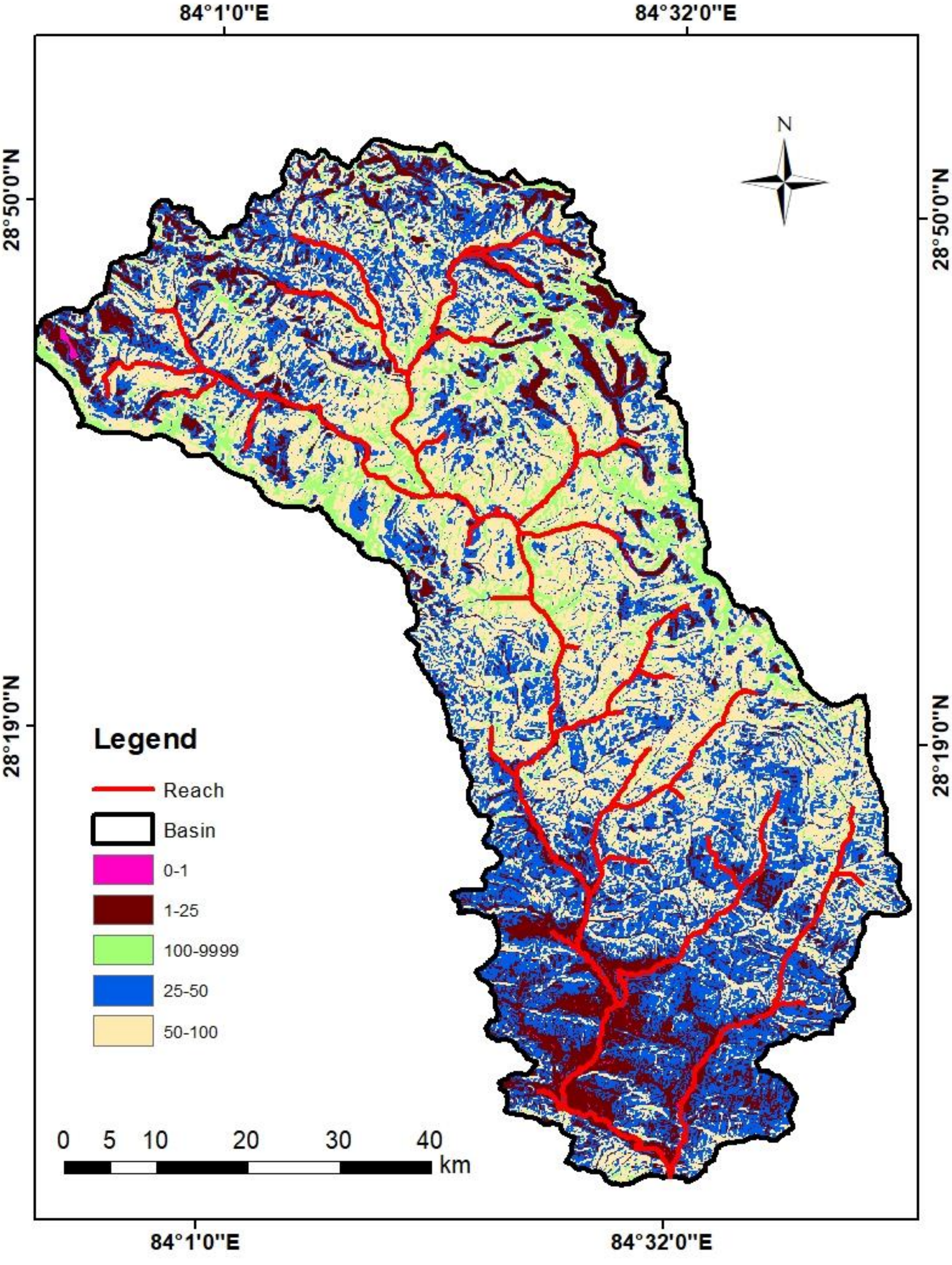

Figure 3.6: Slope map of Marshyangdi Watershed

3.5.2.5 Weather Data

Weather data, daily rainfall, temperature, humidity, wind speed, and sunshine hour, for the study area, were collected from the Department of Hydrology and Meteorology (DHM), Nepal. As the unit for daily precipitation and temperature data collected from DHM have the same unit that needs to be fed in the SWAT model these data were directly fed in SWAT (i.e., mm, °C), without any conversion in the unit. In the case of wind speed, DHM data was in km/hr unit so it was converted into m/s unit before feeding to the SWAT model. Similarly, observed relative humidity data from DHM has morning and evening values in percentage per day which have been conv erted into a fraction to feed in SWAT. For the case of solar radiation, data from DHM has been received in a form of the sunshine hour so it has been converted to MJ/m^2/day data as per the SWAT template. The Angstrom Prescott (AP) model was used to convert sunshine hours to solar radiation (Allen *et al*., 1998). All the time-series data were quality-checked and filled with the normal ratio method. Finally, all of the above-prepared data are converted into a ".txt" file and become ready for SWAT input (1987-2015).

3.5.3 Model calibration and validation

Calibration is the process of comparing model outputs to historical meteorological data (Danqing *et al.*, 2015). SWAT-CUP an interface developed for SWAT was employed for auto-calibration and validation of the model. Among various programs supported by SWAT- CUP (SUFI2, PSO, GLUE, Para Sol, and MCMC) we used SUFI2 software with SWAT CUP version 5.1.6.2 for model calibration, validation sensitivity, and uncertainty analysis.

For calibration and validation daily observed hydrological data at three stations have been used (Table 3.2). Such multisite calibration approaches are considered best against the calibration at a single site (Hasan & Pradhanang, 2017). The observed data length was then divided into two groups for calibration and validation based on the data quality of each station. Exploratory analytic tools like hydrographs, mass curves, and data reading were used to examine the observed hydrological data. At the station, the Q439.35 timeframe of 1998–2010 was selected for the simulation with calibration and validation periods of 2003–2004 and 2006–2007, respectively. At the station, Q439.7

calibration and validation periods were from 2000–2005 and 2006–2010 respectively. At Q440 calibration and validation periods were taken from 2000-2005 and 2006-2010, respectively. Finally, at Q439.3 calibration and validation periods were taken from 1987-1991 and 1992-1995, respectively.

Two years of warmup period was taken to generate soil and groundwater conditions before calibration. The model was calibrated in three stages: i) Sensitivity analysis, ii) Auto-calibration in SWAT-CUP, and iii) Manual calibration. During manual calibration, sensitivity was determined using SUFI-2 global sensitivity analysis, in which one parameter value is altered at a time while the others remain constant. With parameter ranges recommended in SWAT documentation, auto-calibration was run for 200 iterations (Neitsch *et al.,* 2011). Twenty (28) model parameters (Table 3.4) were selected for sensitivity analysis based on a literature review (Bajracharya *et al.,* 2018; Pandey *et al*., 2020). The simulated and observed hydrographs did not match well, although the range of values for the sensitive parameters was cut down during autocalibration. The results of the autocalibration were then manually calibrated using relevant model parameters to match the simulated hydrograph to the observed data. During manual calibration, the most sensitive parameters were adjusted first, followed by the less sensitive ones. Other parameters that were not detected during the sensitivity analysis were changed to more realistic values, resulting in better model performance. The basis for evaluating model performance was a visual inspection of the hydrographs (peaks, time to peak, shape of the hydrograph, and baseflow), scattered plots, flow duration curves, statistical parameters, and water balance comparison at daily, monthly, and annual scales. For performance evaluation, the following statistical metrics were used: coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), change in mean values, and residual variation (RSR). Monthly and daily simulations were used to assess the model's performance. Efforts were made throughout the calibration procedure to maintain physically based parameters within an optimum range (Table 3.4).

Table 3.4: SWAT parameters selected for calibration of Marshyangdi Watershed at Bhakundebesi

Parameters	Description	unit	Adjustment	Process	Initial value range	Calibrated value
Parameters Controlling Surface Water Response						
CN2	Initial SCS Curve no	-	Varies	Runoff (.mgt)	35-98	1.48 times
SURGLAG	Surface Runoff lag coefficient	days	Replace	Runoff (.bsn)	0.05-24	4.56
Parameters Controlling Sub-Surface Water Response						
GW_DELAY	Delay time for aquifer recharge	days	Replace	Groundwater (.gw)	0–500	55
GWQMN	Threshold depth of water in shallow aquifer for groundwater return flow to occur	mm	Replace	Soil (.gw)	0-5000	26
GW_REVAP	Groundwater revap coefficient	-	Replace	Groundwater (.gw)	0.02–0.2	0.02
REVAPMN	Threshold depth of water in shallow aquifer for revap to occur		Replace	Groundwater (.gw)	0 – 500	480
RCHRG_DP	Deep aquifer percolation fraction		Varies	Groundwater (.gw)	0 – 1	0.05
ALPHA_BF	Baseflow recession constant	days	Replace	Groundwater (.gw)	0 – 1	0.415
OV_N	Manning's n value for overland flow	-	Varies	HRU(.hru)	0.01-30	6
LAT_TTIME	Lateral flow travel time	days	Replace	HRU(.hru)	0– 80	22.58
Parameters Controlling Soil's Physical Properties						
SOL_AWC	Available water storage capacity of the soil layer	-	Varies	Soil (.sol)	0 – 1	0.1times
SOL_K	Saturated soil conductivity	mm/hr	Varies	Soil (.sol)	0 – 2000	0.75
SOL_Z	Depth from soil surface to bottom of layer	mm	Varies	Soil (.sol)	0 – 3500	0.05
SOL_BD	Moist bulk density		Varies	Soil (.sol)		0.02
Parameters Controlling Channels's Physical Properties						
CH_K2	Effectivity hydraulic conductivity in main channel alluvium	mm/hr	Replace	Channel (.rte)	0–150	108.7
CH_N2	Manning's "n" value for the main channel	-	Replace	Channel (.rte)	0 – 1	0.95
AlPHA_BNK	Baseflow alpha factor for bank storage	days	Replace	Channel (.rte)	0-1	0.205
TLAPS	Temperature lapse rate	°C/km		Topographic effect (.sub)	-10-10	-0.279
PLAPS	Precipitation lapse rate	mm/km		Topographic effect (.sub)	0-100	95.36
Parameters controlling Water balance						
EPCO	Plant uptake compensation factor	-	Replace	Evaporation (.hru)	0 – 1	0.75
ESCO	Soil evaporation compensation factor	-	Replace	Evaporation (.hru)	0 – 1	0.32
CANMX	Maximum canopy storage	mm	Replace	Runoff (.hru)	0 – 100	79.5
SLSUBBSN	Average Slope Length	m	Varies	Geomorphology(.hru)	10-150	0.75
SFTMP	Snowfall temperature	°C	Replace	Snow (.bsn)	-20 – 20	-3.65
SMTMP	Snow melts base temperature	°C	Replace	Snow (.bsn)	-20 – 20	6.5
SMFMX	Minimum melt rate for snow during the year	mm/°C /day	Replace	Snow (.bsn)	0-20	4.9

SMFMN	Minimummelt rate for snow during the year	mm/°C /day	Replace	Snow (.bsn)	0-20	5.6
TIMP	The snowpack temperature lag factor dictates how quickly the snowpack temperature is affected by the air temperature.	°C	Replace		0-1	0.9

The performance of the model was checked for both calibration and validation by using the following performance indicators.

Coefficient of Determination (R^2): R^2 is used to calculate the fitness of good between observed and final best simulation. In the same way, it helps to determine the agreement between the projected and observed values. It has a range of 0 to 1, with higher values suggesting lower error variance, and values greater than 0.5 are generally regarded as acceptable (Cheng, 2014). R^2 equal to 1 indicates a perfect fit (Moriasi *et al.*, 2007).

$$R^2 = \frac{\left[\sum_i\left(Q_i{}^{obs}-\overline{Q^{obs}}\right)\left(Q_i{}^{obs}-\overline{Q^{sim}}\right)\right]^2}{\sum_i\left(Q_i{}^{obs}-\overline{Q^{obs}}\right)\sum_i\left(Q_i{}^{obs}-\overline{Q^{sim}}\right)^2} \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where,

Q_{iobs} = i^{th} observation value

Q_{isim}= i^{th} simulated value

Q_{imean} = mean of observed value

n = total number of observations

Nash-Sutcliffe (NS): Nash-Sutcliffe shows how good enough simulated or projected data and observed data fit in the ratio of 1:1 and its value ranges between -∞ and 1, where 1 is considered as optimal value. However, there is also the disadvantage of using NS; the difference between observed and simulated values is squared, resulting in undervaluation of small values and overvaluation of big ones (Krause *et al.*, 2005).

$$NS = 1-\left[\frac{\sum_{i=1}^{n}\left(Q_i{}^{obs}-Q_i{}^{sim}\right)^2}{\sum_{i=1}^{n}\left(Q_i{}^{obs}-Q_i{}^{mean}\right)^2}\right] \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where,

$Q_i$obs = i^{th} observation value

Qisim = i^{th} simulated value

$Q_i$mean = mean of observed value

n = total number of observations

Percent bias (PBIAS)**:** PBIAS gives the average tendency of simulated data to be greater or smaller than observed data. In other words, it is the deviation of simulated or projected data which is expressed in percentage (Cheng *et al.*, 2014). The low magnitude of PBIAS indicates better simulations. PBIAS < 15% is acceptable as recommended (Santhi *et al.*, 2001). Similarly, if the value is less than or equal to 20%, it is considered good and between 20% and 40% are taken as satisfactory and values above 40% are taken as unsatisfactory (Santhi *et al.*, 2001).

$$\text{PBIAS} = \left[\frac{\sum_{i=1}^{n}(Q_i{}^{obs} - Q_i{}^{sim}) \times 100}{\sum_{i=1}^{n}(Q_i{}^{obs})}\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

where,

$Q_i$obs = i^{th} Observation value

Qisim= i^{th} simulated value

$Q_i$mean = mean of observed value

n = total number of observations

The rating value for percentage bias given by (Moriasi *et al.*, 2007) is given below in Table 3. 5.

Table 3.5: General recommended performance ratings statistics for SWAT

RSR	**NSE**	**PBIAS (%)**	**Performance rating**
0≤RS ≤ .05	0.75<NSE≤1	PBIAS<±10	Very good
0.5<RS ≤0.6	0.65<NSE≤0.75	±10≤PBIAS<±15	Good
0.6<RSR≤0.7	0.5<NSE ≤0.65	±15≤PBIAS<±25	Satisfactory
RSR>0.7		PBIAS>±25	Unsatisfactory

Moriasi et al. (2007)

3.5.4 Analysis of hydrological extremes

The Indicators of Hydrologic Alterations (Mathews & Richter, 2007) tool (IHA7.1) was used to assess the hydrological extremes in the Marshyangdi Watershed. This tool employs a non-parametric range of variability method (RVA) to characterize changes in river flow, (Ritcher *et al.,* 1997). RVA performs statistical analysis of the temporal variability in the hydrologic regime and quantifies the degree of change in 33 ecologically significant hydrologic parameters (Table 3.6), which define critical linkages between flow and hydrologic characteristics.

Table 3.6: Summary of hydrologic parameters in the Indicators of Hydrologic Alteration Tool

IHA statistics Group	Regime characteristics	Hydrological characteristics
Group 1: Magnitude of monthly water conditions	• Magnitude	• Mean value for each calendar month
	• Timing	
Group 2: Magnitude and duration of annual water extreme conditions	• Magnitude • Duration	• Annual maxima and minima of 3 day mean • Annual maxima and minima of 7 day mean (weekly) • Annual Maxima and Minima of 30 day mean(monthly) • Annual maxima and minima of 90 day mean
	• Timing	• Julian date of each annual 1-day maxima • Julian date of each annual 1-day maxima
Group 3: Timing of annual extreme	• Magnitude	• No of high pulses in each year
Group 4: Frequency and duration of high and low pulses	• Frequency	• No of low pulses in each year
	• Duration	• Mean duration of high pulses within each year • Mean duration of Low pulses within each year
	• Frequency	• Mean of all positive differences between consecutive daily means
Group 5: Rate and Frequency of water	• Rate of change	• Mean of all negative differences between consecutive daily means • No of rises • No of falls

The Nature Conservancy, (2009)

RVA targets are based upon values at ± 1 SD from the mean for each of the 33 IHA parameters except when such targets would fall outside the pre-dam range limit. RVA analysis sets the boundaries of 17 percentiles from the median value. The lowest category (low alteration) contains values less than or equal to the 33th percentile. The middle category (moderate alteration) ranges from 34th to 67th percentile and the highest category (high alteration) the values greater than 67th percentile **(**Richter *et al.,* 1998). A positive hydrologic alteration value (with a maximum value of infinite) indicates that the frequency of values in the category has increased from the pre-impact to the post-impact period, whereas a negative value indicates that the frequency of values has decreased (with a minimum value of -1). Further to determine the consequences of the intervention on alterations, each IHA is calculated in terms of median value, deviation degree, and degree of hydrological alteration between two periods: pre-impact and post-impact, as shown in eq. 5. The percentage of deviation degree of each hydrologic alteration of streamflow regime is calculated as (Timpe & Kaplan 2017; Xue *et al.,* 2017)

$$Pi\ (\%) = \frac{(Mpost - Mpre)}{Mpre} * 100 \quad \text{...(5)}$$

Where $M_{\mathbf{post}}$ is the median for the post-impact period and $M_{\mathbf{pre}}$ is the median for the pre-impact period. After calculation of the percentage of deviation degree, these values were then averaged by parameter groups and across all parameters. A positive *Pi* value indicates an increased median value in the post-impacted period compared to the pre-impacted period while a negative *Pi* suggests a decreased median value in the post-impacted period compared to the pre-impacted period. The following equation can be used to calculate the degree of hydrological change in a river regime for each indicator (Ritcher *et al.,* 1998).

$$D_i = \left|\frac{OF - EF}{EF}\right| \times 100 \quad \text{......................................(6)}$$

where *OF* is the observed number of post-impacted years for which the value of the indicator falls within the RVA target range, from 25th percentile to 75th percentile, as suggested by Richter et al. (1998); *EF* is the expected number of post impacted years for which the value of indicator falls within the targeted range and can be estimated by $r \times NT$ (r is the percentage of pre-impacted years for which the value of an indicator falls within the RVA target range) and NT is a total number of post impacted years).

In general, RVA considers a natural flow sequence of a hydrological flow to be an ideal situation. The flow regime is expected to be healthy if an environmental flow scheme meets a predetermined target range at the same frequency as it occurs naturally. Because different hydrologic indices may reveal varying levels of flow regime variability. As a result, the overall degree (OD) of hydrologic change for all indices can be calculated as:

$$D = \sqrt{\frac{\sum_{i=1}^{32} D_i^2}{32}} \qquad \text{………………….……………. (7)}$$

Hydrologic change is zero when the observed frequency of post-development annual values falling within the RVA target range equals the predicted frequency (The Nature Conservancy, 2009).

Furthermore, for a homogenous time series (i.e., before and after the change point), gradual trends in the time series were calculated using the Mann-Kendall test and Sen's slope estimator. The pre-and post-impact periods in the Marshyangdi Watershed were determined using Pettitt's (Pettitt, 1979) test in R software using annual average time series data. This test is useful for determining the occurrence of abrupt changes in climatic data (Tarhule &Woo, 1998). It compares hypothesis H_0: The variables follow one or more distributions with the same location parameter (no change) against hypothesis H_1: There is a change point.

3.5.5 Climate Change impacts on water availability and hydrological regime

Effects of climate change on hydrologic regime were evaluated by feeding bias-corrected RCM outputs into well-calibrated and validated hydrological models (Bastola *et al.*, 2011). Projected time series data of flow (Q) at each sampling sites was calculated by using the drainage-area ratio method as shown in equation 8 after applying suitable formula at the respective sampling sites. Then IHA software was run to determine the hydrologic alteration in the flow regime for both RCP scenarios by using the projected time series data (Q).

Further water availability was determined based on river flow on a monthly and seasonal basis in the watershed and at the sample sites for the near (NF) and mid-future (MF) under both RCP scenarios. Similarly, flow health was also determined with the Flow health software (version-3.0) at the watershed and sampling stations to determine the hydrological condition using the projected simulated data from the SWAT model (Q).

$$Q_2 = \frac{A1}{A2} \times Q1 \qquad (8)$$

Where,

Q_1 is the estimated streamflow for a site of interest
Q_2 is the streamflow at the gauging station
A_2 is the drainage area for the site of interest
A_1 is the drainage area, for the streamflow-gaging station

3.6 Assessment of River Health

3.6.1 Identification of indicators and metrics

River health status along the mainstream and tributaries of the Marshyangdi Watershed is characterized in the form of river health index (RHI), which is an aggregation of components: hydrological, water quality, biological and physical, and 43 metrics as shown in Fig 3.7. Based on a thorough literature review related to river health assessment and protocols of various countries, an overall customized framework (Fig.3.7; Annex 1) and a comprehensive table have been prepared (Annex 3). The selected indicators and metrics (Fig.3.7) capture the river health status easily, and they are cost-effective, representative, scientific, practical, and could be easily adapted for future users (government or any private authority). Description of each component and their indicators, estimation of weights, and criteria for characterizing river health status are elaborated in the following sub-sections.

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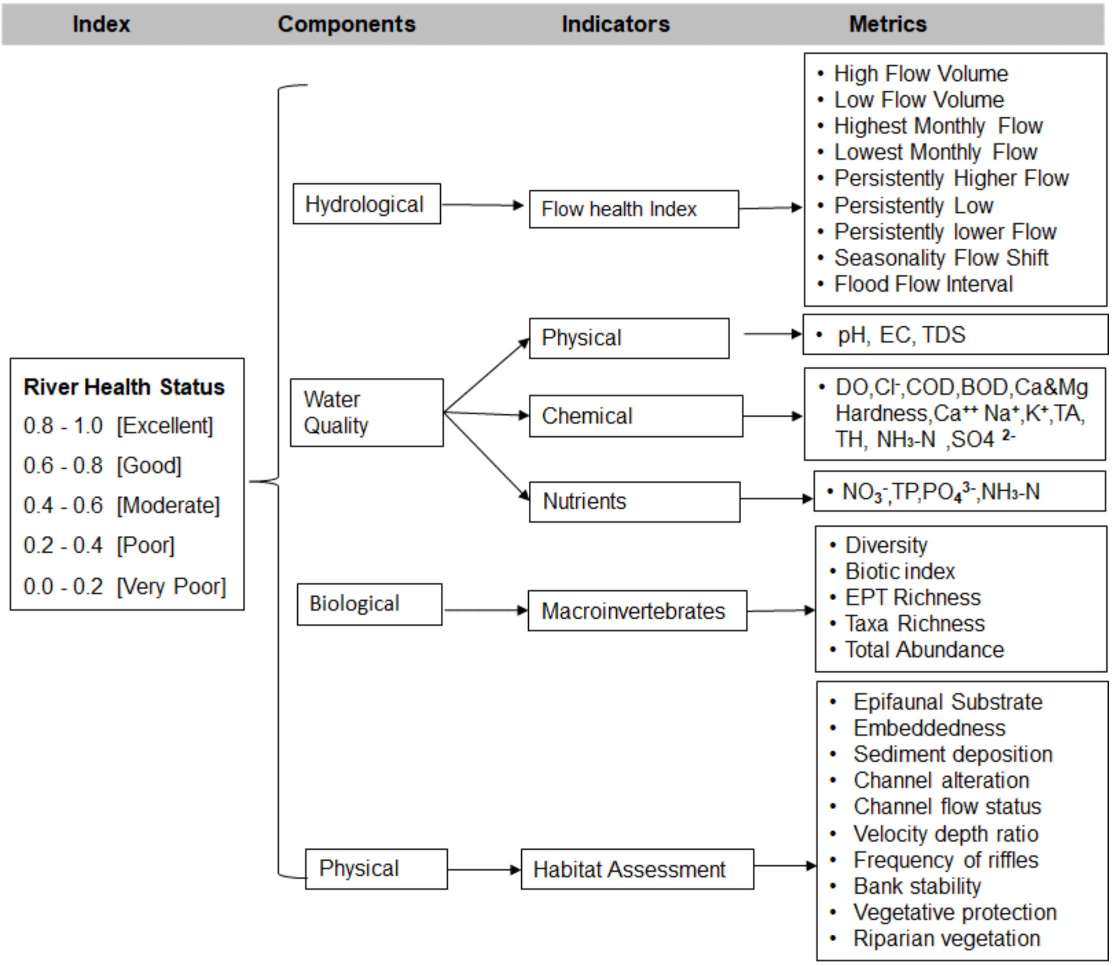

Figure 3.7: Framework for river health assessment in the Marshyangdi Watershed

3.6.1.1 Computation of river health index

The river health was evaluated using the four components, hydrological water quality, biological and physical by using the following equation (9). This method overcomes the defects of traditional methods used for river health assessment and gives quantitative and objective results (Zhao *et al.*, 2019).

$$RHI = \sum_{i=1}^{n} W_i . P_i \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(9)}$$

Where, $Pi = \sum_{i=1}^{m} W_{ij} . P_{ij}$

Where RH is the integrated health score weighted by its components including hydrology, water quality, biology, and physical.

P_i, w_i, P_{ij}, and w_{ij} are the first level index, first-level index weight, second-level index, and second-level index weight, respectively; n and m are the total number of first level indices, i.e., components and second level indices; and P_i, w_i, P_{ij}, and w_{ij} are the first level index, first-level index weight, second-level index, and second-level index weight, respectively. Hydrology, water quality, biology, and habitat condition were addressed by the first-level indices, whereas the second-level indices quantify the first-level indices' characteristics. The entropy weight technique, which is based on the thermodynamic notion of entropy information theory, was used to determine the weights of the indices. This strategy identifies the relevance of different indicators more objectively by reducing the anthropogenic interference created by typical weight assignment methods (Xie *et al.*, 2018; Xue *et al.*, 2020).

Entropy weight method

Entropy weight can be calculated in three steps. First of all, the original data of indices are normalized (non-dimensional value) to remove the differences in the scope of the selected indexes, by using equation 10 before analyzing the indexes. Then information on Entropy of the index (H_j) and degree of divergence (d_j) and finally Entropy weight values (w_j) are calculated using equations 10-14 respectively. Eq. (13) is used to normalize the concentration values of the benefit indicators, such as DO:

$$rij = \frac{x_{ij} - MIN_i\{x_{ij}\}}{MAX_i\{x_{ij}\} - MINI_i\{x_{ij}\}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

As for the cost indicators, such as COD, Eq. (12) is used

$$rij = \frac{Max_i\{x_{ij}\} - xij}{MAX_i\{x_{ij}\} - MINI_i\{x_{ij}\}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

where r_{ij} (i =1, 2, …, m and j =1, 2, …, n) is the standardized dimensionless value of the i-th object with the j-th index; m and n represent the number of indicators and the number of years surveyed, respectively; x_{ij} is the initial value of the index i in j-th year, and r_{ij} is the normalized value of x_{ij}.

The divergence degree d_j of the intrinsic information of jth index is calculated as

$$H_j = -k \sum_{i=1}^{m} In(r_{ij}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

Where the constant k =1/ln (m),

When rij =0, ln (fij) becomes meaningless, hence r_{ij} is then substituted as

$$\frac{0.001}{maxi(xij) - mini(xij)}$$

The divergence degree dj of the intrinsic information of jth index is calculated as (Eq -14)

$$dj = 1 - Hj \text{ .... } (13)$$

Therefore, the entropy weight wj of the jth index could be calculated as

$$w_{j=}\frac{d_j}{\sum_{j-1}^{n} d_j} \text{.................................. } (14)$$

Where w_j is the entropy weight of the index j

Finally, river heath was categorized and presented in Annex 4.

3.6.2 Computation of components for the river health condition

3.6.2.1 Water quality sub-index

For the physicochemical assessment of the water, twenty-one sampling stations were chosen from downstream (before mixing with the Trisuli River) to upstream (non-impact area). The sampling stations were chosen based on the presence of major tributaries, anthropogenic factors like tourism and hydropower, and accessibility. Among the total 21 stations: 15 were in the mainstream and 6 were in the tributaries. This study was conducted for four seasons namely post-monsoon 2018, pre- and post-monsoon 2019, and pre-monsoon 2021, respectively. The detailed characteristics of the sampling stations are shown in Fig 3.8, Table 3.7.

Table 3.7: Description of sampling sites in the Marshyangdi River

Site Name	Site Code	Latitude (°N)	Longitude (°E)	Altitude (masl)	Description of sites
Kangsar	M1	83°56’55.12"	28º 40' 28. 23"	3714	Undisturbed site (M)
Dhukurpokhari	M2	84°09’36.53"	28º 36' 29.33"	3156	Undisturbed site (M)
Chame	M3	84°15’30.61"	28º 33' 11.53"	2604	Below Chame Bazar and Hotspring (M)
Dharapani	M4	84°21’31.08"	28º 30' 25.20"	1813	Cross-sectional point, the site after mixing with Dudh Khola (M)
Tal Bazzar	M5	84°22’24.57"	28º 27' 56.54"	1675	Settlement; tourism area (M)
Upper Marshyangdi U/S	M6	84°23’58.86"	28º 19' 52.52"	861	Upstream to Upper Marshyangdi HP (M)
Upper Marshyangdi D/S	M7	84°23’18.67"	28º 18' 12.39"	851	Downstream to Upper Marshyangdi HP (M)
Khudi	M8	84°21’’15.90"	28º 16' 58.55'	798	Tributary
Middle Marshyan gdi U/S	M9	84°24’05.40"	28º 12' 13.11"	610	Upstream to Middle Marshyangdi HP (M)
Middle Marshyangdi D/S	M10	84°25’58.00"	28º 10'59.70 "	582	Downstream to Middle Marshyangdi HP (M)
Dordi	M11	84°27’24.89"	28º 11' 22.33"	640	Tributary
Bhoteodar	M12	84°26’14.88"	28º 07' 49.52"	492	Upstream of Paudi River (M)
Paudi	M13	84°25’40.28"	28º 06'42.16"	477	Tributary
Chepe	M14	84°28’48.69"	28º 03' 23.90"	490	Tributary
Turture	M15	84°27’47.59"	28º 02' 06.57"	368	Downstream to the confluence of Tributary River Chepe to Marshyangdi (M)
Chudi	M16	84°24’53.67"	27º 57' 33.00"	378	Tributary river, dominated by human activities (washing, bathing)

Marshyangdi D/S	M17	84°27’59.37”	27º 56' 59.13"	335	Upstream of Marshyangdi HP
Marshyangdi D/S	M18	84°30’53.17"	27º 54' 55.25"	286	Downstream from Marshyangdi HP
Daraudi	M19	84°33’06.11"	27º 54' 54.68"	271	Tributary
Lower Marshyangdi	M20	84°32’25.58"	27º 53' 20.80"	227	Below the confluence point after mixing of Daraudi River with Marshyangdi (M)
Mugling	M21	84° 33’22.21"	27º 51' 26.67"	216	Downstream of the river, before mixing with Trisuli River (M)

Note: M is Mainstream of Marshyangdi River;D/S is Downstream;U/S is Upstream;HP is Hydropower

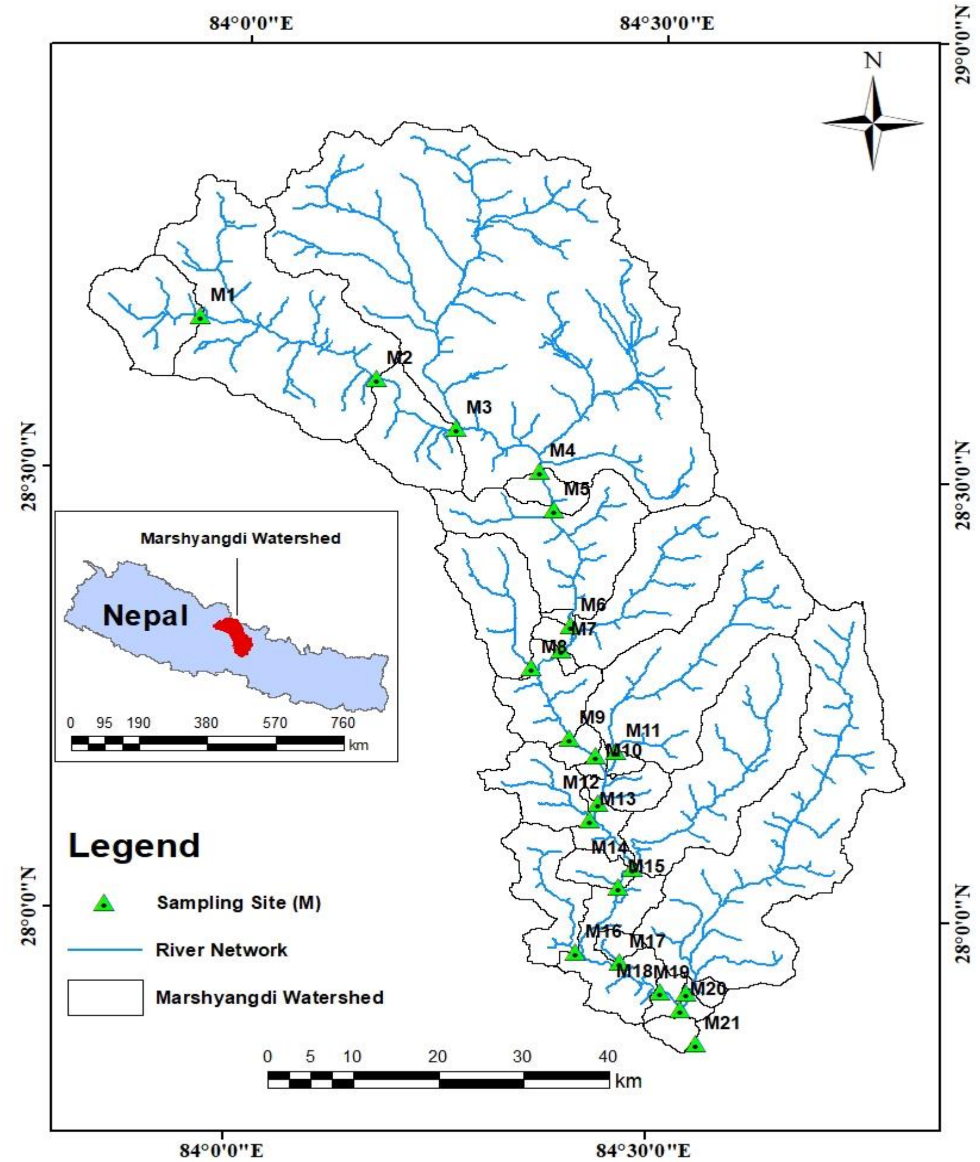

Figure 3.8: Sampling sites along the Marshyangdi Watershed

A) Water sample collection and analysis

Water samples were collected from the river's surface using a composite sampling technique for physicochemical parameter measurement. Three duplicates of surface water samples were collected, composited, and stored in a clean 500 mL polyethylene bottle. Following standard procedures, water samples were maintained in a cold box at 4° C to reduce microbial activity before being transported to the laboratory for chemical analysis (APHA, 2005).

B) Analysis of physio-chemical parameters

Twenty parameters representing the physiochemical characteristics of water were analyzed. But for the river health assessment, only 19 parameters including physical (i.e., pH, TDS, EC), chemical (i.e., DO, Cl^-, HCO_3^-, Ca^{2+}, K^+, Na^+ ions, NH_3-N, Total Hardness, Ca & Mg Hardness, COD, BOD, and SO_4^{2-}) and nutrients (i.e., TP, PO_4^{3-}, NO_3^-) were selected. Among these parameters, dissolved oxygen (DO), pH, conductivity, and total dissolved solids (TDS) were measured at the field (APHA, 2005) by using a multiparameter probe (HANNA; HI98129), Turbidity meter (SGZ1000BS/1710200), and Ecosense DO200A (Table 3.8). These probes were immersed in composite water in a beaker and the parameter readings were noted after the stabilization of the instrument. For some parameters like chloride, total hardness calcium hardness, and alkalinity, water samples were titrated at the field. For other parameters like potassium and calcium ions, chemical oxygen demand (COD), sulfate, total phosphorous (TP), ammonia (NH_3-N), nitrate-nitrogen (NO_3−N), and dissolved phosphate (PO_4^{3-}), 1 litre of water sample was collected in an acid rinsed high-density polyethylene (HDPE) bottle for laboratory analysis and was transferred in an icebox maintaining the temperature of 4°C. Similarly, water samples were preserved in a concentrated sulphuric acid in a separate 200 mL sampling bottle for the COD analysis. Details regarding methods adopted for the analysis of water quality are presented in (Table 3.8)

Table 3.8: Analytical method of water quality

SN	Parameters	Unit	Method	Instrument
		Chemical		
1	Dissolved oxygen (DO)	mg/L	Multipurpose	Ecosense DO200A
2	Chloride (Cl^-)	mg/L	Argentometric (APHA-AWWA-WEF, 2005)	Laboratory Glassware
3	Chemical Oxygen Demand (COD)	mg/L	Open Reflux (APHA-AWWA-WEF, 2005)	Reflux Apparatus
4	Ca^{2+}, Na^+, K^+, ions	mg/L	Flame Photometric (APHA-AWWA-WEF, 2005)	Flame photometer: JENWAYPFP7; Wagtech International Ltd
5	Total Alkalinity (TA)	mg/L	Titration APHA-(AWWA-WEF, 2005)	Laboratory Glassware
6	Total Hardness (TH): Ca & Mg	mg/L	EDTA Titrimetric (APHA-AWWA-WEF, 2005)	Laboratory Glassware
7	Sulphate (SO_4^{2-})	mg/L	Turbidimetric	Laboratory Glassware

8	Biological Oxygen Demand (BOD)	mg/L	5-Day BOD Test (APHA-AWWA-WEF, 2005)	Laboratory Glassware
		Physical		
1	Electrical Conductivity (EC)	µS/cm	Electrometric	HANNA; HI98129
2	pH	pH units	Electrometric	HANNA; HI98129
3	Total Dissolved Solids (TDS)	NTU	Electrometric	Turbidity meter, SGZ-1000BS/1710200
4	Temperature	ºC	Thermometric	HANNA; HI98129
		Nutrients		
1	Nitrate (NO_3^-)	mg/L		Spectrophotometer SS1 UV 2101
2	Total Phosphate (TP)	mg/L	Ascorbic Acid (APHA-AWWA-WEF, 2005)	Spectrophotometer SS1 UV 2101
3	Ammonia (NH_3-N)	mg/L	Phenate (APHA-AWWA-WEF, 2005	Spectrophotometer SS1 UV 2101
4	Phosphate (PO_4^{3-})	mg/L	Stannous Chloride (APHA-AWWA-WEF, 2005)	Spectrophotometer SS1 UV 2101

The correlation analysis using SPSSV.26 software was used to obtain a set of linearly independent water quality variables. Annex 5.1-5.2. shows the correlation at 95 as well as 99 percent confidence intervals. As the conductivity shows a significantly high correlation (at 99% confidence interval with the total dissolved solids, as well as it varies widely due to the concentration of sulfates and chlorides present in the water (Zhao *et al.,* 2019) so it was dropped for integration purposes. Similarly, calcium and magnesium hardness were also removed for integration purposes due to their high significant correlation with the Total hardness. Further, all the water quality indices whose correlation was below 0.8 (Zhao *et al.,* 2019) were taken for integration. Overall, 17 water quality indices, were selected for the river health evaluation. In this study, water quality standard limits of various countries were adopted which are essential for the sustenance of aquatic living organisms (Annex 6).

For determining the water quality index (WQI), the mean of eight physicochemical parameters, including TDS, pH, EC, DO, Cl^-, NH_3-N, PO_4^{3-}, and NO_3^- were applied to evaluate the suitability of water for aquatic ecosystem sustenance. These eight parameters were chosen based on a literature review (Kannel *et al.,* 2007a, b; Pesce & Wunderlin, 2000; Regmi *et al.,* 2017; Said *et al.,* 2004). Then, based on percent compliance to the objective value (Annex 6), weight was assigned to each parameter (wi) based on its relative importance (Sanchez et al., 2007) in the overall quality of water for the sustenance of the aquatic organisms. Weights of 5, 4, 3, 2, and 1 were assigned to the quality parameters when the range of 0-20, 21-40, 41-60, 61-80, and 81-

100% of samples are within the permissible limit respectively (Raychaudhuri *et al.*, 2014). Second, the relative weight (Wi) was calculated for each parameter based on equation (15).

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (15)$$

Where, Wi is the relative weighting; wi is the weighting of each parameter, and $\sum wi$ is the sum of all parameters and n is the number of parameters.

The next stage was to assign a quality rating for each parameter by dividing the concentration in each water sample by the standard specification, as per the guidelines, and multiplying the result by 100 as per equation (16)

$$Qi = \frac{Ci}{Si} \times 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (16)$$

where, q_i= is the quality rating; C_i= is the concentration of each chemical parameter in each water sample in milligrams per litre; S_i = is the standard for each chemical parameter in milligrams per litre.

Finally, using equation (17), the water quality index was generated by adding the sub-index of water quality (SIi) for each parameter, which was then summed to get the final WQI (18).

$$SI_i = W_i . q_i \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (17)$$

$$WQI = \sum_{i=1}^{n} SIi \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (18)$$

Where SI_i is the sub-index of water quality, Wi is the relative weighting, qi is the quality rating scale, and WQI is the water quality index.

At last, the water quality of the river is categorized into five classes Excellent, Good, Poor, Very Poor, Unfit for Drinking based on the WQI value range (Table 3.9).

Table 3.9: Classification of computed water quality index (WQI) values

WQI Range	Type of water
< 50	Excellent water
50.1 – 100	Good water
100.1 – 200	Poor water
200.1– 300	Very poor water
>300.1	

Source: Raychaudhary et al. (2014)

3.6.2.2 Biological sub-index

Benthic macroinvertebrates have been selected to represent biological health as they are widely used as a bio-indicator representing site-specific ecological conditions (Barbour *et al.*, 1999; Cook, 1976; Rosenberg & Resh, 1993; Shah *et al.*, 2020).

Benthic macroinvertebrate assemblages were sampled at each site with the multi-habitat time-limited approach (Barbour *et al.*, 1999; Moog, 2007). In this approach, organisms are collected from all available habitats by kicking and jabbing the substrate with a D-frame dip net (0.3 m width and 500 mm mesh size) in a 100 m stretch. Only multi-habitat samples were taken, reflecting the percentage of microhabitat categories with greater than 5% coverage at each stream reach. Then sorting was done at the field by removing larger materials, and rinsing the branches, sticks stones, leaves, twigs, etc thoroughly. For the field sorting operation, several white trays measuring 300 x 150 x 50 mm were employed.

Macroinvertebrate specimens were then moved to a plastic bottle of wide mouth with the help of forceps and then labeled according to the respective sites and preserved in a 70% ethanol solution until further identification in the laboratory The preserved macroinvertebrates were then identified with the help of a compound microscope and hand lens, using relevant keys (Subramanian & Sivaramakrishan 2007; Winterbown & Katherine, 1981) up to family level. Chessman et al. (2002) claim that family-level identification is sufficient for diagnosing distress in the aquatic macroinvertebrate ecosystem at a reasonable cost and on time. Similarly, Marshall et al. (2006) found that family-level abundance data accurately represented species richness.

Finally, the biological condition was calculated by measuring three aspects, namely, richness, composition, and tolerance measures as shown in Table 3.10 based on Ganga River System biotic score (GRSbios) (Nessman *et al.*, 2007; Shah & Shah, 2013). This score represents the overall health of the river ecosystem by taking into account the accumulated effects of organic pollution, land-use change, and hydromorphological deterioration (Shah & Shah, 2013). Diversity indices (Shannon Weiner-diversity) were calculated using R software.

Table 3.10: Metrics used for the biological assessment

Category	Metrics	Calculation/Definition
Richness measure	• Taxa richness • No of EPT taxa • Total abundance	• Total number of present taxa in a site • Sum of Ephemeroptera, Plecoptera, and Trichoptera • Total number of Taxa
Composition measures	• Percentage of EPT	• Total number of individuals on a site • Sum of EPT individuals in a site/Total abundance in a site ∗ 100
Tolerance measures	• GRSbios	• Sum of taxa scores by number of scored taxa
Diversity	• Shannon -Weiner	• $\bar{H} = -\sum((ni/N)\ \log10\ (ni/N))$

Source: Nessman et al.(2007); Shah and Shah (2012, 2013)

Note: EPT is Ephemeroptera, Plecoptera, and Trichoptera

3.6.2.3 Hydrology sub-index

Flow regime (hydraulic conditions) is a key determinant factor of the physical habitat in assessing river health. Flow Health (Version 3) software tool was used to analyze flow health based on nine different pre-defined sub-indicators: High flow (HF), Low flow (LF), Highest Monthly (HM), Lowest Monthly (LM), Persistently Higher (PH), Persistently Lower (PL), Persistently Very Low (PVL), Seasonality Flow Shift (SFS), and Flood Flow Interval (FFI), which are ecologically relevant hydrological sub-indices (Gippel *et al.,* 2012). The basic flow components of a natural flow regime are strongly related to these nine indicators such as cease-to-low, low flow, high flow, baseflows, high flows, and timing (seasonality). This software compares the attributes of the natural flow regime between the test periods (present flow) with the characteristics of the flows over the reference (minimum human influence) period. It highlights the effects of flow regulation as well as years with lower-than-average flows, both of which are major predictors of ambient ecological health as determined by bioassessment methodologies. The flow health tool compares the monthly flow values, in the test period with that of the reference period and assigns a score in such a way that the flow which is more or less the same as that of the virgin condition will have a flow health score close to 1, while the flow which deviates considerably from the virgin condition will be assigned a value close to zero.

The scoring system considers that i) flow decreases are more detrimental to river health than flow increases, and ii) greater flows during high flow seasons aren't harmful to river health. For distinct flow measures (hydrological attributes), Flow Health uses the interquartile range (25th to 75th percentile) as the range within which the hydrological health score is 1. Any deviations in an attribute outside this range could potentially affect the flow health and hence assign a value less than 1. Finally, the average of the modified Low flow (LF) score and the other 7 individual metric scores is used to create the overall Flow Health index score.

3.6.2.4 Physical habitat sub-index

Physical habitat provides a natural link between the physical environment and its inhabitants upon which the ecological organization and dynamics of ecosystems are observed (Norris & Thoms, 1999). A visual-based approach using modified Barbour's system of Rapid Bio Assessment Protocol (RBP) (Barbour *et al.*, 1999; Plafkin *et al.*, 1989) was adopted to evaluate the physical habitat of the Marshyangdi River, which consists of ten parameters. Every parameter was assigned into four different categories as optimal (score 20–16), sub-optimal (15–11), marginal (10–6), and poor (5–1) condition. Then the sum of scores for the 10 habitat parameters was divided by 200, the total possible score for RHA (Rai *et al.*, 2019). Based on the range of HA scores, the condition of the physical habitat was categorized as natural or less human disturbance site excellent (0.85–1), good (0.65–0.84), fair (0.35–0.64), and poor (0.0–0.34).

In addition, the following physical habitat characteristics were also measured in the field after the sampling of water quality and macroinvertebrates.

- Velocity: The velocity of water in a river was measured within the stretch of 100m with an interval of 20 m with the help of a digital flowmeter (Flow probe, 3.7-6'; model no: FP111) following the procedure of measurement mentioned in the non-wadable stream (Wilhem *et al.*, 2005). Using the rod attached to the flowmeter, a

30-s averaged flow velocity data was taken exactly adjacent to each invertebrate sample at 60 percent of the channel depth.

- Water depth: Depth profiles are measured to characterize river size, channel complexity, pools as well as proportions of habitat types (Kaufmann, 2000). It was measured longitudinally along the thalweg with the same flowmeter at an interval of 1m from the bank of the river up to where it was feasible to move inside the river.
- Width: The channel type and stream size are determined by width parameters, which provide crucial boundaries for biological interactions and riparian influences in rivers (Flotemersch *et al.,* 2006). Both wetted and dry width was measured at both banks of the river to the extent possible with the help of 100 m measuring tape. We have measured the dry as well as wetted width of the stream at each of the sampling sites.

3.7 Assessment of Climate Change Impact on River Health

River health for the future was determined in an index ranging from 0 to 1 by using equation 9 as mentioned in section 3.6. But for determining the future river health condition only three components water quality, biological status, and hydrological regime were integrated by keeping the habitat assessment component constant. Future predictions for each of the components are explained briefly in the following subsections.

3.7.1 Prediction of water quality condition

The water quality component was predicted by using equation-19, assuming that the types and quantities of pollutants from human settlement remained constant (Zhao *et al.,* 2019). Pollution and runoff concentrations can be stated as:

$$Vol = \int (F.\ C)\ dt$$

$$F'.C' = F.C\ /C' = 1/\ F'.\ dVol/dt = F.C/\ F' \ldots\ldots\ldots\ldots\ldots\ldots\ldots (19)$$

Where F is the measured runoff, C is the measured concentration of pollutants, F′ is the predicted future runoff, and C′ is the concentration of pollutants.

After calculating the concentration of water quality for future scenarios by above eq.19 water quality index (WQI) was determined for the future under both RCPS 4.5 and 8.5 as per equation 18 mentioned in section 3.6.2 A above.

3.7.2 Prediction of biological condition

For predicting biological conditions, among the various species distribution model, MaxEnt software was used. The selection of species and model building process are explained briefly hereunder.

Species Selection: Three insect orders: Ephemeroptera (E; 4 families), Plecoptera (P; 1 family), and Trichoptera (T; 1 family) to 15 occurrence points at each sampling site (21) among the four studied seasons. EPT orders are an important component of rivers worldwide representing freshwater ecosystems that can even occur in harsh environmental conditions at the highest elevations (Monterbrand *et al.*, 2019).

Environmental Variables and Projection Layers: WorldClim (version 1.4) was used to retrieve 19 bioclimatic variables (raster) with the greatest resolution (30 arc-seconds 1 (km) for present conditions (1960-1999). Additionally, three topographic variables slope, aspect, and elevation were also included for modeling. Then, to estimate future climate 19 bioclimatic variables (30 seconds spatial resolution raster) were downscaled from IPCC5 (CMIP5) projections from Global Climate Models. For the prediction of macroinvertebrates distribution, two representative concentration paths (RCPs) for the years 2050 (Hijmans *et al.*, 2005) and three RCMs (CNRM, ACCESS, and MPI) were ensembled. To avoid multicollinearity among the environmental variables which can lead to overfitting of the model prediction results (Graham, 2003), Pearson's correlation coefficient method was used between the 22 environmental variables. One of the two related variables was removed ($-0.75\ r > 0.75$) to ensure the model simulation accuracy (Yan *et al.*, 2021; Zhang *et al.*, 2016). Finally, five-set of variables were considered for modeling out of 22 (Annex 7). While screening a variable in the case of collinearity between two variables, the biological meaning, and importance of the variable for the 6 specific families was taken into account. The package stats (R Core Team, 2019) were used to perform all collinearity tests.

Model Building: Using MaxEnt version 3.4.1, the Species Distribution Modeling (SDM) was used to predict the existing and future distribution ranges of six families of macroinvertebrates (Phillips *et al.,* 2006; Elith *et al.,* 2011, Kramer-Schadt *et al.,* 2013; Pearson *et al.,* 2007; Yan, 2021; Zhang *et al.,* 2016). Then, the selected bioclimatic variables and occurrence data of macroinvertebrates were uploaded to MaxEnt for modeling and predicting the distribution. For a species with presence points less than or equal to 15, the leave-one-out cross-validation method was used, where the data were divided into subsets; one set for training and the other for validation. A training dataset was used to develop the SDM, and the validation subset was used to test the predictions of the modeled species' presence/absence (Pearson *et al.,* 2007). The majority of studies using SDMs used a cross-validation approach (a combined resubstitution approach) to project species distributions (Araujo *et al.,* 2005). All the models were run using auto features, 4000 backgrounds, and all the settings at default to predict the distribution of the species and project them onto one of the future scenarios at a time.

Outputs Evaluation: Predictions were evaluated based on higher Area under Curve of ROC (AUC) values which were accepted after a visual inspection of the predicted result based on the known occurrence. The predicting model outperforms the random prediction (AUC value = 0.5 or nearer) if the AUC value is closer to 1.0 and indicates a high probability of suitability for AUC value > 0.7 towards 1 (DeLeo, 1993). We employed equal test sensitivity and specificity, a threshold approach considered adequate for the purpose (Liu *et al.*, 2005), to transform the continuous predicted output probability into the binary response of presence and absence. Jackknife procedure was implemented in MaxEnt (Phillips *et al.,* 2006) to determine the contribution of variables. To evaluate the importance of a given variable, the process compares the gain of the model using a variable, excluding the variable, and all the variables (Torres *et al.,* 2010). For the preparation of different layers/files for the model input and output maps ArcGIS 10.3 was used.

3.7.3 Prediction of hydrological condition

Future hydrological conditions were predicted based on the Flow Health tool (Gippel *et al.,* 2012). The future time series discharge data were obtained from section 3.5.5. and then software was run by providing that data as input under both RCPs scenarios for the future to determine the Flow Health of Marshyangdi River. Further, the weights of each of the nine metrics were determined by the entropy method. Finally, each of the three river health components for future periods was aggregated and computed in the form of RHI as elaborated in the above section.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 Historical Trends in Climate and Climatic Extremes

This section presents historical climate analysis using the RClimDex tool, including their trend, amount, and significance. The suitable length of the historical period (Table 4.1) was chosen based on data consistency and exploratory data analysis as mentioned in the methodology section.

4.1.1 Trends in temperature and temperature-based climatic extremes

Trends for both maximum and minimum temperature (Tmax & Tmin) has been analyzed based on four meteorological stations as depicted in Table 4.1. As the Marshyangdi Watershed has multiple meteorological stations extending from the snow-capped mountains in the north to the plains in the south, the assessment of climate change in this watershed encompasses various geographic regions of Nepal. As depicted in Fig. 4.1 the annual average maximum temperature (Tmax) shows a significant rising trend at all the studied stations. However, the magnitude of the trend for Tmax at Chame and Gorkha is at the same rate of 0.13^{o}C per year, whereas at Khudi and Thakmarpha with the same rising trend of 0.05^{o}C per year (Table 4.1). Such an increasing trend in Tmax was observed at all the stations with varying magnitude in this watershed in a study led by (Khadka & Pathak, 2016; Parajuli *et al.,* 2015). Looking at the overall trend in Tmax (Fig.4.1), a similar increasing trend was observed at stations 802 and 809 whereas at stations 604 and 816 trend was similar. Observing the trend for Tmax at four climatic stations, it is different at stations located at higher elevations (Index:604, Index:816) in comparison with stations located at the lower elevations (Index: 802 & Index:809) i.e., temperature at higher elevation stations shows a decreasing trend with an increase in altitude. Such a decreasing trend of temperature with the increase in elevation matches well with the trend in Nepal (APN, 2005; Agrawala *et al.,* 2003; Bajracharya *et al.,* 2018; Cruz *et al.,* 2007; CDKN, 2016; NCVST, 2009; Sharma, 2017). Thus, it can be concluded that the trend of maximum temperature inthis watershed aligns with the increasing trend of temperature in Nepal (Agrawala *et al.*, 2003; DHM, 2008; MoFE, 2019; Marahatta *et al.*, 2009; Shrestha *et al.,* 1999; WWF, 2005).

However, the minimum average annual temperature (Tmin) shows a significant decreasing trend at Chame, while insignificant decreasing trend at Thakmarpha but at Khudi it shows the insignificant increasing trend and at Gorkha significant with the same trend amount i.e.,0.03^{o}C per year indicating mixed trend in minimum average (Tmin) temperature at the watershed (Table 4.1; Fig. 4.2). A similar decreasing trend at Chame and an increasing trend at Khudi and Gorkha in Tmin have been also observed in the watershed by Khadka & Pathak (2016). The decreasing trend of Tmin at stations Chame and Thakmarpha might be due to elevational differences in comparison with two other stations 802 and 809.

Table 4.1a: Historical trends versus future climatic condition at the watershed

Station Index	Historical/Baseline			RCP4.5						RCP8.5					
				NF			MF			NF			MF		
	Tmax (ºC)	**Tmin (ºC)**	**PPT %**	**Tmax (ºC)**	**Tmin (ºC)**	**PPT (%)**	**Tmax (ºC)**	**Tmin (ºC)**	**PPT (%)**	**Tmax (ºC)**	**Tmin (ºC)**	**PPT (%)**	**Tmax (ºC)**	**Tmin (ºC)**	PPT (%)
604	27.2**(0.05)**	15.0(0.03)	406	0.3	1.0	12.3	0.7	1.4	19	0.3	0.3	19	1.2	1.8	15
816	26.6**(0.1)**	15.8**(0.03)**	1059	0.1	1.6	12.7	0.6	2.0	15	0.3	0.3	12	1.1	2.5	10
802	17.2**(0.1)**	4.5**(-0.1)**	3383	0.4	0.4	6.9	0.7	0.9	8	0.5	0.5	7	1.1	1.4	7
809	16.6**(0.05)**	5.3(-0.02)	1681	-0.4	0.9	3.8	-0.1	1.3	4	-0.4	-0.4	7	0.2	1.9	6

Note: Bold values inside the bracket represent trends at 5 percent levels of significance

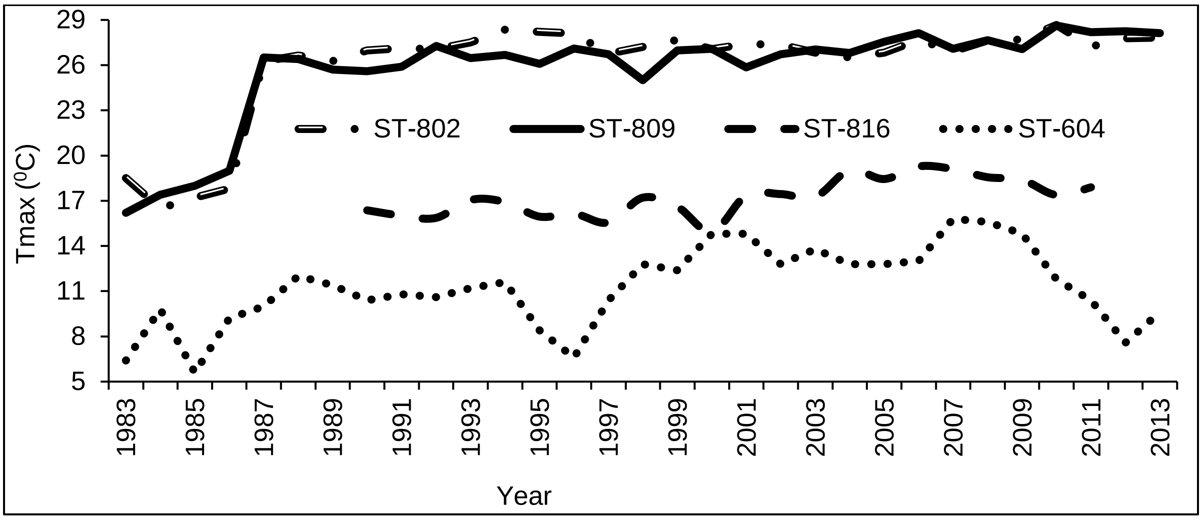

Figure 4.1: Historical trends in maximum annual average temperature (ST: Station)

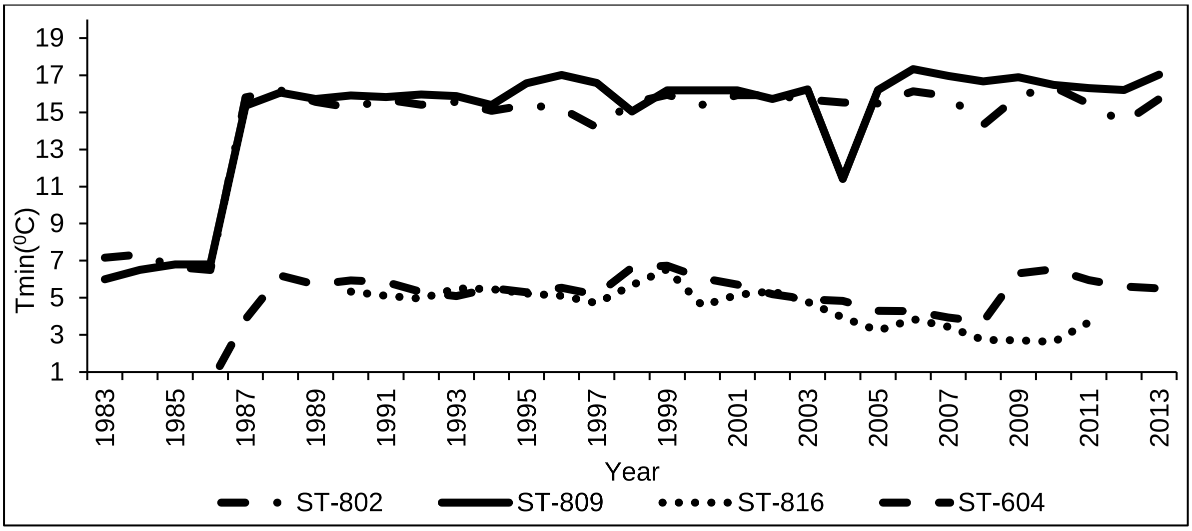

Figure 4.2: Historical trends of minimum annual average temperature (ST: Station)

Seasonal variation in climatic condition

Seasonal variation among the climatic variables (Tmax, Tmin & Precipitation) was analysed based on four seasons namely winter (DJF), pre-monsoon (MAM), monsoon (JJAS) and post-monsoon (ON) which is presented in (Table 4.1b, Annex 8- Annex 8.2).

Annual seasonal temperature (Tmax and Tmin) varies among the seasons at all the studied stations. However, maximum temperature (Tmax) was maximum at all the stations in monsoon season (June-September) from baseline to future for both RCPs. For example, at Khudi Station (Index: 802) Tmax reaches upto 31.6ºC for RCP8.5MF (Table 4.1b). Similarly average annual precipitation has been projected to be maximum for monsoon (June-September) season followed by post-monsoon (October-November) which reaches upto 2860 mm for RCP 85MF at the same station.

Temperature based extreme indices

Trends in thirteen temperature-based extreme climatic indices at four climatic stations are shown in Table 4.2, and the trend values for statistically, significant indices at a 5% level of significance. The results indicate various trends in climatic indices magnitude, direction, and statistically significant across the meteorological stations. Furthermore, such variances can be seen within the same group of indices (i.e., fixed-threshold, absolute extreme, percentile-based, and duration-based indices respectively).

Table 4.1b: Projected seasonal variation in climate at Khudi Station with respect to baseline

		Tmax (⁰C)				Tmin (⁰C)					PPT (average annual in mm)				
Variable		**RCP4.5**		**RCP8.5**			**RCP4.5**		**RCP8.5**			**RCP4.5**		**RCP8.5**	
Period	**BA**	**NF**	**MF**	**NF**	**MF**	**BA**	**NF**	**MF**	**NF**	**MF**	**BA**	**NF**	**MF**	**NF**	**MF**
Annual	27.1	27.6	27.9	27.7	28.3	15.8	15.4	15.9	15.5	16.3	3370	1193	3657	3622	3623
DJF	21.3	21.6	21.9	21.5	22.3	8.8	7.9	8.3	8.0	8.7	2124	120	143	149	126
MAM	29.1	29.6	30.0	29.7	30.6	16.7	16.3	16.8	16.3	17.4	4373	237	518	472	509
JJAS	30.4	30.8	31.2	31.0	31.6	21.1	21.3	21.8	21.4	22.3	10055	749	2857	2871	2860
ON	26.4	26.7	27.1	27.1	27.4	14.1	13.3	13.9	13.9	14.2	16325	87	138	129	128

Table 4.2: Historical trend in climatic extremes of Marshyangdi Watershed.

Temperature-based extreme indices														
Station Index	Station Name	Fixed Threshold Indices	Absolute Extreme Indices					Percentile based Indices					Duration-based Indices	
		SU 25	TR20	TXx	TNx	TXn	TNn	TN90p	TN10p	TX90p	TX10p	WSDI	CSDI	DTR
604	Thakmarpha	0.02	0.00	0.00	-0.01	***0.08***	-0.02	-0.14	0.20	***0.50***	***-0.38***	0.30	0.15	***0.09***
816	Chame	-0.03	0.00	-0.07	***-0.42***	***0.71***	***0.12***	***-0.48***	***0.57***	0.42	***-0.94***	0.75	***0.80***	***0.30***
802	Khudi	***0.24***	1.13	0.01	0.09	0.06	0.09	0.15	***-0.87***	***0.38***	***-0.26***	0.17	-2.40	-0.02
809	Gorkha	***1.81***	***1.33***	***0.10***	***0.04***	***0.09***	-0.01							***0.07***

Precipitation-based extreme indices											
Station Index	Station Name	Fixed Threshold Indices		Absolute Extreme Indices			Percentile-based Indices		Duration-based Indices		
		R10	R20	RX1day	RX5day	PRCPTOT	R95p	R99p	CDD	CWD	SDII
604	Thakmarpha	-0.02	0.03	0.67	0.82	0.51	1.00	-0.07	1.14	-0.05	0.02
802	Khudi	-0.26	-0.11	***-2.47***	***-3.78***	-18.71	-15.55	-7.18	0.95	-0.32	-0.11
806	Larke Samdo	-1.32	-0.49	-0.04	-1.67	***-21.58***	***-8.06***	-3.32	-1.87	0.18	-0.17
807	Kunchha	0.04	0.06	0.32	1.44	1.42	3.35	-0.31	1.00	-0.04	0.17
808	Bandipur	-0.52	-0.33	-0.07	-0.46	***-15.83***	-1.25	-0.76	0.73	0.08	-0.09
809	Gorkha	-0.24	-0.14	-0.23	0.30	-5.36	2.65	0.01	0.40	-0.08	-0.01
816	Chame	0.76	-0.26	-0.72	0.80	-0.20	-9.33	-4.20	2.45	0.91	0.08
817	Damauli	0.04	0.00	-0.59	-0.08	-1.60	-2.73	-2.03	0.33	-0.10	0.07
820	Manang Bhot	-0.37	-0.11	-0.56	-1.67	***-8.38***	***-3.18***	-0.60	0.57	-0.04	-0.01
823	Gharedunga	0.31	0.28	0.73	0.7	10.07	10.13	2.76	0.59	-0.30	0.27

Note: Statistically significant indices are bold and italic

Ice days (ID), one of the threshold-based indices doesn't show any trend at three sites and was insignificantly negative at Chame Station, thus this index was excluded for further study. However, at Khudi and Gorkha stations, the index 'summer days (SU25)' shows significant positive trends but the trend was insignificantly positive at Thakmarpha, and insignificantly negative at Chame Station (Table 4.4). Among the absolute extreme indices, 'tropical nights (TR20), for example, reveals a significant positive trend at Gorkha Station while the trend was insignificantly positive at Khudi Bazar, but at two other stations trends were not observed. Similarly, TXn shows positive trends among all stations with various degrees of significance and amount, whereas the other three indices (TNx, TNn, and TXx) show mixed trends in terms of magnitude, direction, and level of significance (Table 4.2).

At three stations, the number of warm days (TX90p) increased insignificantly throughout the baseline (excluding Khudi, which lies in the southern part of the watershed). However, it shows significantly increasing trends for both RCPs in NF at all the stations, except for Khudi, where the trend was significantly reduced, and Gorkha, where no obvious pattern in trend has been identified. Similar increasing patterns were observed among all stations in the mid-future for both RCP scenarios (significant at MF8.5). Similar historical trends have been also observed in other parts of Nepal by different researchers (Baidya *et al.*, 2008; Rajbhandari *et al.*, 2017; Shrestha *et al.*, 2016a).

Warm nights (TN90p) show significantly increasing trends in the north part of a mountainous region of the watershed from baseline to NF and MF for both RCPs scenarios. However, at Chame Station, it reveals significantly decreasing trends, while at Thakmarpha an insignificant decreasing trend was observed for baseline scenarios. For all future periods and scenarios, trends in the cold night (TN10p) are decreasing at all stations; however, baseline patterns are variable, with increasing trends at stations in the northern mountain region of the watershed. These findings are congruent with those of Pandey et al. (2015) and Rajbhandari et al. (2017) for the eastern Himalayas.

Duration-based indices, like diurnal temperature range (DTR) exhibit statistically significant positive trends at three stations, while WSDI also showed positive trends at those three stations but was statistically insignificant, and CSDI has positive trends at two stations only (Table 4.2). Other recent research has found similar rising patterns in warm temperature indices and declining trends in cool temperature indices (e.g., Karki *et al.*, 2020; Poudel *et al.*, 2020).

Though the temperature-related extreme indices have a magnitude of trends over time, as indicated in Fig. 4.3, the actual index value varies over time. For example, TX90p from 1984 to 2013 at Khudi Bazar Station has an average value of 9.3°C, with an annual increase of +0.36°C/year, and an index value ranges from 0.81°C to 25.8°C.

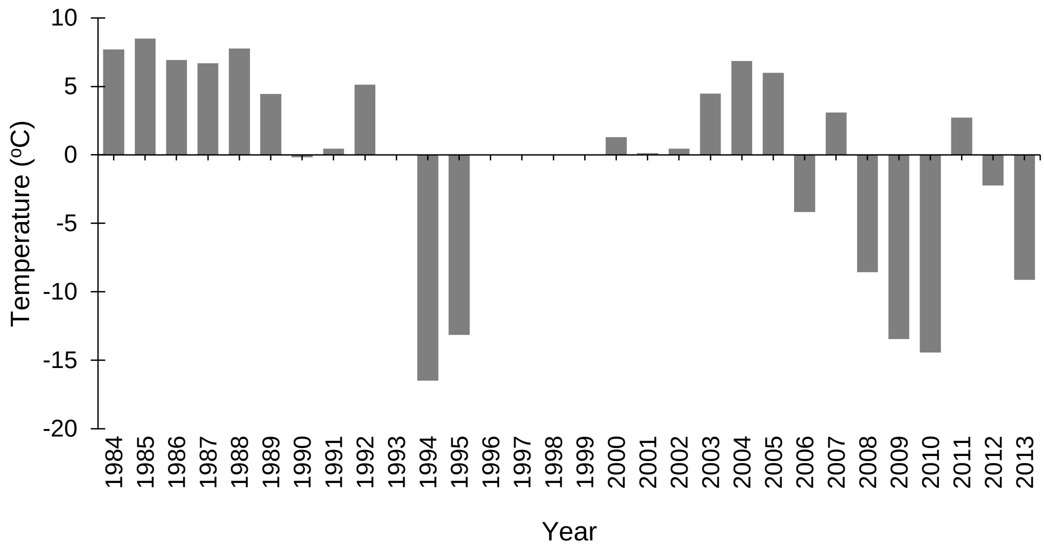

Figure 4.3: Anomaly trend for warm days (TX90p)

4.1.2 Trends in precipitation and precipitation-based climate extremes

The trend in annual total precipitation at all the meteorological stations within and surrounding the Marshyangdi Watershed shows a decreasing trend in the baseline period (Fig.4.4; Annex 9). Precipitation amount shows the decreasing trends at all the stations throughout the period (1983-2013) with a sharp decline during late 1992. This declining trend in annual precipitation was observed in parts of the northwest in one of the studies by Duncan et al. (2013). As the Marshyangdi Watershed lies in the northwest part of Nepal, the result corresponds well to the overall trend of the country.

The mean annual precipitation amount at all the stations exceeds 1000 mm except at Manang Bhot, Thakamrpha, and Ranipauwa. The maximum average annual precipitation of 3787 mm was observed at Siklesh followed by Gharedunga and Khudi Bazar (Annex 9). We can observe strong seasonal variation in the rainfall pattern of

Marshyangdi, like in other watersheds in Nepal, with more than 80% of the annual rainfall occurring during the monsoon season (June-August) at all stations (Fig. 4.5). Such seasonal variation in rainfall is typical all over the country as rainfall is caused by the southwest monsoon which lasts from June to September (APN, 2005; CDKN, 2016).

Table 4.3: Projected changes in future climate with respect to baseline

Station Index	Historical/Baseline			RCP 4.5 Scenario (% change)						RCP 8.5 Scenario (% change)					
				NF			MF			NF			MF		
	Tmax	Tmin	PPT	Tmax	Tmin	PPT	Tmax	Tmin	PPT	Tmax	Tmin	PPT	Tmax	Tmin	PPT
802	27	15	3383	1	3	7	3	6	8	2	4	7	4	9	7
809	27	16	1683	-2	6	4	0	8	4	-1	38	7	1	12	6
816	17	5	1059	1	35	13	3	44	15	2	37	12	6	55	10
604	17	6	406	2	19	12	4	25	20	2	20	19	7	33	15

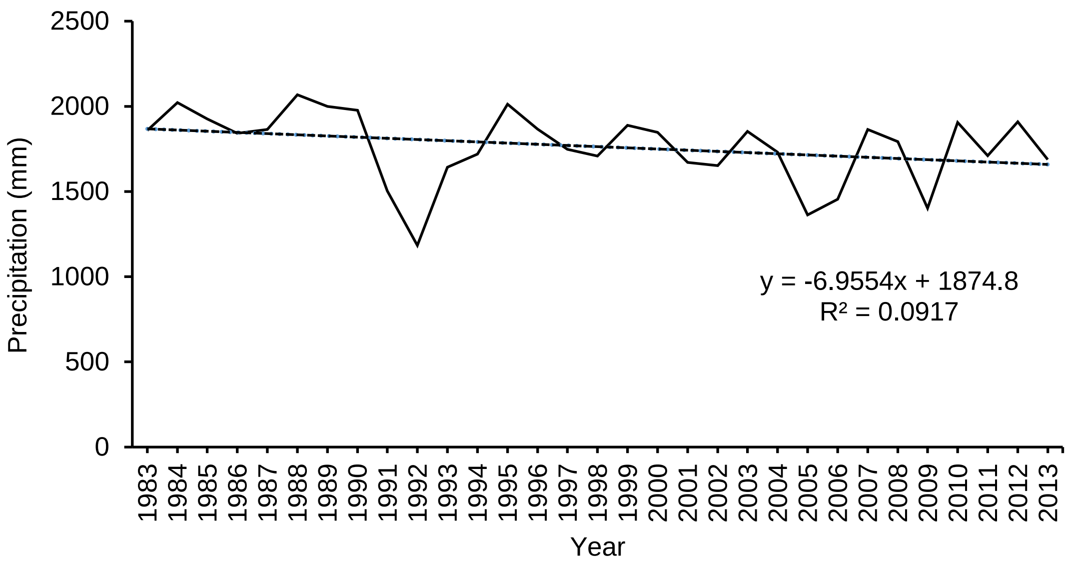

Figure 4.4: Annual average trend of precipitation at Khudi Station

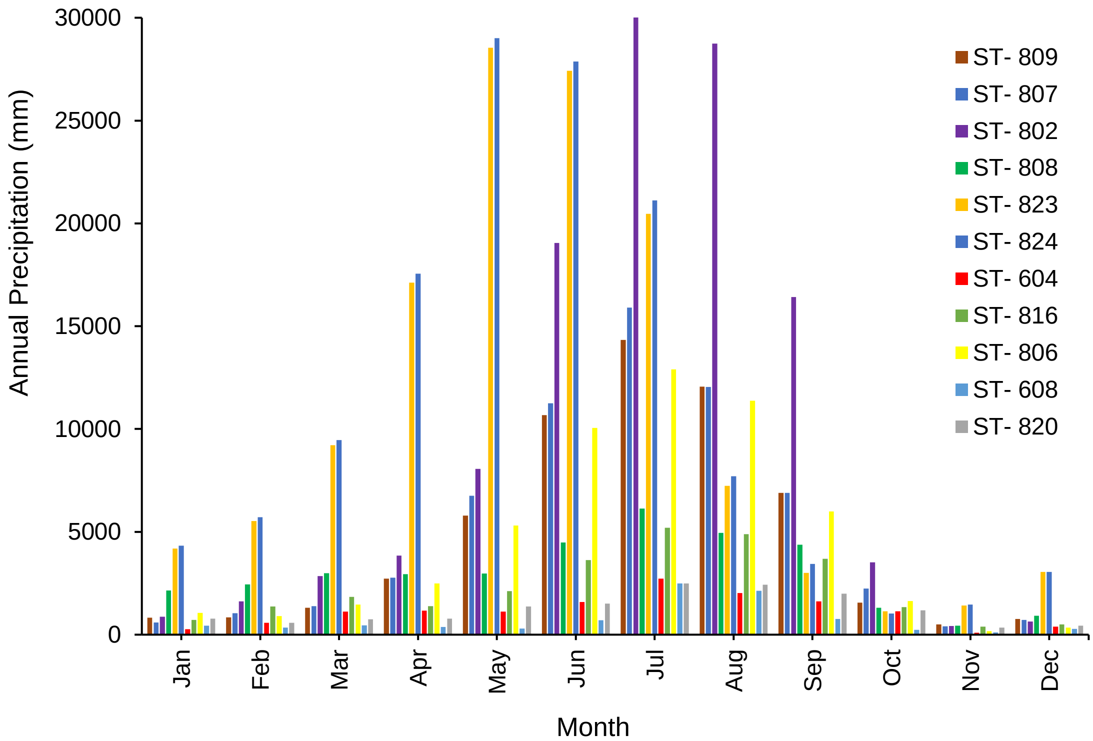

Figure 4.5: Historical trends in monthly average precipitation at all the stations

Precipitation based extreme indices

Extreme climatic trends in ten precipitation-based indices are presented in Table 4.2. These indices are also grouped under the following four categories, namely, fixed threshold Indies, absolute extreme indices, percentile-based indices, and duration-based indices. Trends in the indices are evaluated at a 5% level of significance at ten stations dispersed across the Marshyangdi Watershed. Precipitation-based indices reveal variance in trend amount, directions, and statistical significance across the studied stations with no discernible regional patterns.

At six out of ten stations, both indices in the threshold-based category, R10, and R20 show insignificant decreasing trends. In most situations, those indices show a similar pattern in terms of direction and significance but the magnitude of trends varies (Table 4.2). Similar results are reported in another research as well (e.g., Lamichhane *et al.*, 2020). Among the duration-based indices, ‘Consecutive Dry Days (CDD) indicate insignificant positive trends at 7 out of 10 stations but significant positive trends at two stations Kunchha and Chame. Trends in the simple daily intensity index (SDII) indicate insignificant positive at five out of ten stations ' whereas three out of ten stations 'consecutive wet days (CWD)' show insignificant positive trends (Table 4.4). All the trends in the remaining stations are found to be negative but statistically insignificant. In the case of three absolute extreme indices two of them, RX1day and PRCPTOT have negative trends with different magnitudes at seven out of ten stations. Some of the indices such as PRCPTOT are statistically significant, at three stations (Larke Samdo, Bandipur, and Manang Bhot) and RX1day at Khudi (Table 4.4). Index RX5 day on the other hand shows negative trends only at five out of ten stations, with only one (i.e., Khudi) being statistically significant. For all three indices, the magnitude of the indices varies greatly between stations. Finally, for two percentile-based indices (R95p and R99p), R99p trends are negative (insignificant) at all eight stations, while R95p trends are negative at five out of ten stations, with two of them statistically significant (Table 4.2).

Such an increasing trend in CDD index has been observed over the southern and northern slopes of the Central Himalayas, as well as in the Narayani River Basin (Lamichhane *et al.*, 2020; Sigdel & Ma, 2016). Similarly, Karki et al. (2017) noticed a similar trend of CDD across the country warning that such an increase in the dry period could have a severe influence on agricultural activity and hydropower generation, thereby affecting economic aspects of livelihood. Many stations in Nepal's Koshi Basin have similarly documented increasing trends in climate indices (Shrestha *et al.*, 2017). Such climate extremes in Nepal may have public health effects as well as respiratory-related health issues (Karki *et al.*, 2017).

Extreme precipitation-based extreme indices, like temperature-based extreme indices, have inter-annual fluctuation, as seen in Fig.4.6 for Rx5day. Between 1984 and 2013, the average value of Rx5day at Khudi Bazar station was 2997 mm, with a -3.78 mm/yr trend, while the index value ranged from 244 mm to 414 mm with a coefficient of variation of 43.6 mm.

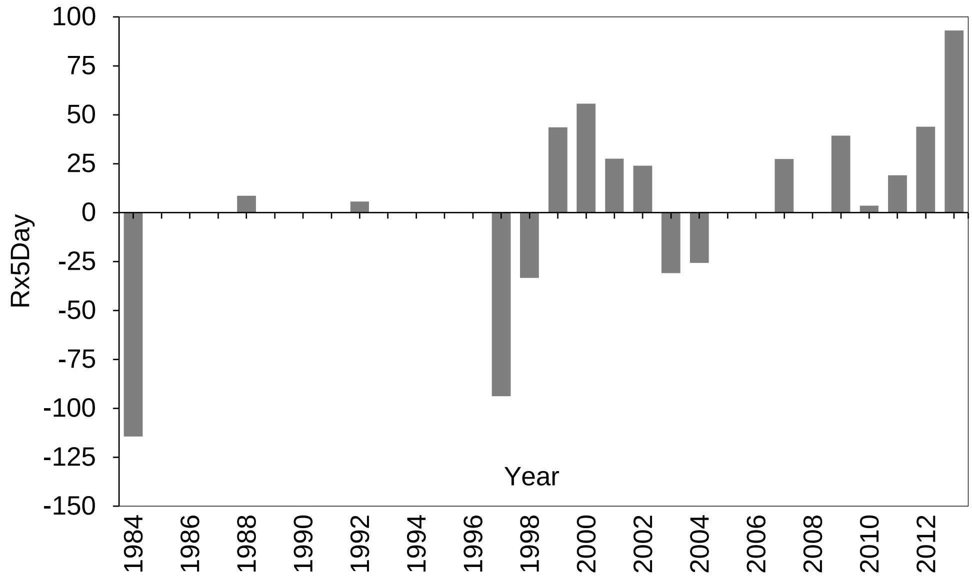

Figure 4.6: Anomaly trend for maximum five day

4.2 Projected Change in Climate and Climatic Extremes

4.2.1 Variation in projected climatic trends across the RCMs

For two future periods and two RCP scenarios, the projected climatic extremes related to temperature and precipitation based on bias-corrected regional climate models (RCM1: CNRM, RCM2: ACCESS, RCM3: MPI) are summarized in (Table 4.4a -Table 4.4b). Climatic extreme indices are projected to vary significantly across three RCMs at all four stations (Thakmaprha, Chame, Khudi, and Gorkha considered in this study. For example, projected trends of cool days (Tx10p) at Thakmarpha under RCP 4.5 scenarios and NF show a wide variation from 0.08 days/year (insignificant) with CNRM to -0.44 days/year (significant) with ACCESS (Table 4.4a). For the same RCM, some indices show decreasing to increasing trends from RCP 4.5 (NF) to RCP8.5 (MF). For example, trends in Tx90p for CNRM RCM are projected to vary from -0.02 days/year (insignificant) to 0.35 days/year (significant) from RCM 4.5(NF) (Table 4.4a) to RCP 8.5 (MF) (Table 4.4b). Likewise, the trend of (PRCPTOT) at Thakmarpha for RCP 4.5 scenarios (Table 4.4a) and NF vary from 2.06 mm/yr (projected by CNRM RCM) to 3.38 mm/yr (projected by MPI RCM) (Table 4.4b). For some indices, all RCMs show an increasing trend, albeit with varying magnitudes. For example, SDII is projected to increase by all three RCMs for RCM 4.5 (NF), but with rates varying from +0.05 mm/day (projected by MPI) to +1.02 mm/day (projected by CNRM).

The variation of trends across the RCMs is true for other climatic stations as well. For example, cool days (Tx10p) at Chame Station show decreasing trends across all the RCMs for RCP 4.5 and 8.5 scenarios for both NF and MF except by CNRM RCM which shows a positive trend during MF for RCP 4.5 (Table 4.5a & Table 4.5b). Furthermore, the trend of (TXn) does not show much variation among the three RCMS however CNRM RCM shows a positive significant trend of 0.17°C/yr for RCP 8.5(MF) (Table 4.5b). Similarly, an insignificant negative trend has been observed for (PRCPTOT) (-3.18 mm/yr) to a significant trend of (11.16 mm/yr) for RCP4.5 (MF) whereas for RCP 8.5 (NF) varies from 8.32 to 6.96 mm/yr. Likewise, the Rx5day index, for RCP 4.5 (NF) varies from 3.07 mm/yr to 2.50 mm/yr showing a statistically significant trend by ACCESS RCM (9.95 mm/yr). Furthermore, cool nights (Tn10p) show a statistically significant decreasing trend ranging from 0.19 days/yr to 0.29 days/yr by CNRM RCMs while moving from NF (RCP 4.5) (Table 4.5a) to MF (RCP 8.5) (Table 4.5b)

These results indicate that selection of appropriate RCM depending upon climatic characteristics of the study area is crucial before using projected climate for any impact studies as trends in climatic extremes vary across the RCMs. As all RCMs do not project similar trends, a safer way to reduce uncertainty related to a selection of RCMs is to use an ensemble of a set of RCMs (Hawkins & Sutton 2009; Knutti *et al.*, 2010; Tebladi & Knutti 2007). Therefore, we have taken an ensemble of three selected RCMs (i.e., CNRM, ACCESS, and MPI) for evaluating future trends in climatic indices.

Table 4.4a: Variation in projected climatic trends across RCMs at Thakmarpha (RCP 4.5)

S.N	Indices	Baseline	Near Future			Mid future		
			RCM1	**RCM2**	**RCM3**	**RCM1**	**RCM2**	**RCM3**
1	SU25	0.02	-0.14	0.22	0.51	0.06	0.83	0.24
2	Id0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	TR20	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	Fd0	0.31	0.00	0.00	0.00	0.00	0.00	0.00
5	GSL	1.36	0.00	1.82	-0.22	0.14	-0.37	0.36
6	TXx	0.00	-0.17	0.11	0.05	0.04	0.08	0.00
7	TXn	0.08	0.02	0.27	0.10	0.15	0.12	0.09
8	TNx	-0.01	-0.10	0.03	0.01	0.04	0.08	0.05
9	TNn	-0.02	0.18	0.00	0.00	0.00	0.00	0.00
10	TX10p	-0.38	-0.08	-0.44	-0.22	-0.15	-0.22	-0.34
11	TX90p	0.50	-0.02	0.55	0.27	0.08	0.29	0.27
12	TN10p	0.20	0.01	-0.07	-0.15	-0.31	-0.35	-0.19
13	TN90p	-0.14	0.35	0.28	0.15	0.28	0.40	0.32
14	WSDI	0.30	0.10	1.11	0.52	0.15	0.56	0.77
15	CSDI	0.15	-0.01	0.13	0.07	-0.26	-0.31	0.01
16	DTR	0.09	0.08	0.07	0.03	-0.03	-0.02	0.02
17	RX1day	0.67	-0.02	3.40	1.55	-3.19	0.37	-0.88
18	RX5day	0.82	-0.02	7.02	2.32	-3.28	1.35	-1.40
19	SDII	0.02	1.02	0.18	0.05	-0.08	0.07	-0.03
20	R10mm	-0.02	-0.03	0.20	0.09	-0.11	0.22	-0.13
21	Rr20mm	0.03	-1.72	0.23	0.08	-0.03	0.09	-0.05
22	R25mm	0.03	-0.80	0.21	0.06	-0.07	0.06	-0.09
23	CDD	1.14	-2.06	0.34	-1.27	0.38	0.74	1.84
24	CWD	-0.05	-0.03	0.03	-0.17	-0.03	0.17	-0.12
25	R95p	1.00	-1.72	13.16	4.94	-5.89	3.66	-3.70
26	R99p	-0.07	-0.80	9.18	3.50	-5.99	1.51	-1.58
27	PRCPTOT	0.51	-2.06	12.09	3.38	-7.25	5.85	-4.07

Note: RCP is Representative Concentration Pathways; RCM1 is CNRM; RCM2 is ACCESS, and RCM3 is MPI. Bold and italics values represent significance at 95 confidence intervals.

Table 4.4b: Variation in projected climatic trends across RCMs at Thakmarpha (RCP 8.5)

S.N	Indices	Baseline	Near Future			Mid future		
			RCM1	RCM2	RCM3	RCM1	RCM2	RCM3
1	SU25	0.02	0.16	0.18	0.34	0.05	-0.07	0.12
2	Id0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	TR20	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4	Fd0	0.31	0.00	0.00	0.00	0.00	0.00	0.00
5	GSL	1.36	-0.32	1.43	-0.33	0.02	0.16	-0.53
6	TXx	0.00	0.10	0.05	0.01	0.04	-0.01	0.00
7	TXn	0.08	0.20	0.23	0.04	0.12	0.13	0.12
8	TNx	-0.01	0.00	0.05	0.01	0.02	0.05	0.07
9	TNn	-0.02	0.00	0.00	0.00	0.00	0.00	0.00
10	TX10p	-0.38	-0.24	-0.49	-0.17	-0.20	-0.21	-0.17
11	TX90p	0.50	0.36	0.40	0.19	0.35	0.02	0.11
12	TN10p	0.20	-0.10	-0.36	-0.07	-0.19	-0.16	-0.31
13	TN90p	-0.14	0.04	0.42	0.11	0.26	0.20	0.36
14	WSDI	0.30	0.33	0.62	0.84	0.79	-0.16	-0.03
15	CSDI	0.15	-0.04	-0.07	-0.12	0.00	-0.12	-0.23
16	DTR	0.09	0.03	0.03	0.03	0.01	0.00	-0.04
17	RX1day	0.67	0.75	-2.68	-0.49	-1.82	-3.00	0.41
18	RX5day	0.82	0.65	-3.83	-1.21	-1.16	-3.09	-0.12
19	SDII	0.02	0.05	-0.06	0.01	-0.05	-0.01	0.00
20	R10mm	-0.02	0.01	0.06	0.12	-0.12	0.13	0.05
21	Rr20mm	0.03	0.04	-0.11	0.02	-0.04	0.09	0.04
22	R25mm	0.03	0.07	-0.08	0.05	-0.06	0.01	0.03
23	CDD	1.14	0.89	2.50	-0.53	0.69	0.51	1.25
24	CWD	-0.05	0.00	0.01	0.07	0.01	0.14	0.14
25	R95p	1.00	3.42	-6.64	0.32	-3.56	-0.40	1.48
26	R99p	-0.07	2.72	-4.37	-0.94	-1.48	-4.82	1.80
27	PRCPTOT	0.51	1.02	-4.41	0.66	-5.50	2.12	0.68

Table 4.5a: Variation in projected climatic trends across RCMs at Chame (RCP 4.5)

S.N	Indices	Baseline	Near Future			Mid future		
			RCM1	RCM2	RCM3	RCM1	RCM2	RCM3
1	SU25	-0.03	-0.12	0.14	0.57	0.19	1.07	-0.08
2	Id0	-0.01	0.0	0.0	0.0	0.1	0.0	0.0
3	TR20	0.0	0.0	0.0	0.0	0.17	0.0	0.0
4	Fd0	0.41	0.0	0.0	0.0	0.05	0.0	0.0
5	GSL	1.99	1.06	0.0	0.0	0.0	-0.11	0.91
6	TXx	-0.07	0.01	0.01	0.13	-0.34	0.06	0.0
7	TXn	0.71	0.12	0.14	0.11	0.2	0.08	0.13
8	TNx	-0.42	0.06	-0.02	0.08	-0.29	0.08	0.05
9	TNn	0.12	0.0	0.0	0.0	0.36	0.0	0.0
10	TX10p	-0.95	-0.05	-0.28	-0.05	0.15	-0.24	-0.2
11	TX0p	0.42	0.02	0.32	0.16	-0.4	0.4	0.04
12	TN10p	0.57	-0.19	-0.09	-0.15	-0.01	-0.25	-0.1
13	TN90p	-0.48	0.14	0.13	0.06	-1.99	0.46	0.23
14	WSDI	0.75	0.03	0.35	0.38	-3.12	0.78	-0.15
15	CSDI	0.8	-0.01	-0.24	0.1	-0.05	-0.21	-0.09
16	DTR	0.3	-0.01	0.04	0.01	0.18	-0.02	-0.02
17	RX1day	-0.72	1.94	3.83	1.06	-0.09	0.05	2.42
18	RX5day	0.8	3.07	9.95	2.5	-0.08	1.94	1.65
19	SDII	0.08	-0.01	0.17	0.08	0.46	0.09	0.06
20	R10mm	0.76	-0.16	0.15	-0.12	0.37	0.22	0.61
21	Rr20mm	-0.26	-0.31	0.16	0.08	-7.58	0.36	0.07
22	R25mm	-0.18	-0.3	0.22	0.1	-5.75	0.38	0.06
23	CDD	2.45	0.14	0.67	-0.03	-2.8	0.09	0.18
24	CWD	0.91	-0.34	0.01	-0.34	-0.24	0.32	0.21
25	R95p	-9.33	-3.61	18.19	9.14	-5.16	11.1	1.94
26	R99p	-4.2	2.05	12.92	5.8	-5.49	0.18	2.91
27	PRCPTOT	-0.2	-6.17	13.32	3.14	-3.18	11.69	11.16

Table 4.5b: Variation in projected climatic trends across RCMs at Chame (RCP8.5)

S.N	Indices	Baseline	Near Future			Mid Future		
			RCM1	RCM2	RCM3	RCM1	RCM2	RCM3
1	SU25	-0.03	0.16	0.18	0.34	0.05	-0.07	0.12
2	Id0	-0.01	0.00	0.00	0.00	0.00	0.00	0.00
3	TR20	0	0.00	0.00	0.00	0.00	0.00	0.00
4	Fd0	0.41	0.00	0.00	0.00	0.00	0.00	0.00
5	GSL	1.99	-0.32	1.43	-0.33	0.02	0.16	-0.53
6	TXx	-0.07	0.10	0.05	0.01	0.04	-0.01	0.00
7	TXn	0.71	0.20	0.23	0.04	0.12	0.13	0.12
8	TNx	-0.42	0.00	0.05	0.01	0.02	0.05	0.07
9	TNn	0.12	0.00	0.00	0.00	0.00	0.00	0.00
10	TX10p	-0.95	-0.24	-0.49	-0.17	-0.20	-0.21	-0.17
11	TX0p	0.42	0.36	0.40	0.19	0.35	0.02	0.11
12	TN10p	0.57	-0.10	-0.36	-0.07	-0.19	-0.16	-0.31
13	TN90p	-0.48	0.04	0.42	0.11	0.26	0.20	0.36
14	WSDI	0.75	0.33	0.62	0.84	0.79	-0.16	-0.03
15	CSDI	0.8	-0.04	-0.07	-0.12	0.00	-0.12	-0.23
16	DTR	0.3	0.03	0.03	0.03	0.01	0.00	-0.04
17	RX1day	-0.72	0.75	-2.68	-0.49	-1.82	-3.00	0.41
18	RX5day	0.8	0.65	-3.83	-1.21	-1.16	-3.09	-0.12
19	SDII	0.08	0.05	-0.06	0.01	-0.05	-0.01	0.00
20	R10mm	0.76	0.01	0.06	0.12	-0.12	0.13	0.05
21	Rr20mm	-0.26	0.04	-0.11	0.02	-0.04	0.09	0.04
22	R25mm	-0.18	0.07	-0.08	0.05	-0.06	0.01	0.03
23	CDD	2.45	2.17	-0.17	0.46	0.69	0.51	1.25
24	CWD	0.91	0.1	0.16	0.37	0.01	0.14	0.14
25	R95p	-9.33	-7.75	8.44	-7.58	-3.56	-0.40	1.48
26	R99p	-4.2	-6.8	5.99	-5.75	-1.48	-4.82	1.80
27	PRCPTOT	-0.2	-3.63	6.96	-2.8	-5.50	2.12	0.68

4.2.2 Projected trends in temperature and temperature-based Indices

Projected future trends in climate and climatic extremes are based on an ensemble of three RCMs (CNRM, ACCESS, and MPI) under RCP 4.5 and 8.5 scenarios for both the near future (NF-2014-2033) and mid future (MF-3034-2053) periods and presented in Table 4.6a and Table 4.6b. The RCM outputs were bias-corrected for the historical period (1983-2013) and projected for future periods. The performance of the RCM outputs for the historical periods was of acceptable quality after bias corrections.

Maximum temperature (Tmax) increases at all the stations in the future for both RCPs but for the case of RCP 8.5 its magnitude was high (Table 4.2; Fig. 4.7). Except at station 809 situated at Gorkha, the temperature increases by more than 1^{o}C at the rest of the stations showing consistency with the rising trend of maximum temperature for Nepal (MOFE, 2019). Similar increasing trends of Tmax were also observed at all the stations of the Bagmati Basin (Babel *et al.,* 2014). Similarly, the annual average minimum temperature (Tmin) also shows an increasing trend from the historical to the future period for both RCP at all the stations but its magnitude was higher than the maximum average annual temperature (Tmax). For example, at station 802 Tmin (Fig .4.8) increases from 16^{o}C to 18^{o}C for RCP 8.5 mid-future i.e, increases by 2^{o}C. Such increases in future temperature (Tmax &Tmin) under the higher greenhouse gas (GHG) concentration emission scenario (RCP 8.5) to be around 1°C higher than for the lower GHG concentration emission scenario (RCP4.5) were also observed in South Asian River basins (Shrestha *et al.,* 2021). This increasing trend in projected maximum temperature is consistent with the projected temperature trend of Nepal (CDKN, 2016; NCVST, 2009; MoFE, 2019).

Furthermore, the minimum temperature (Tmin) was found to increase higher in terms of magnitude than the maximum temperature (Tmax), when comparing the projected with the baseline. For example, at Chame Station, Tmin was 5^{0}C during the baseline which is, projected to increase up to 7^{o}C for RCP 8.5 MF (i.e., Tmin increases by 2^{o}C). Such increases in Tmin at Chame Station indicate faster warming of the climate in the northern part (or upstream) of the watershed faster compared to the southern part (or downstream). This may have implications for the accelerating snowmelt that is stored in the northern of the Marshyangdi Watershed thus increasing the availability of water during the non-monsoon season observed in western Nepal (Pandey *et al.*, 2019).

Such incidence of increase in maximum and minimum temperature for the future periods have been also been observed for Nepal during 2030 and 2050 based on GCM model MAGICC/SCENGEN (Agarwala *et al.,* 2003). Similarly based on GCM projection (NCVST, 2009) potential increase in temperature over Nepal has been observed to be 0.5-2.0°C, with a multimodel mean of 1.4^{o}C by 2030 and up to 2030 and rising to 3.0- 6.3°C, with multi-model mean of 4.7°C, by 2090.

Table 4.3: Projected changes in future climate with respect to baseline

Station Index	Baseline			RCP 4.5 Scenario						RCP 8.5 Scenario					
				NF			MF			NF			MF		
	Tmax	Tmin	PPT	Tmax	Tmin	PPT	Tmax	Tmin	PPT	Tmax	Tmin	PPT	Tmax	Tmin	PPT
802	27	15	3383	28	15	7	28	16	8	28	16	7	28	16	7
809	27	16	1683	26	16	4	27	17	4	26	21	7	27	18	6
816	17	5	1059	17	6	13	18	7	15	17	6	12	18	7	10
604	17	6	406	17	7	12	18	7	20	17	7	19	18	7	15

Note: PPT is precipitation; change in precipitation is in percentage

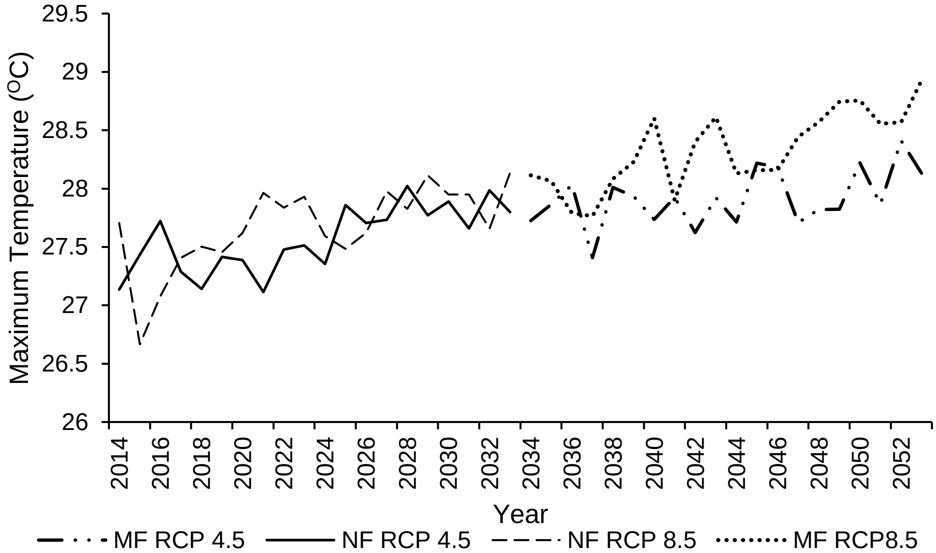

Figure 4.7: Future trends in maximum temperature at Khudi Station

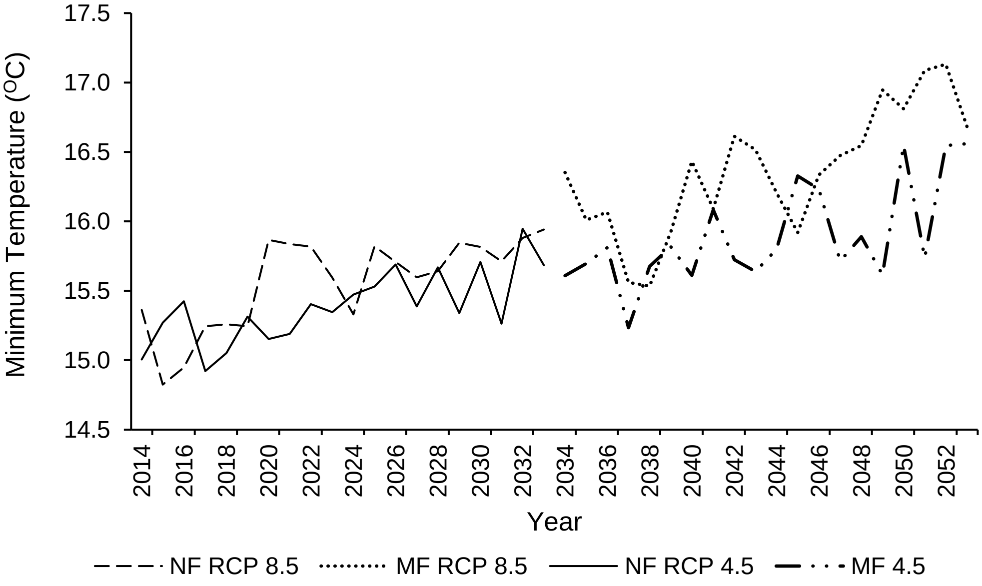

Figure 4.8: Future trends in projected minimum temperature at Khudi Station

Temperature based extreme indices

The trends in extreme climatic indices were examined across the stations for an ensemble time series based on the three RCMS (i.e., CNRM, ACCESS, and MPI). The findings indicate a steady increase in extreme temperature indices from baseline to mid-future (MF) at some stations, whereas some indices are observed to be dropping gradually at all stations, and some indices exhibit mixed trends (Table 4.6a & Table 4.6b). For example, 'summer days (SU25) show a steady increase (insignificant) at Chame Station from baseline (-0.03 days/yr) to MF (0.11 days/yr) under RCP 4.5 and 8.5 scenarios, but no trend was observed during NF under RCP 8.5. Similarly, TXx at Chame also shows an increasing (insignificant) trend from baseline (-0.07°C/yr) to NF and MF for both RCPs with a comparable trend of (0.05 °C/yr), but during MF under RCP 4.5 shows decreasing trend of 0.03°C/yr. Under RCP 4.5, TNx does not change from baseline (-0.01°C/yr) to NF, but it increases (significantly) to NF and MF for both RCP 4.5 and 8.5, with a trend of 0.07°C/yr at Thakmarpha. Under RCP 4.5 and 8.5, TNx at Chame showed an increasing (significant) trend from baseline (-0.42°C/yr) to MF (0.09°C/yr), although the trend was insignificant during NF.

Under RCP 4.5 and 8.5, TXn exhibits a steady increasing (insignificant) trend from baseline (0.06^{oC} per/yr) to a significant increasing trend in MF at Khudi Bazar Station. However, for future scenarios, several percentile-based extreme temperature indices show an increasing tendency at more than one station. For example, TN90p increases from baseline to MF at stations Thakmarpha (insignificant), Khudi (insignificant) and Chame (significant) (0.1days/yr, 0.15days/yr -0.48 days/yr) with significant trends at all the three stations for both RCPs (0.56 days/yr, 0.61days/yr, 0.62 days/yr). Though there is no change in the baseline at Gorkha Station, it increases significantly from 0.2 days/yr in NF 4.5 to 0.5 days/yr from NF to MF under both RCPs with exception of MF under RCP 8.5 where it decreases slightly to 0.07 days/yr. Other climatic extremes such as 'Warm Spell Duration Indicator (WSDI)' indicates an increasing (insignificant) trend from baseline (0.17 days per/yr) to MF under both RCP scenarios (0.52 days/yr) at Khudi Bazar Station but the trend is significant at NF for both RCPs (Table 4.6a)

4.2.3 Projected trends in precipitation and precipitation based extreme indices

In general, the annual average precipitation is increasing for all scenarios and future timeframes analyzed. The amount of increase, however, varies across the stations and was observed to be of more magnitude for RCP 4.5 MF in comparison to RCP 8.5MF. For example (Fig.4.9) above at station 802; the precipitation amount increases from 3383 mm to 3657 mm during the near future (MF4.5) but it slightly decreases for RCP 8.5 MF (3628 mm). Moreover, in terms of percentage highest increase in rainfall occurred at Thakmarpha i.e., 20% followed by Chame i.e., 13% during mid-future for RCP 4.5. Thus, the precipitation trend indicates the increase in the precipitation amount from the northern part of the watershed to the southern part which may affect the downstream part of the watershed by inducing the natural hazard in terms of the extreme climatic events. However, such an increasing trend in precipitation have been also been observed in the Koshi Basin for all the future periods based on ensembles of 17 GCMs (Agarwal *et al.,* 2014) as well as this trend is also consistent with the average annual trend for Nepal (Agarwala *et al.,* 2003; Bharati *et al.,* 2014; MOFE, 2019; NCVST, 2009; WWF, 2005).

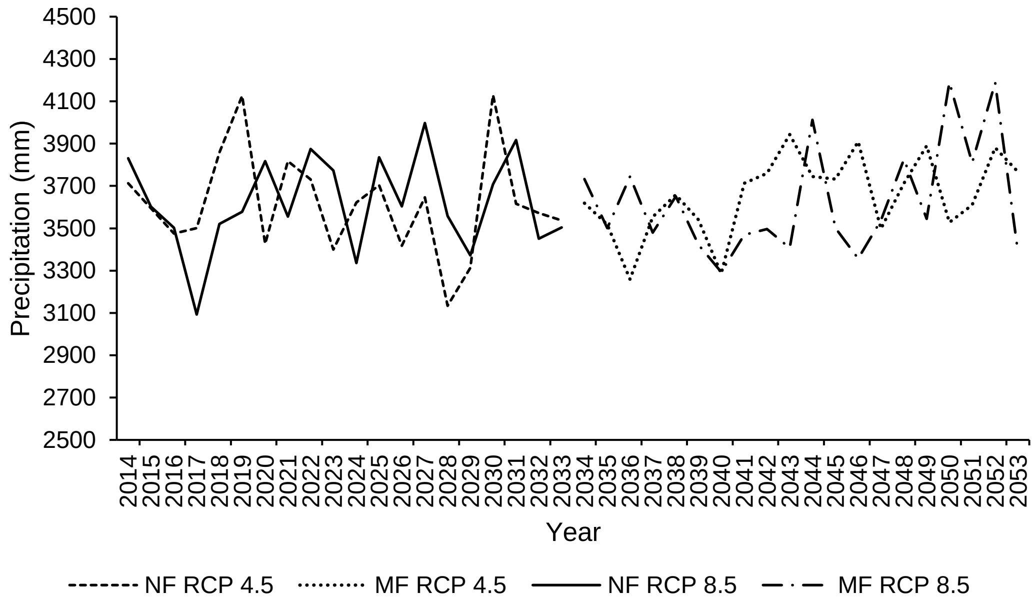

Figure 4.9: Future trends in precipitation at Khudi Station

Precipitation based extreme indices

Under both RCP scenarios (4.5 and 8.5), precipitation-based climatic extreme indices do not show a consistently increasing trend at any station from baseline to future periods (NF and MF) (Table 4.6b). for example, Rx1day at Khudi Bazar is expected to increase (insignificantly) from baseline (-2.47 mm/yr) to NF and MF (0.1 mm/days) under both RCPs, however, the magnitude of the trend was lower with respect to NF for both RCPs.

Under both RCPs, index like 'simple daily intensity index (SDII)' and other indices like very heavy precipitation days (R20**)** do not indicate any steady increases from baseline to MF under both at all the stations (Table 4.6b). Similarly, annual total wet-day precipitation (PRCPTOT) at Chame Station indicates an increasing (insignificant) trend from baseline (-0.20 mm/yr) to MF (3.18 mm/yr) under both RCPs but a negative (insignificant) trend (-1.81 mm/yr) during NF under RCP 8.5.

Some extreme precipitation indicators indicate an upward trend from baseline to NF, then a downtrend during MF. For example, RX5day, increases (insignificantly) from baseline (0.82 mm/yr) to NF (1.38 mm/yr), then drops (insignificantly) during MF at Thakmarpha Station under RCP 4.5 (-1.22 mm/yr) and RCP 8.5 (-0.27 mm/yr) (Table 4.6b). Similarly, at the same station, the number of heavy precipitation days (R10) increases (insignificantly) from baseline (-0.20 mm/yr) to a significant increasing trend, (0.29 mm/yr) in NF for RCP4.5, but declines (insignificantly) in MF (-0.15 mm/yr) for RCP 8.5.

Furthermore, in both RCP scenarios, some stations exhibit decreasing trends in extreme precipitation indices from baseline to NF and then to MF. For example, at Chame station, the number of consecutive dry days and wet days declines (insignificantly) from baseline (2.45 days/yr, 0.91 days/yr) to NF and MF (0.24 days/yr, -0.30 days/yr) under RCP (4.5 and 8.5). The SDII indicates a declining tendency from baseline (0.08 days/yr) to MF (0.02 days/yr), but no trend during MF under RCP 4.5 was observed. Moreover, declining trend have been projected in consecutive dry days (CDD) at all stations. Thus, based on observed climatic extreme indices related to precipitation and average annual precipitation we can conclude that climate would be wetter in future. However, climate could be wetter due to the melting of snow and glaciers groundwater recharge but these things are not considered in this study.

Table 4.6a: Projected trends in future climatic extreme indices based on an ensemble of three RCM outputs

S.N		Baseline				Near Future, RCP 4.5				Mid Future, RCP 4.5				Near Future, RCP 8.5				Mid Future, RCP 8.5			
	Indices	**604**	**816**	**802**	**809**	**604**	**816**	**802**	**809**	**604**	**816**	**802**	**809**	**604**	**816**	**802**	**809**	**604**	**816**	**802**	**809**
1	SU25	0.02	-0.03	***1.09***	***1.81***	0.00	0.01	**0.85**	**0.71**	-0.03	0.06	0.39	0.17	0.00	0.00	**0.51**	0.43	0.01	0.11	0.40	**0.12**
2	Id0	0.00	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	TR20	0.00	0.00	***1.13***	***1.33***	0.00	0.00	**1.07**	**0.66**	0.00	0.00	**1.07**	**1.84**	0.00	0.00	0.73	0.37	0.00	0.00	**1.13**	0.00
4	Fd0	0.31	0.41	-0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	GSL	***1.36***	1.99	-0.01	0.03	0.50	0.53	0.00	0.00	-0.16	-0.14	0.00	0.00	-0.11	0.28	0.00	0.43	-0.01	0.06	0.00	0.00
6	TXx	0.00	-0.07	0.01	***0.10***	0.02	0.05	**0.06**	-0.04	-0.02	0.03	0.03	**-0.08**	**0.04**	0.05	0.03	0.00	-0.02	0.05	0.03	0.05
7	TXn	***0.08***	***0.71***	0.06	***0.09***	***0.14***	0.07	0.11	0.08	0.05	-0.02	**0.11**	-0.02	0.11	0.02	0.02	0.37	0.07	0.06	**0.11**	-0.02
8	TNx	-0.01	***-0.42***	0.09	***0.04***	-0.01	0.02	0.00	0.01	**0.06**	**0.08**	**0.08**	**0.05**	**0.04**	0.06	**0.06**	0.00	**0.07**	**0.09**	**0.08**	**0.08**
9	TNn	-0.02	**0.12**	0.09	-0.01	0.00	0.00	**0.09**	0.07	0.00	0.00	0.02	**0.08**	0.00	0.00	0.08	**0.00**	0.00	0.00	0.02	0.00
10	TX10p	***-0.38***	***-0.95***	***-0.26***		***-0.48***	**-0.23**	**-0.38**	**-0.36**	-0.24	**-0.23**	**-0.45**	**-0.38**	**-0.63**	**-0.43**	**-0.46**	**-0.01**	**-0.41**	**-0.46**	**-0.44**	**-0.21**
11	TX90p	0.50	*0.42*	***0.38***		***0.44***	**0.34**	**0.34**	**0.23**	0.16	0.13	**0.47**	0.24	**0.41**	**0.26**	**0.28**	**0.04**	**0.34**	**0.45**	**0.47**	0.25
12	TN10p	0.20	***0.57***	***-0.87***		***-0.23***	**-0.26**	**-0.47**	**-0.32**	**-0.33**	**-0.33**	-0.55	**-0.63**	**-0.43**	**-0.38**	**-0.45**	**0.03**	**-0.51**	**-0.49**	**-0.54**	**-0.33**
13	TN90p	-0.14	***-0.48***	0.15		***0.28***	**0.21**	**0.27**	**0.24**	**0.49**	**0.50**	**0.62**	**0.63**	**0.31**	**0.25**	**0.30**	**0.07**	**0.56**	**0.62**	**0.61**	**0.50**
14	WSDI	0.30	0.75	0.17		0.58	0.68	**0.52**	-0.01	0.39	0.11	0.52	0.13	0.57	0.37	**0.44**	-0.35	-0.01	0.13	0.52	0.28
15	CSDI	0.15	***0.80***	-2.40		-0.14	**-0.09**	**-0.74**	**-0.18**	-0.17	-0.25	-0.85	-0.13	**-0.22**	**-0.23**	-0.19	0.30	-0.49	-0.26	-0.69	-0.25

Table 4.6b: Projected trends in future climatic extreme indices based on an ensemble of three RCM outputs

S.N		Baseline				Near Future, RCP 4.5				Mid Future, RCP 4.5				Near Future, RCP 8.5				Mid Future, RCP 8.5			
	Indices	**604**	**816**	**802**	**809**	**604**	**816**	**802**	**809**	**604**	**816**	**802**	**809**	**604**	**816**	**802**	**809**	**604**	**816**	**802**	**809**
16	DTR	***0.09***	***0.30***	-0.02	***0.07***	***0.04***	0.01	0.00	0.01	-0.01	**-0.03**	-0.01	**-0.03**	**0.03**	0.02	0.00	-0.36	-0.01	-0.02	-0.01	-0.02
17	Rx1day	0.67	-0.72	***-2.47***	-0.23	0.87	0.88	0.54	-0.23	-1.12	-0.17	0.10	-0.99	-0.58	-0.14	0.31	0.25	-0.14	-0.46	0.10	-0.17
18	Rx5day	0.82	0.80	***-3.78***	0.30	1.38	**2.44**	-0.58	-1.60	-1.12	-0.14	-0.13	-0.20	-0.80	0.18	0.24	0.43	-0.27	-0.13	-0.13	-0.14
19	SDII	0.02	0.08	-0.11	-0.01	0.04	0.01	-0.04	-0.05	**-0.03**	0.00	0.06	0.03	0.00	0.01	0.04	-0.34	-0.01	0.02	0.06	0.00
20	R10mm	-0.02	0.76	-0.26	-0.24	***0.29***	0.04	0.18	**-0.48**	**-0.20**	-0.11	0.55	0.47	0.10	0.03	-0.09	**0.00**	-0.15	0.31	0.56	-0.11
21	R20mm	0.03	-0.26	-0.11	-0.14	0.07	0.14	-0.24	-0.07	-0.04	-0.04	0.25	0.10	-0.08	-0.07	0.11	1.00	-0.07	0.08	0.24	-0.04
22	R25mm	0.03	-0.18	-0.07	-0.12	***0.09***	0.16	-0.36	-0.01	-0.05	-0.09	0.35	-0.04	-0.04	0.04	0.29	1.77	-0.06	0.04	0.34	-0.09
23	CDD	***1.14***	***2.45***	0.95	0.40	0.28	0.23	-0.08	0.26	0.29	-0.25	**0.94**	0.66	**0.94**	0.45	0.37	0.07	0.31	0.24	**0.94**	-0.25
24	CWD	-0.05	0.91	-0.32	-0.08	-0.09	0.29	-0.03	0.23	0.07	-0.22	-0.32	0.03	0.10	-0.27	-1.35	0.57	-0.02	-0.30	-0.32	-0.22
25	R95p	1.00	-9.33	-15.55	2.65	***5.83***	7.12	-3.29	-3.92	**-4.44**	-0.43	7.22	0.54	0.16	-1.65	9.53	0.00	-3.45	1.99	7.64	-0.43
26	R99p	-0.07	-4.20	-7.18	0.01	3.01	5.48	5.48	-4.02	-2.47	-0.88	3.59	-0.99	-1.50	-1.52	-3.81	0.09	-1.90	-0.55	3.59	-0.88
27	PRCPTOT	0.51	-0.20	-18.71	-5.36	5.42	3.54	-6.46	-9.57	-2.34	0.89	14.67	7.17	-0.99	-1.81	3.30	0.48	-1.71	3.18	14.77	0.89

Note: Bold and Italics values indicate significant at 95% confidence

4.3 Impacts of Climate Change on Streamflow andWater Resources Availability

4.3.1 Hydrological model performance

The Soil Water and Assessment Tool (SWAT) was used to assess the water availability and streamflow variation at the Marshyangdi Watershed. A multi-site calibration approach was applied with calibration at the four (3) hydrological stations (Table 4.7). The details of the calibration and validation period along with the model performance values are presented in (Table 4.7). As discussed in Liu & de Smedt (2004) and Moriasi et al. (2007) the model replicates the hydrological regime reasonably well for daily and monthly flows, recreating the flow duration curve (FDC), and keeping statistical parameters within a respectable range. A brief description of model performance at each hydrological station is presented here below.

Table 4.7: Performance evaluation at hydrological stations

Hydrological station name (Index)	Calibration period	Validation period	Indices	Model performance (for daily simulation)	
				Calibration	Validation
Bimalnagar (439.7)	2000-2005	2006-2010	R2	0.78	0.77
			NSE	0.62	0.71
Bhakundebesi (439.35)	2003-2004	2006-2007	R2	0.72	0.72
Khudi (439.3)	1987-1991	1992-1995	R2	0.77	0.73
			NSE	0.60	0.49

4.3.1.1 Bhakundebesi Hydrological Station

Graphs depicting daily calibration at Bakhundebesi Hydrological Station (Fig. 4.10) show that the peak flows of observed discharge were found to be higher than simulated throughout the calibration period (2003-2004). Further looking into the hydrograph and scatter plots during calibration reveals that the model accurately predicts low flows and the long-term average for both daily and monthly simulations, while peak flows are slightly underestimated (except for a few years 2004-2005 & 2007-2008). It suggests that poor data quality could be a factor in the model's overall poor performance for high flows. For high flows, the scattering spots spread out much more (Fig. 4.11), indicating that the model is less capable of simulating high flows. The equation of the linear fit shows that the model underestimates high flow at both the daily and monthly periods. Nonetheless, during the entire period of daily simulation (Qobs = 136.5 m^3/s; Qsim = 114.82 m^3/s), average flow conditions are replicated to a considerable extent with a bias of roughly 15.5 percent (Qobs = 136.5 m^3/s; Qsim = 114.82 m^3/s). For monthly simulation, the NSE is 0.77 for calibration and 0.83 for the validation period. The NSE values greater than 0.8, represent a good condition for monthly simulation (Fig.4.12)

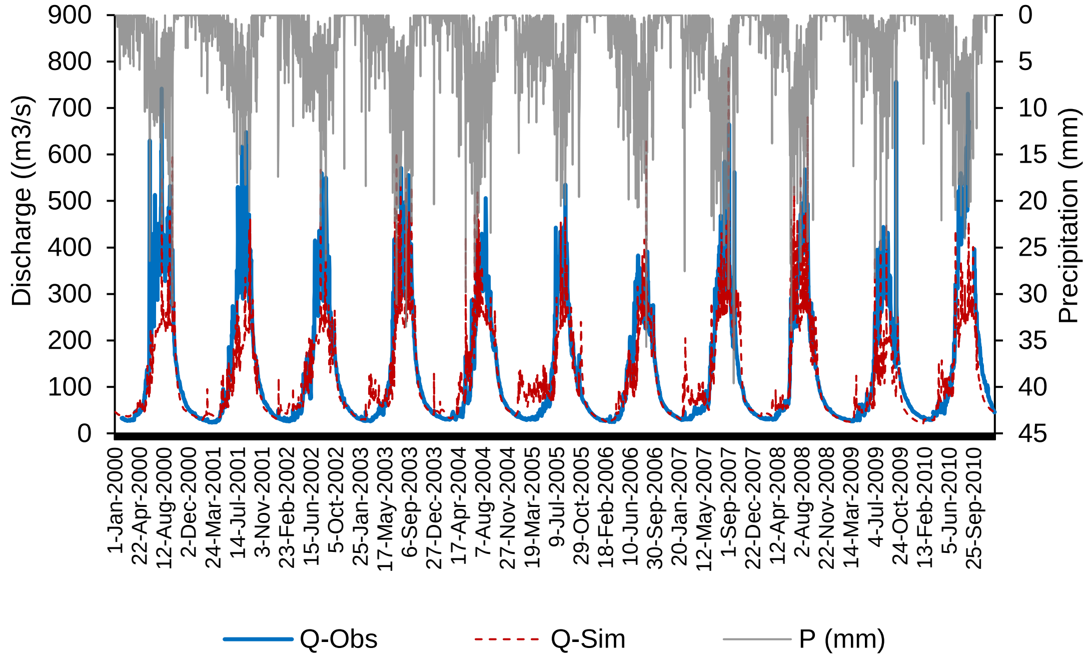

Figure 4.10: Daily Hydrograph Observed versus Simulated at Bhakundebesi Station

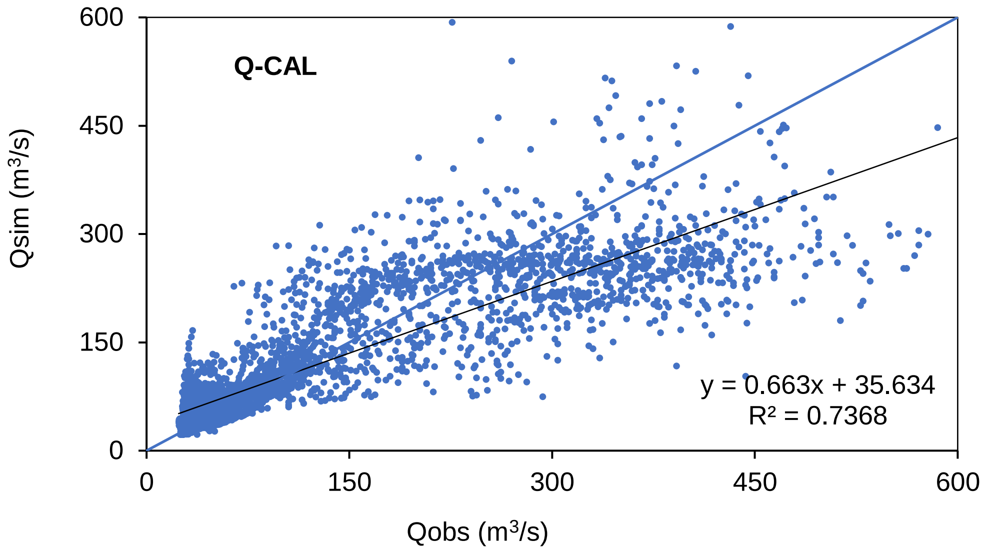

Figure 4.11: Scatter plots for daily simulation during calibration at Bhakundebesi Station

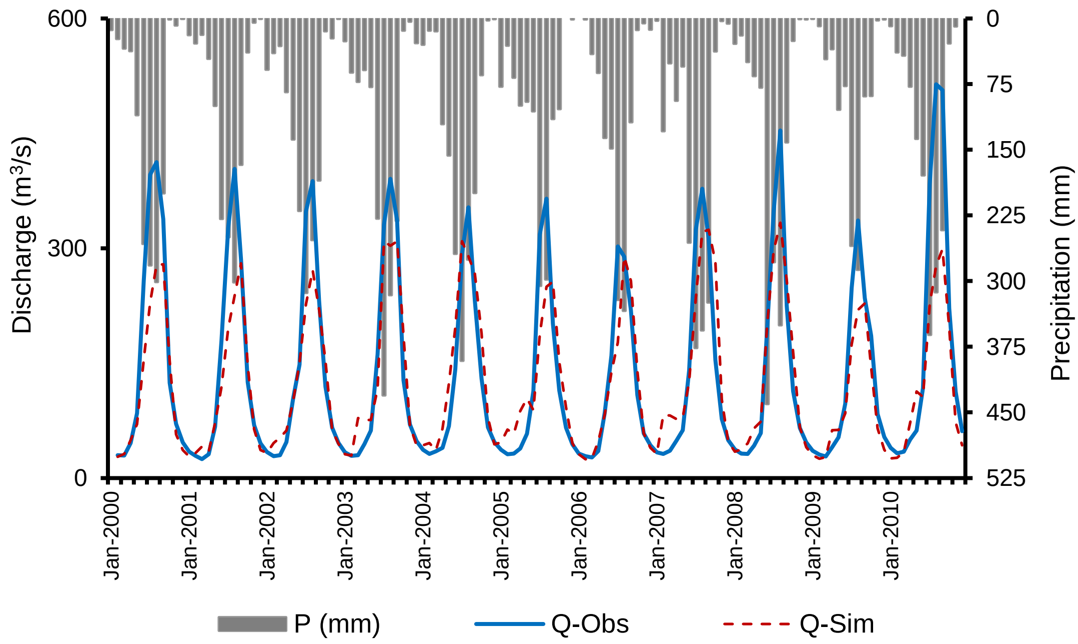

Figure 4.12: Monthly hydrograph observed versus simulated at Bhakundebesi Station

4.3.1.2 Khudi Hydrological Station

The daily calibration for the Khudi Hydrological Station is shown in (Fig. 4.13), which shows that the simulated discharge peak flows were found to be higher than observed throughout the calibration period (1987-1991), except for the year1989 and 1994. A closer look at the hydrograph and scatter plots during calibration reveals that the model appropriately predicts high flows and the long-term average for both daily and monthly simulations (except during 1987). The scattering spots spread out even more for high flows (Fig. 4.14), suggesting that the model can simulate high peaks. The model is also projecting high flows on a daily and monthly basis, according to the linear fit equation. Nonetheless, average flow conditions are adequately replicated, with a 26.1 percent bias over the whole daily simulation period (Table 4.7) (Qobs = 11.37 m^3/s; Qsim = 14.36 m^3/s). The NSE is 0.73 for calibration and 0.71 for validation for monthly simulation (Fig. 4.15).

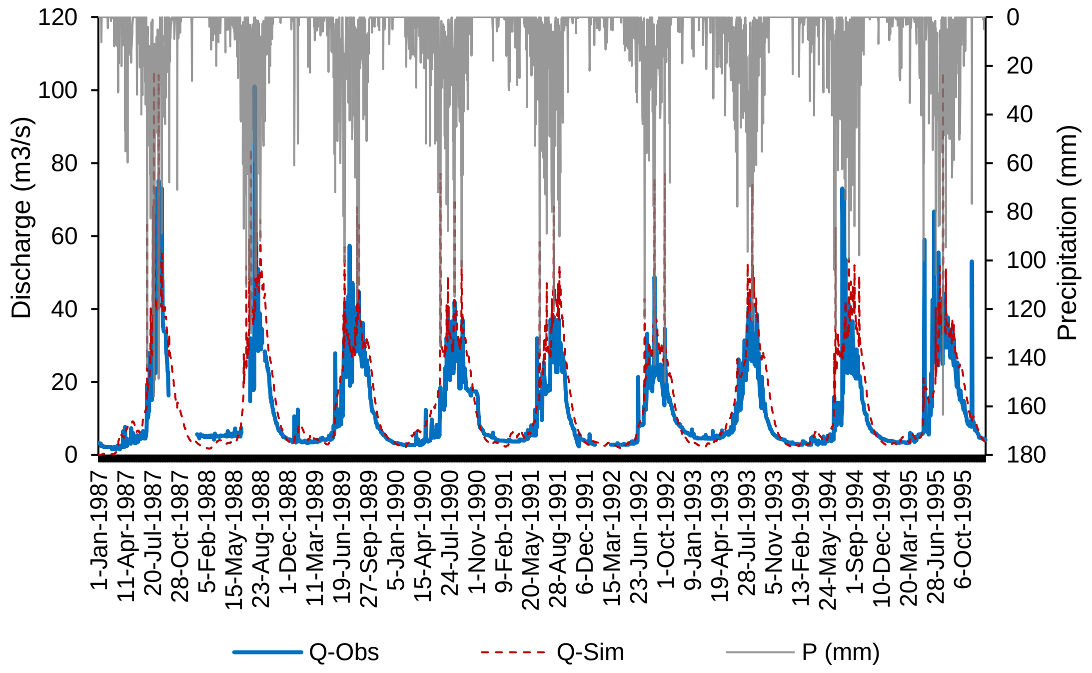

Figure 4.13: Daily hydrograph observed versus simulated at Khudi Station

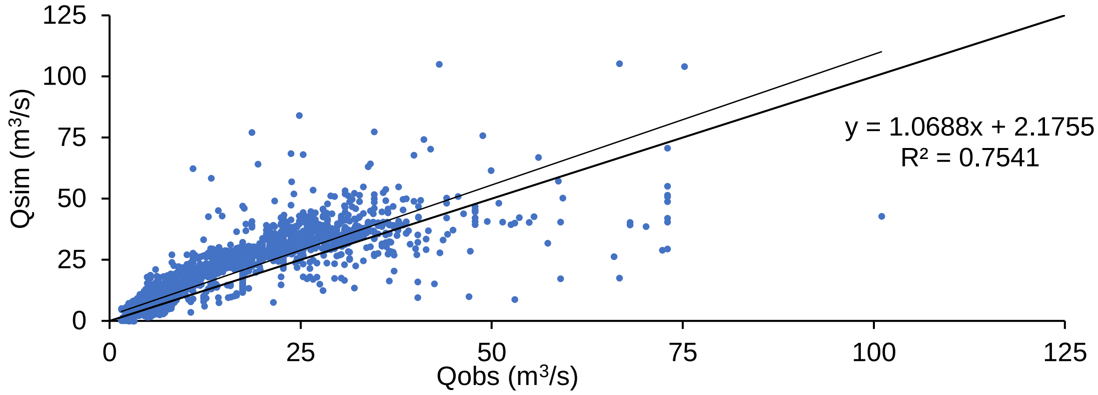

Figure 4.14: Scatter Plots for Daily Simulation during calibration at Khudi Station

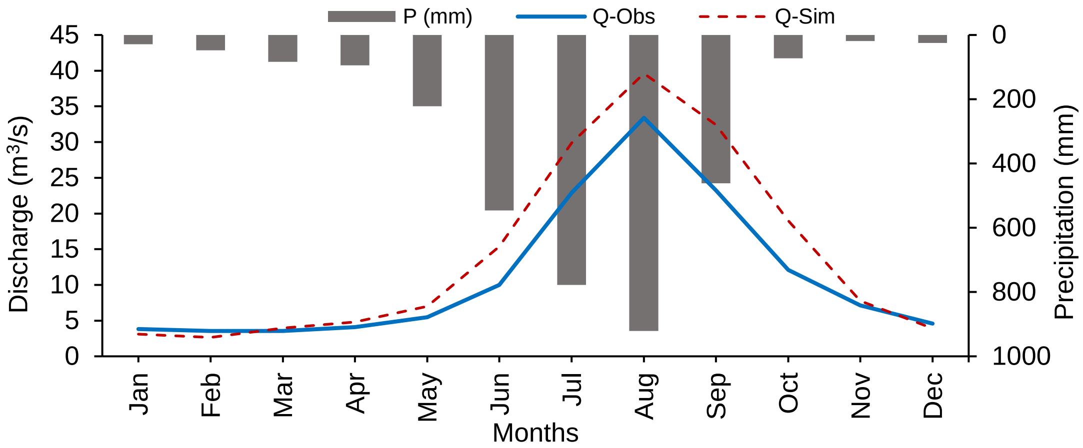

Figure 4.15: Monthly Hydrograph Observed versus Simulated at Khudi Station

4.3.1.3 Bimalnagar Hydrological Station

At Bimalnagar Hydrological Station, very good performance was shown with R^2, NSE, RSR, and PBIAS for the daily calibration and validation period as depicted in (Table 4.7) indicating the satisfactory fitness between observed and simulated values. Daily calibration (Fig. 4.16) graphically depicts those low flows that were well simulated throughout the calibration period (1998-2010). During calibration, a closer examination of the hydrograph and scatter plots (Fig. 4.17) reveals that the model accurately predicts low flows and the long-term average for daily and monthly simulations. For the whole duration of the daily simulation (Qobs = 230.68 m^3/s; Qsim = 211.90 m^3/s), overall average flow conditions are well recreated, with a bias of roughly -8.5 percent. For monthly simulation, the NSE for calibration is 0.84, and for validation, it is 0.83 (Fig. 4.18).

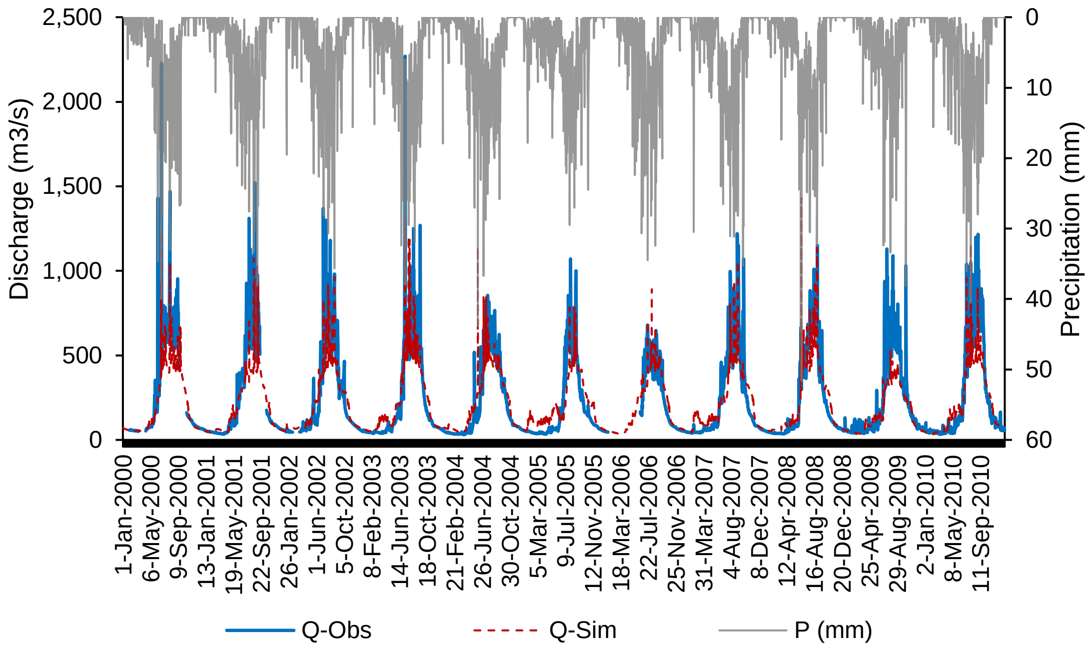

Figure 4.16: Monthly Hydrograph Observed versus Simulated at Bimalnagar Station

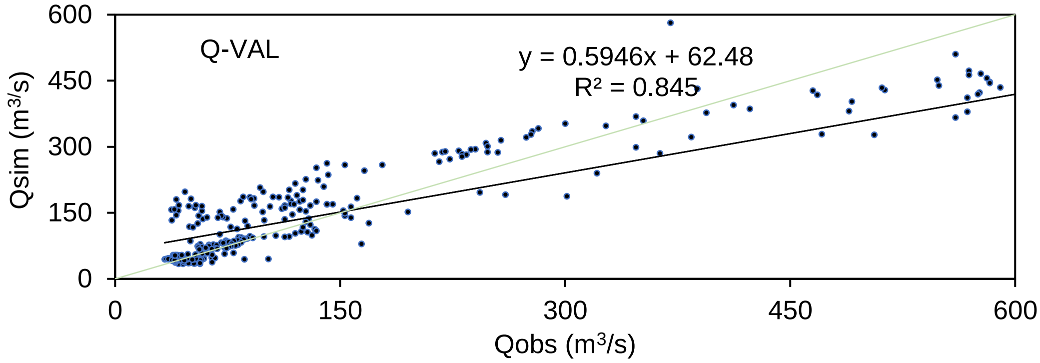

Figure 4.17: Scatter Plots for Daily Simulation during Calibration at Bimalnagar Station

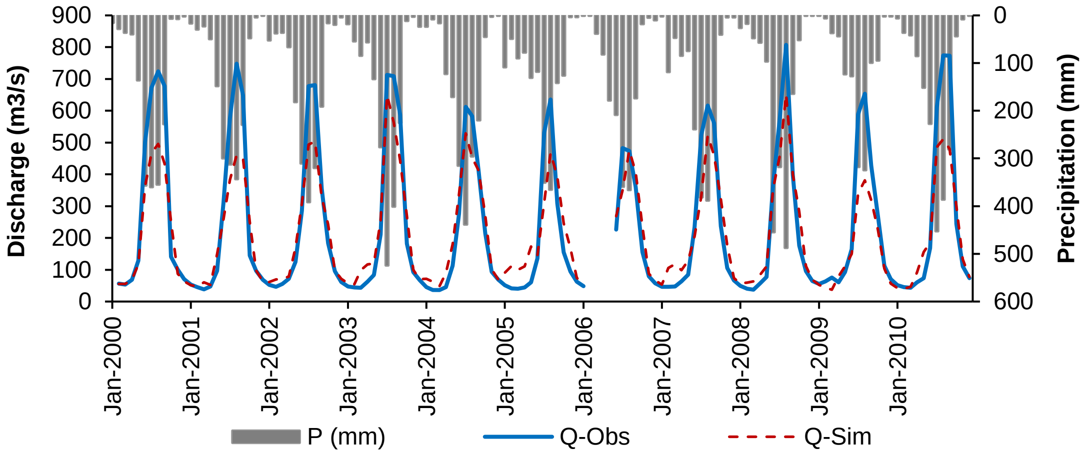

Figure 4.18: Monthly Hydrograph Observed versus Simulated at Bimalnagar Station

Uncertainty analysis

The combination of P-factor and R-factor reveals the quality of the model calibration as well as they are effective for uncertainty evaluation. Abbaspour et al. (2007) suggested using two measures, referred to as the P-factor and the R-factor to analyze uncertainty. The P-factor is a measure of the model's capacity to incorporate uncertainty as a percentage of the measured data bracketed by the 95PPU. The degree to which the 95PPU does not bracket the observed data reflects the prediction inaccuracy because all "real" processes are reflected in the measurements. the P-factor should ideally be 1, indicating that the measured data has been bracketed 100%, capturing or accounting for all of the proper processes. The R-factor, on the other hand, represents the thickness of the 95PPU and is a measure of the calibration's quality. Its value should ideally be close to zero, matching the measured data.

At Bhakundebesi, P-factor was 0.75 whereas R-factor was 0.6. Similarly, at Chepe**:** P-factor was 0.51 whereas R-factor was 0.96 while at Bimalnagar, P-factor was 0.57 whereas R-factor was 0.45 acceptable range of uncertainty with a prediction (Abbaspour *et al.*, 2009).

4.3.2 Climate change impacts on water resource availability

Streamflow at Bimalnagar Station (index:439.7) was projected for the future period under RCP 4.5 and RCP 8.5 scenarios based on calibrated and validated SWAT model. The annual average streamflow at the basin outlet was observed as 296 m^3/s during the baseline which is projected to increase in the future with varying magnitude (Fig.4.19; Annex 10). For instance, in the near future for RCP 4.5 scenarios streamflow is projected to increase (16%) Magnitude of flow has been observed to be more for RCP 4.5 in comparison to RCP 8.5(Annex 10). The hydrograph (Fig. 4.19; 4.20) shows the peak discharge in August for both RCPs (4.5 and 8.5) and the baseline period, while peak rainfall is in July. This mismatch between the months may be due to the groundwater delay in the watershed. In the Tamor Basin also peak discharge was observed during the same month (K.C *et al.,* 2018). It is important to note that peak discharge has been observed during the same month from baseline to future scenarios for both RCPs.

Analyzing the trends in streamflow for the future period under both RCPs scenarios reveals that streamflow is projected to decrease insignificantly in the near future whereas it increased insignificantly in the mid future for both RCPs scenarios indicating the potentiality of extreme hydrological events (Table 4.8).

The maximum average seasonal streamflow during baseline and future (NF&MF) under both RCPs scenarios considered has been observed in monsoon season (JJAS) followed by post-monsoon (ON) whereas minimum streamflow has been observed in the winter season (DJF). However, seasonal streamflow was projected to be more for the near future in comparison to mid-future under RCP 4.5 and RCP 8.5 except for RCP 8.5 during pre-monsoon and winter seasons (same volume of streamflow) (Annex 9). A similar case of increase in streamflow was reported in Marshyangdi Watershed based on HBV model (Parajuli *et al.,* 2015). Similarly, in other basins like Koshi (Bharati *et al.,* 2012; Bharati *et al.,* 2014), Chamelia Watershed of Karnali Basin (Pandey *et al.,* 2019), Kaligandaki (Bajracharya *et al.,* 2018), Budhigandki (Marahatta *et al.,* 2021) increase in streamflow have been projected to increase in the future.

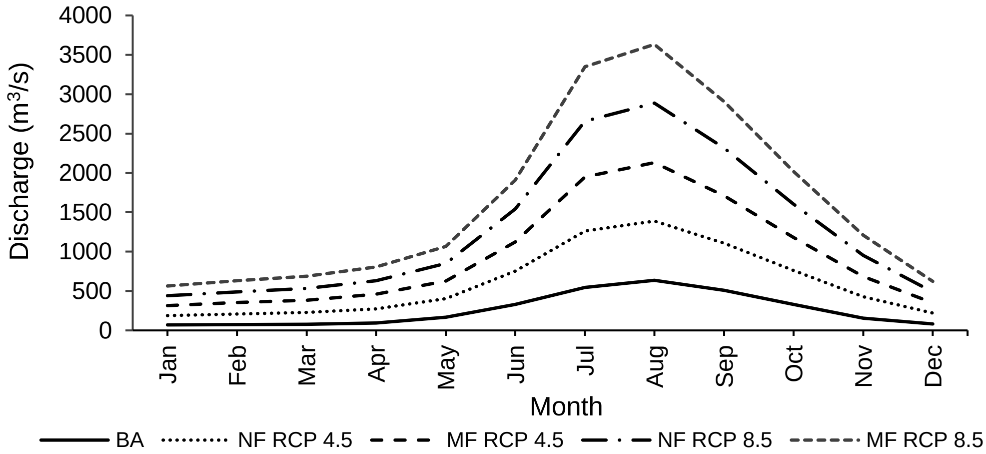

Figure 4.19: Monthly average flow hydrograph for the baseline and two future periods at Bimalnagar Hydrological Station (NF: near-future; MF: mid- future; RCP: Representative concentration pathways)

Water availability in the Marshyangdi Watershed has been expressed as a percentage of the seasonal discharge as well as in million cubic meters (MCM) (Table 4.8; Fig.4. 20). Annual flow volume has been observed to be approximately 9,335 million cubic meters in the Marshyangdi Watershed during the baseline scenario. Overall water availability is projected to increase in terms of flow volume and MCM in all the seasons for both RCPs 4.5 and 8.5 scenarios (Table 4.8). Among the seasons flow volume was projected to increase in monsoon seasons (JJAS) as well as in post-monsoon with more magnitude in RCP 8.5 NF (Table 4.8; Fig 4.20). Such higher flow in the river was also found in upper Tamakoshi during the monsoon season as well as in Kaligandaki Basin (Bajracharya *et al.*, 2018; Shrestha *et al.*, 2016c). However, in terms of percentage during post-monsoon for RCP4.5 MF increases in flow volume have been observed to be more in comparison to the near future.

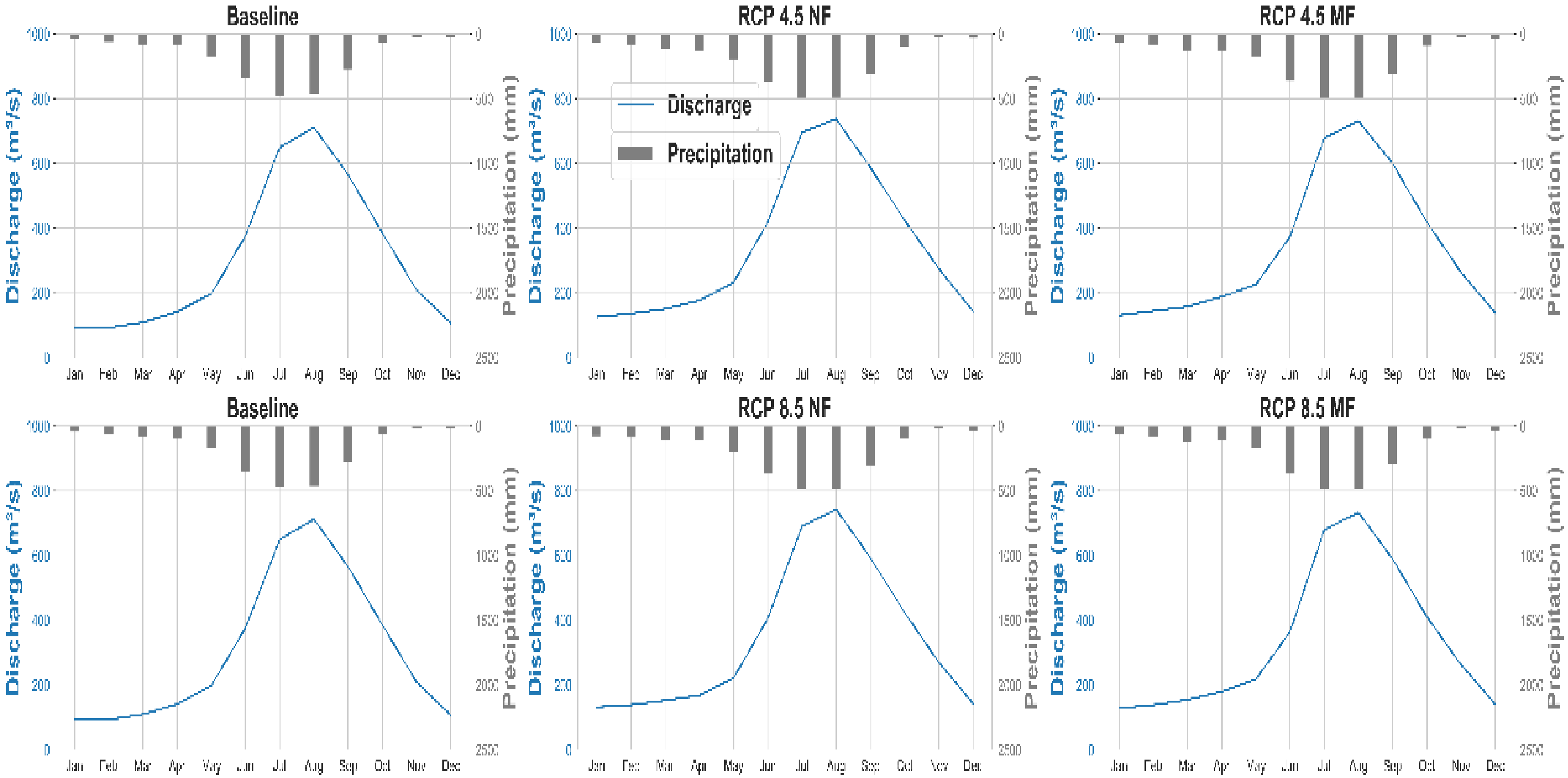

Figure 4.20: Monthly average hydrograph of the Marshyangdi Watershed in the future with respect to baseline (NF: near-future; MF: mid-future: RCP is Representative Concentration Pathways)

For example, water availability is expected to increase by 15 % for RCP 4.5 NF but up to 12 % only for RCP8.5. An increase in water availability in all the seasons has been reported in the Bagmati River under the B2 scenario based on Hadley Centre Coupled Model, version 3 (HadCM3), and the Hydrologic Engineering Center's Hydrologic Modeling System (HEC-HMS) (Babel *et al.,* 2014). In the snow-dominated Kaligandaki Basin also water availability was not expected to decrease until the 21st century based on Representative Concentration Pathways Scenarios (RCP 4.5 and RCP 8.5) for ensemble downscaled data from Coupled Model Intercomparison Project (CMIP5), General Circulation Model outputs (Bajracharya *et al.*, 2018). Bharati et al. (2014) also reported that climate change is unlikely to alter annual fluctuations in the flow volume in Nepal's Koshi Basin, hence having no impact on the basin's water availability.

Table 4.8: Water availability and seasonal change in average annual streamflow at Bimalnagar Station

Seasons	**Seasonal flow**					**Water Availability (%)**				
	BA	**NF RCP4.5**	**MF RCP4.5**	**NF RCP8.5**	**MF RCP8.5**	**BA**	**NF RCP4.5**	**MF RCP4.5**	**NF RCP8.5**	**MF RCP 8.5**
Winter (DJF)	86	133	135	132	135	8	54	54	57	57
Pre-monsoon (MAM)	142	187	180	186	180	13	32	31	27	27
Monsoon (JJAS)	573	608	608	595	589	53	6	4	6	3
Post-monsoon (ON)	280	350	345	332	655	26	25	19	23	134
Trends	0.6	-2	1	-0.5	1					
	Million Cubic Meter (%)					9335	10797(15)	10549(12)	10731(14)	10392(11)

4.3.3 Changes in streamflow due to climate change

The SWAT model was used to analyze the hydrological effects of climate change on streamflow variation at the watershed (Annex 10) and sampling sites (Table 4.9). The average annual streamflow at the sampling stations, during the baseline period, varies from 296 m^3/s at site M21 to 2 m^3/s at site M1. However, for RCP 4.5 NF scenarios, it varies from 198 m^3/s to 2 m^3/s, and for MF and RCP 4.5 scenarios, it varies from 335 m^3/s to 2m^3/s at the respective sites (Table 4.9). It is interesting to note that for the future under both RCPs, a similar volume of streamflow was observed at site M1. However, streamflow at the tributaries (M8, M11, M13, M14 &M16) has been observed to be much less in magnitude in comparison to the mainstream. Average annual streamflow shows increasing trends at all the samplings sites with respect to baseline except for RCP 8.5 MF (Table 4.9). Like average annual streamflow, seasonal streamflow has been also projected to increase during the monsoon season at all the sampling sites in the future for both RCPs scenarios (Annex 10.1).

Table 4.9: Variation in annual average streamflow in the future with respect to baseline at sampling sites

Sampling sites	Baseline (m^3 /s)	RCP4.5NF	RCP4.5MF	RCP8.5NF	RCP 8.5MF
M1	2	2	2	2	2
M2	7	7	7	8	7
M3	12	13	13	14	13
M4	70	93	100	13	99
M5	71	95	101	106	101
M6	92	130	127	129	124
M7	122	165	161	163	157
M8	16	18	18	18	18
M9	148	194	191	192	186
M10	149	196	192	194	187
M11	37	38	38	38	37
M12	191	238	234	236	229
M13	7	7	7	7	7
M14	30	30	30	31	30
M15	217	259	256	259	251
M16	6	5	5	6	5
M17	212	249	246	249	241
M18	215	253	250	253	245
M19	45	46	45	46	46
M20	296	198	335	340	330
M21	296	198	335	340	330

Note: RCP is Representative Concentration Pathways; NF is near- future; MF is mid -future

4.4 Historical Trends in Hydrologic Extremes

4.4.1 Trends in average annual discharge

The average annual runoff at the Bimalnagar Station (Index: 439.7) is 222 m^3/s with a coefficient of variation of 17.3% and the highest and lowest values were recorded in 2000 as 290 m^3/s and 160 m^3/s in1997, respectively (Table 4.10). The overall trend in annual average runoff gradually increases insignificantly with a magnitude of 0.6 m^3/s showing a sharp decline with a statistically significant trend of (7.6 $m^3/s/y$) during 1999 (pre-CP) however its trends again decrease thereafter (post-CP) with a statistically insignificant (-1 $m^3/s/y$). Seasonality trends in average runoff values show a sharp increasing trend during monsoon (JJAS) followed by post-monsoon (ON) and a similar trend was observed during Pre and Post CP as well (Table 4.10).

Table 4.10: Seasonality of trends in discharge at Bimalnagar Station

Types	Streamflow (Index: 439.7) Entire-time series	Pre-CP	Post-CP
Average annual	222	206.5	234.1
	(0.6)	**(-7.6)**	(-1)
Pre-monsoon [MAM]	65.9	67.1	65.1
	(-0.2)	(0.2)	(-0.7)
Monsoon [JJAS]	492.6	465.9	519.4
	(2.8)	(-2.4)	(-1.8)
Post-Monsoon [ON]	148.2	148.1	146.2
	(0.57)	**(-3.7)**	(**3.8**)
Winter [DJF]	55.07	55.3	55.1
	(0.04)	(**-1.1)**	(-0.07)

Note: values in the bracket are trend amount and bold values represent statistically significant trends at a 5 percent level of significance

Seasonality in the trend of streamflow has been observed at watershed which depicts an increasing (insignificant) trend of 2.8 $m^3/s/y$ in monsoon (JJAS), 0.57 $m^3/s/y$ in post-monsoon (ON), and 0.04 $m^3/s/y$ in winter (DJF) seasons; whereas decreasing (insignificant) trend of 0.2 $m^3/s/y$ in pre-monsoon (MAM) season (Table 4.10). But the seasonal trends in pre-CP and post-CP periods are not consistent with trends in average annual values, thus indicating the significance of the CP. The pre-CP trend in all the seasons is decreasing except pre-monsoon whereas, for the post-CP period, the trend is decreasing in all seasons except post-monsoon, in which it is increasing (significantly) at a rate of 3.8 $m^3/s/y$ (Table 4.10).

4.4.2 Changes in flow regime in baseline

The Petitt test (1979) was used to uncover sudden changes in a time series to distinguish pre-impact and post-impact periods for assessing hydrological extremes. In 1999, a change point (CP) in the river discharge time series was observed (insignificant) whereas significant CP was also observed in the precipitation time series at Manang Bhot (Singh *et al.*, 2020) during the same year. Therefore, to break continuous time series in the IHA tool, this year was taken to split into pre (1987-1999) and post-impact (2000-2015) periods. In the same year, the CP was observed, Khadka & Pathak (2016) recorded flood fatalities in the Barpak village in Gorkha district, which is located within the watershed.

At the Bimalnagar Hydrological Station in the Marshyangdi Watershed, the median value, degree of deviation, and degree of change for the IHA parameters characterizing five groups of extreme flow regimes are presented in Table 4.11. The values of hydrologic alterations for each indicator are shown in Figure 4.21. Equations (8) and (9) and (10) in section 3.5.4 were used to calculate percent deviation (P), degree of hydrologic alteration (HA), and overall hydrologic alteration. The overall mean hydrologic change based on all 32 parameters is calculated to be low at 30%, however, changes in 32 parameters within five groups vary greatly, as detailed in the following sub-sections.

Table 4.11: Degree of hydrologic alterations of IHA parameters at Bimalnagar Hydrological Station

Parameters	Pre-Impact	C.D	Post Impact	C.D	P (%)	HA (%)
Group #1 (Magnitude of monthly water conditions, m^3/s) Parameters						*24.4.0 (L)*
January	50.2	0.09	50.02	0.10	-0.4	59.4
February	43.3	0.16	44.10	0.14	1.8	28.9
March	43.3	0.20	42.90	0.16	-0.9	28.9
April	50.15	0.26	54.53	0.30	8.7	21.9
May	71.4	0.58	82.95	0.42	16.2	28.9
June	197.5	0.38	210.00	0.75	6.3	21.9
July	414	0.70	573.00	0.15	38.4	7.1
August	648	0.25	659.50	0.18	1.8	21.9
September	390	0.24	444.80	0.43	14.1	7.1
October	167	0.26	195.40	0.28	17.0	28.9
November	93.7	0.21	95.60	0.25	2.0	28.9

December	63	0.08	65.45	0.12	3.9	8.6
Group #2 (Magnitude and duration of annual water extreme conditions, m^3/s) Parameters						*16.8*(L)
1-day minimum	39	0.17	37.25	0.12	-4.5	7.1
3-day minimum	39.97	0.17	38.50	0.14	-3.7	7.1
7-day minimum	40.57	0.17	40.70	0.21	0.3	28.9
30-day minimum	42.57	0.17	42.63	0.16	0.1	7.1
90-day minimum	45.7	0.15	45.23	0.14	-1.0	7.1
1-day maximum	1090	0.26	1219.00	0.31	11.8	21.9
3-day maximum	966.3	0.21	1086.00	0.19	12.4	62.5
7-day maximum	836.9	0.31	930.90	0.24	11.2	7.1
30-day maximum	674.4	0.28	761.40	0.21	12.9	21.9
90-day maximum	525	0.27	609.30	0.19	16.1	7.1
Baseflow index	0.20	0.18	0.17	0.26		7.1
Group #3 (Timing of annual extreme, days) Parameters						*29.3(L)*
Date of minimum (Jmin)	73	0.09	69	0.14	-5.5	36.8
Date of maximum (Jmax)	207	0.13	208	0.09	0.5	21.9
Group #4 (Frequency and duration of high and low pulses, numbers) Parameters						*16.0*
Low pulse count	4	1.13	5.0	2.0	25.0	36.8
Low pulse duration	5.5	2.64	5.0	3.2	-9.1	21.9
High pulse count	3	1.50	3.0	0.3	0.0	0.7
High pulse duration	5	9.25	3.5	10.3	-30.0	4.5
Group #5 (frequency and rate of change of water, m^3/s) Parameters						*54.4(M)*
Rise rate	8.3	0.56	9.5	0.51	14.5	27.8
Fall rate	-3.1	-0.32	-4.75	-1.20	53.2	55.7
Number of reversals (number)	137	0.22	132.5	0.79	-3.3	79.7
Overall degree (OD)						*30.0 (L)*

Notes: CD is the coefficient of Dispersion; H: High; HA: Hydrologic alteration; L: Low; M: Moderate; P: Percentage of deviation

Alterations in the magnitude of monthly streamflow

As depicted in Table 4.11 the monthly median parameters increased from pre-impact to post-impact period under the high RVA category, except in January and March, when the median values have been observed to be decreasing insignificantly indicating the increase in the frequency of observed values than the upper RVA limit. The degree of deviation (P) is also negative only for January and March out of 12 months (Table 4.11) suggesting that streamflow has been increased from the pre- to post-impacted period. Calculation of the degree of hydrological alteration (HA) for monthly streamflow shows that monthly stream flows fall within the category of low alteration (D < 33%), except in January where the alteration is moderate (33% < D < 67%). In a nutshell, median values among the Group-1 IHAs show low hydrologic alteration (24.4%).

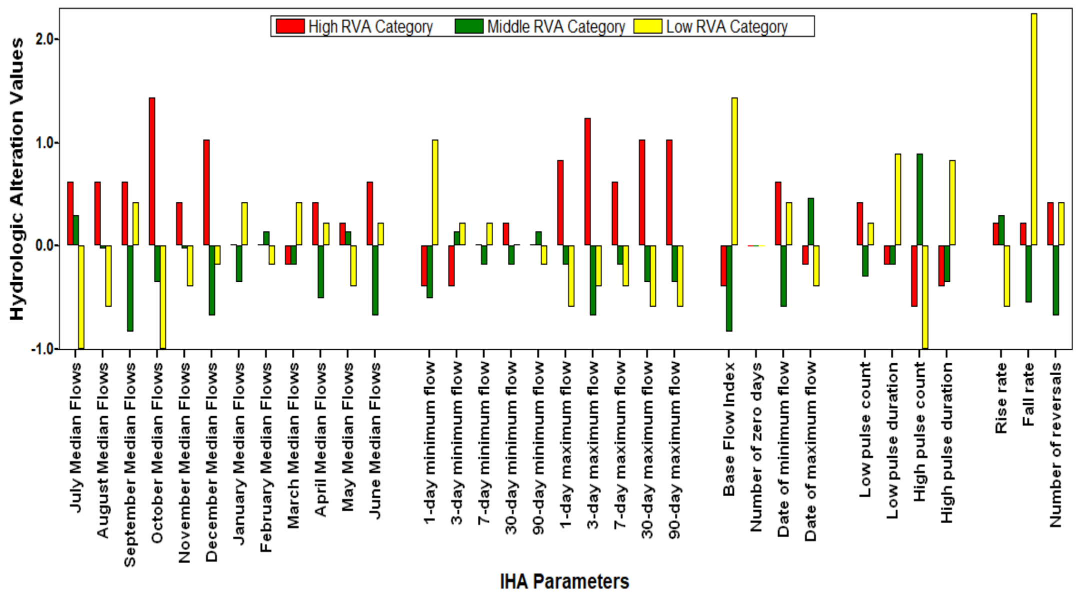

Figure 4.21: Hydrological alterations for all 33 IHAs parameters

Alterations in annual extreme flow

Analysis of median values of degree of deviation and degree of hydrologic alteration for the annual extreme flow conditions (11 IHAs under Group-2 and 2 IHAs under Group-3) reveal that degree of deviation is highest (16.1%) for 90-day maximum, followed by 30-day maximum (12.9%) (Fig. 4.22a; Fig.4.22b) whereas it decreases in 1-day, 3-, 90-day minimum extreme flow parameter from pre- to post-impact period. This means that flood magnitude may increase, which might have both favorable and detrimental consequences depending on channel morphology, substrate types, depth, and other geomorphological factors (Stefanidis *et al.,* 2016). Furthermore, due to the major particle size of bed materials, an increase in 1-, 3-, and 7-day maximum flow produces changes in the floodplains, resulting in ecological implications such as low oxygen and prolongation of stressful high temperatures (Graf, 2006). Hydrologic alteration (HA) suggests a low degree of change (<33 %) among the indices, but for the 3-day maximum, it shows moderate alteration (Table 4.11). Overall, Group-2 has a 16.8 percent degree of hydrologic alteration, suggesting minimal hydrologic alteration (D<33 %).

The degree of deviations (P%) is negative, in the case of timing of annual minimum extremes (indicators under Group-3), i.e., the timing of the 1-day minimum is moving backward from the 59th day to 73th (delayed by 14 days), but, 1-day maximum is also moving forward from 207th day to 208th day from pre-impact to post-impact period. Because of the lag in the Julian date of minimum streamflow, yearly minimum values will appear early in the year, endangering riverine ecology (Xue *et al.,* 2017). The hydrological changes for 1-day minimum (Jmax) and 1-day maximum (Jul-min) timing are classified as moderate and low, respectively (Table 4.11). The overall degree of hydrologic alteration of IHAs under Group-3 is low with a value of 29.3% (33% < D < 67%). As a result, the observed shift in the occurrence of low flows means that the downstream channel may dry up sooner, which could have negative repercussions for floodplain ecosystems, ecology, and river navigability (Sharma *et al., 2019).*

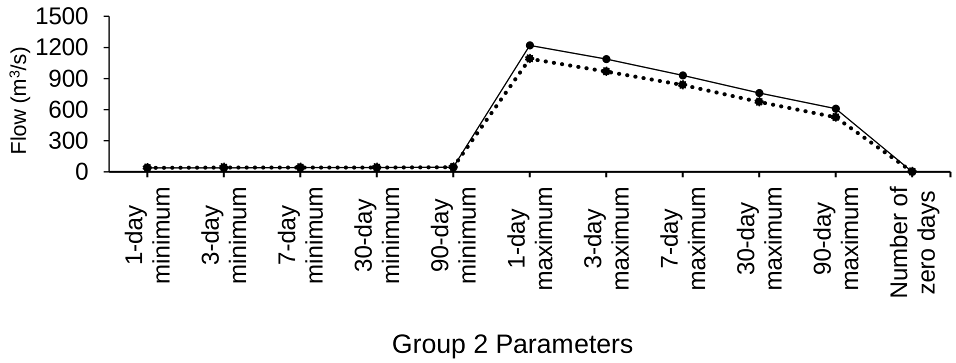

Figure 4.22a: Annual extreme flows

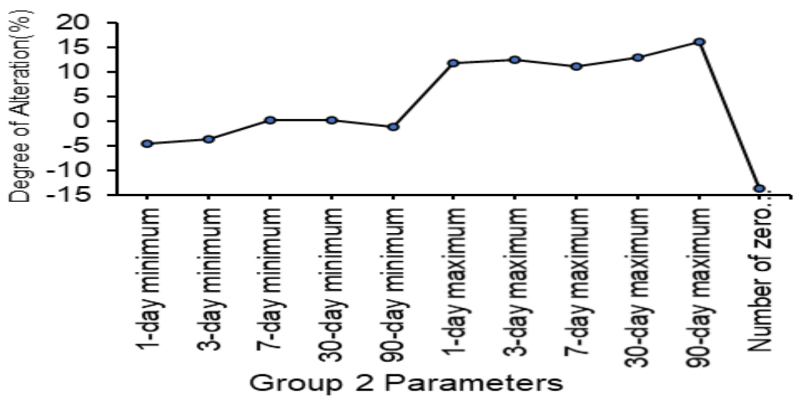

Figure 4.22b: Degree of deviation

Alterations in frequency and duration of high and low flow pulses

Among the Group-4 parameters, the frequency of low (25th percentile) pulse count increases from the pre- to post-impact period, however, high (75th percentile) pulse counts do not show any change, while the duration of high and low pulse count decreases from the pre- to post-impact period (Table 4.11; Fig 4.26a). The degree of deviation (Table 4.11, Fig. 4.22b) for the low pulse counts is 25% which falls under the High RVA category (Fig. 4.21). The degree of hydrologic alteration for low pulse count is characterized as "moderate (M)" but for other three parameters under Group-4 are characterized as "low (L)". Thus, four parameters under Group-4, altogether, show a low degree of hydrologic alteration (16%). Increased low pulse count values could lead to more frequent dry and wet periods, thus worsening the ecological development of the Marshyangdi River floodplain. However, due to limited nutrient availability for plants along the riverbank, the minimal variation in high pulse count and duration may not be beneficial to the riverine environment, impacting the development of river biodiversity (Xue *et al.,* 2017). As a result, a low pulse count can have geomorphic consequences such as channel lengthening and bank stability, as well as an increase in the frequency of depositional regimes in channels. Concomitantly, associated ecological implications include stress for plants due to the changes in frequency and magnitude of soil moisture, which causes the anaerobic condition, and may lack availability of floodplain for aquatic organisms (Graf, 2006; Timpe *et al.,* 2017).

Alterations in rate and frequency of flow conditions

The Group-5 parameters, altogether, exhibit moderate hydrologic alteration of 54.4%. However, the hydrologic change differs among the metrics, with reversals exhibiting the most change (79.9%), followed by the fall rate (55.7%) (Table 4.11). The increase in rising rate and decrease in fall rate in the post-impact period, indicate that the transition from high to low flow conditions and vice versa would be hastened. It suggests that peak streamflow in the downstream channel arrives early (Sharma *et al.,* 2019), which is consistent with the results of backward displacement of 1-day maximum timing as stated previously. From the pre- to post-impact period, the number of reversals (flow switching from one type of period to another) of streamflow conditions that signal a change from rising to falling water conditions and vice versa reduces (Table 4.11) indicating low intra-annual fluctuations in water conditions of the downstream channel. The fall rate has a higher degree of deviation (53.2%) than the number of reversals (-3.3%), indicating substantial hydrologic change for the number of reversals and moderate modification for the fall rate, respectively. The fall rate has a higher degree of deviation (53.2%) than the number of reversals (-3.3%), indicating substantial hydrologic change for the number of reversals and moderate modification for the fall rate, respectively. This increase in the rise and fall rate implies that streamflow is becoming more abrupt. Changes in pulse frequency/rate (Group-5) may limit aquatic creatures in floodplains while stranding terrestrial organisms on floodplain islands (The nature conservancy, 2009). This could affect the ecological stability of plant and animal habitats (Xue *et al.,* 2017). Most parameters in Groups 1 and 2, as well as indications related to low pulse count (Group- 4), and (Group-5) parameters, increase under the High RVA category, implying an increase in the frequency of observed values beyond the upper RVA limit, based on RVA results (Fig. 4.21).

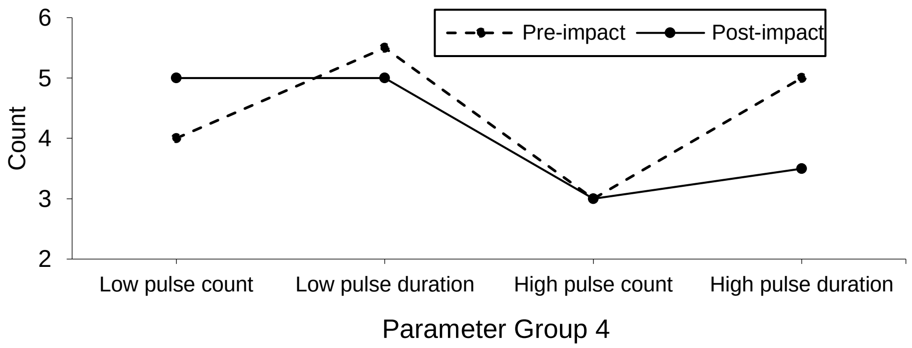

Figure 4.23a: Pulse count and duration

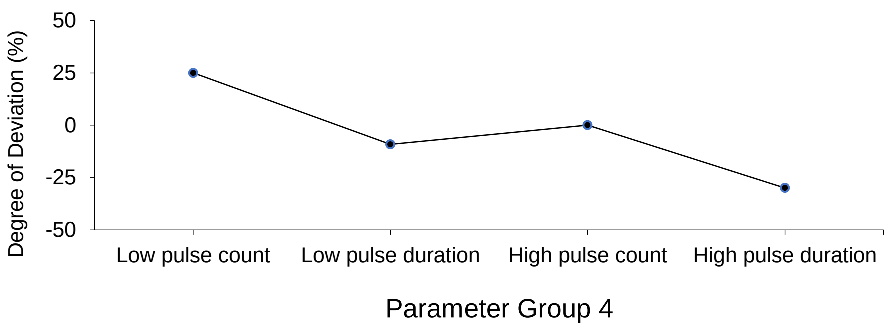

Figure 4.23b: Degree of deviation

4.4.3 Trends in extreme hydrologic indices

This section presents the trends in 15 hydrologic extremes parameters which show varying directions and magnitude of trends. Some indices such as 3-, 7-, and 30-day maximum flows show increasing (statistically insignificant) annual trends of +7.5 $m^3/s/y$, 4.4 $m^3/s/y$, and 5.5 $m^3/s/y$, respectively whereas 1-day and 90-day maximum flows have increased (statistically significant) trends of 0.4 $m^3/s/y$ and 4.8 $m^3/s/y$, respectively. However, 3-, 7-, 30- and 90-day minimum flows have insignificantly decreased trends (Table 4.12).

Hydrological extremes parameters exhibit much inter-annual variability in the index value as indicated in Table 4.12, Fig. 4.24 for 1-day maximum flow. The index has an average value of 1, 287.21 m^3/s with a trend (statistically significant) of +0.36 $m^3/s/yr$ from 1987 to 2015, however, the index value varies from 679 to 2270 m^3/s for the period, with a coefficient of variation of 0.3.

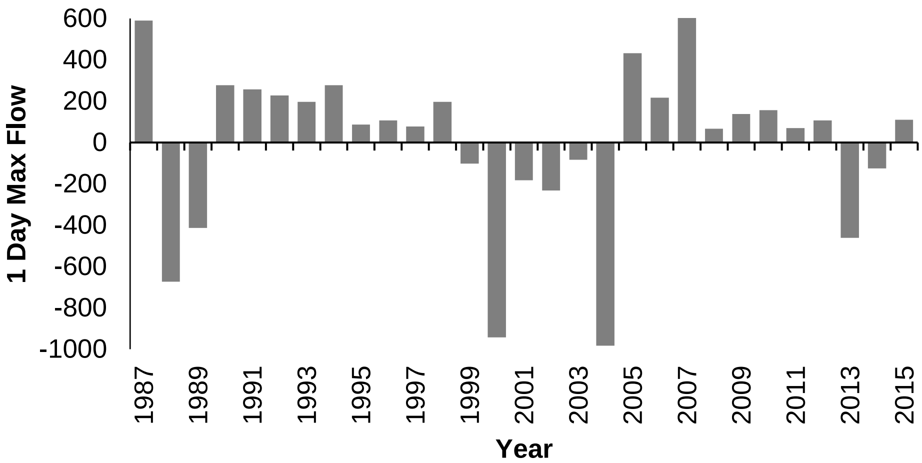

Figure 4.24: Anomaly trends in one day maximum flow

Table 4.12: Trends in selected hydrologic extreme indices in baseline

S. N	Index name	Index value (mean)	Index value range	CV	Amount of trend
1	1daymin	39.3	30.4 – 51.7	0.14	-0.35
2	3daymin	40.1	30.6 – 51.7	0.13	-0.21
3	7daymin	41.1	31.2 – 52.3	0.13	-0.19
4	30daymin	43.3	34.8 – 54.6	0.12	-0.11
5	90daymin	46.7	37.6 – 60.8	0.12	-0.09
6	1daymax	1287.2	679 – 2270	0.30	+0.36
7	3day max	1049.3	450 – 1773	0.25	7.51
8	7daymax	881.1	324.4 – 1140	0.20	4.43
9	30daymax	701.2	210.9 – 909.3	0.21	5.51
10	90daymax	558.6	117.1 – 729.8	0.22	4.77
11	Low pulse Count	6.6	0 – 19	0.81	0.23
12	High pulse count	3.6	1 – 8	0.54	0.00
13	Rise rate	8.8	0.8 – 23	0.49	0.01
14	Fall rate	-4.7	-10.8 – (-1.6)	0.57	-0.12
15	Reversals	139.9	44 – 224	0.33	2.80

Note: Statistically significant trends at 95% confidence level are highlighted as bold

4.5 Projected Future Trends in Hydrologic Extremes

4.5.1 Projected hydrological alterations and extremes

For the projection of hydrologic regime in future simulated flow are run in Indicators of hydrologic alteration software under two RCPs scenarios. Then, using R software, the trends of selected hydrologic extremes were analyzed employing Mann Kendall and Sen's slope methods. The overall degree of hydrological alterations (OD) in the flow regime was observed to be high for both RCP4.5 (78%) and RCP 8.5 (80%) with different magnitudes in the future (Table 4.13; Annex 11) based on 32 hydrologic indices. Also, among the five group parameters, the hydrologic alteration was observed to be high in the future for both RCPs in comparison to baseline. Mean hydrologic alteration (HA), the median value, degree of deviation, and degree of alteration for the IHA parameters characterizing five groups of extreme flow regimes at Bimalnagar Hydrological Station in the Marshyangdi Watershed are listed in Table 4.13, and values of hydrologic alterations for each indicator is shown in Fig. 4.25.

Table 4.13: Degree of hydrologic alterations of IHA parameters at Bimalnagar Hydrological Station for future (RCP 4.5)

Parameters	**Pre-Impact**	**C.D**	**Post Impact**	**C.D**	**P (%)**	***HA (%)***
Group #1 (Magnitude of monthly water conditions, m^3/s) Parameters						*98.7(H)*
January	50.2	0.09	104.9	0.50	109.0	16.4
February	43.3	0.16	125	0.62	188.7	44.4
March	43.3	0.20	148.3	0.52	242.5	44.4
April	50.15	0.26	172.5	0.50	244.0	86.6
May	71.4	0.58	215.1	0.44	201.3	44.4
June	197.5	0.38	293.2	0.52	30.8	156.8
July	414.0	0.70	592.8	0.22	43.2	44.4
August	648.0	0.25	660.3	0.16	1.9	3.7
September	390.0	0.24	539.6	0.09	38.4	156.8
October	167.0	0.26	401.1	0.48	140.2	156.8
November	93.7	0.21	258.7	0.65	176.1	20.4
December	63.0	0.08	111.3	0.56	76.7	164.8
Group #2 (Magnitude and duration of annual water extreme conditions, m^3/s) Parameters						*67.2(H)*
1-day minimum	39.0	0.17	93.63	0.59	140.1	0.30
3-day minimum	40.0	0.17	94.22	0.57	135.7	16.4
7-day minimum	40.6	0.17	95.3	0.57	134.9	44.4
30-day minimum	42.6	0.17	100.1	0.62	135.1	44.4
90-day minimum	45.7	0.15	115.4	0.62	152.5	44.4
1-day maximum	1090.0	0.26	1448	0.36	32.8	44.4
3-day maximum	966.3	0.21	1118	0.21	15.7	44.4
7-day maximum	836.9	0.31	930.9	0.20	11.2	86.6
30-day maximum	674.4	0.28	779.4	0.13	15.6	156.8
90-day maximum	525.0	0.27	670.4	0.16	27.7	86.6
Baseflow index	0.20	0.18	0.28	0.27	40.7	3.7
Group #3 (Timing of annual extreme, days) Parameters						*28.9(L)*
Date of minimum (Jmin)	73	0.09	17.5	0.10	76.0	37.4
Date of maximum (Jmax)	207	0.13	206	0.11	0.5	16.4
Group #4 (Frequency and duration of high and low pulses, numbers) Parameters						*49.9(M)*
Low pulse count	4.0	1.13	0.0	2.0	100	41.4
Low pulse duration	5.5	2.64	6.0	3.2	9	78.9
High pulse count	3.0	1.50	1.0	0.3	67	47.5
High pulse duration	5.0	9.25	146.0	10.3	2820*	16.4
Group #5 (frequency and rate of change of water, m^3/s) Parameters						*67.0(H)*
Rise rate	8.3	0.56	9.5	7.15	13.9	44.4
Fall rate	-3.1	-0.32	-4.75	-5.7	83.9	54.1
Number of reversals (number)	137	0.22	132.5	122	10.9	92.6
Overall degree (OD)						*77.5(H)*

Notes: CD is the coefficient of Dispersion; H: High; HA: Hydrologic alteration; L: Low; M: Moderate; P: Percentage of deviation

Alterations in the magnitude of monthly streamflow

The monthly median flow in all months for both RCPs, as shown in Table 4.13, indicates an increase in the frequency of observed flow values from pre- to post-impact. The degree of deviation (P%) was also found to be positive in all the months suggesting that streamflow increased from the pre- to post-impacted period. Calculation of the degree of hydrological alteration (HA) for monthly streamflow shows that monthly stream flows fall within the category of high alteration (> 67%).

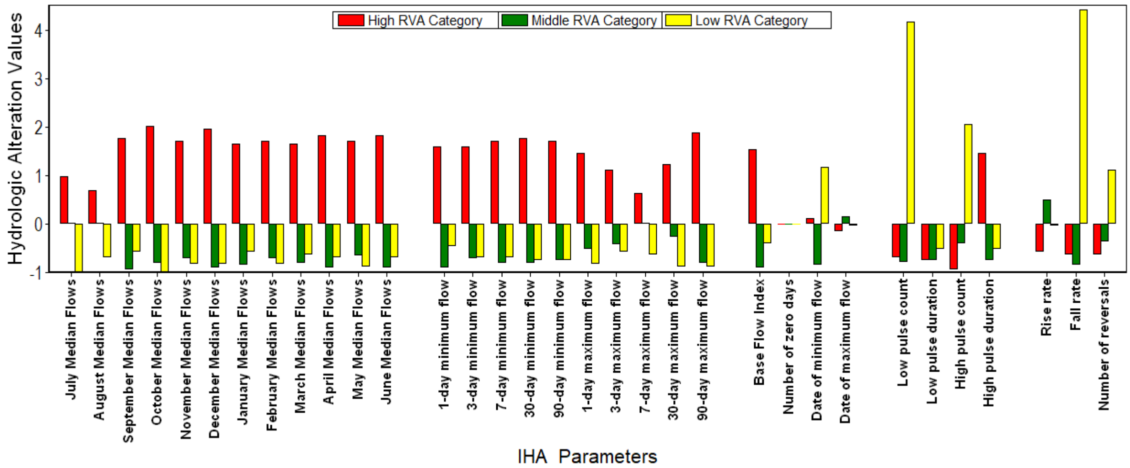

Figure 4.25: Hydrological alterations for all 33 IHAs parameters for RCP 4.5

Alterations in annual extreme flow conditions

From the pre- to post-impact period, analysis of median values, degree of deviation, and degree of hydrologic alteration for annual extreme flow conditions reveals that the degree of deviation (P %) is positive and shows a high deviation for minimum day flow in hydrologic extremes parameters, while deviation (P %) was less in all maximum day flow hydrologic extreme parameters (Table 4.13). In RCP 8.5 scenarios, however, the situation was reversed. In Nepal's Kaligandaki Basin, such decreasing variations in the size of minimum flow and an increase in the magnitude of maximum flow have also been documented (Yuqin *et al.*, 2019). Furthermore, an increase in 1-, 3- 7-and 90-day maximum flow for both RCPs in the future suggests changes in the floodplains (Graf, 2006; Stefanidis *et al.*, 2016). Baseflow index increases from pre- to post-impact period and is found to be altered low (Table 4.13) suggesting that low flow periods will not affect water availability. Furthermore, increases in the baseflow parameter may not interfere with run-of-river hydropower, schemes, and diversions for irrigation during dry seasons, as well as other in-stream water, uses (Bharati *et al.,* 2016). Hydrologic alteration (HA) indicates a high degree of alteration within the parameters (Table 4.13) while for 90-day maximum and minimum it shows significant moderate HA. Overall, the degree of hydrologic change for Group-2 parameters is > 67%, suggesting significant hydrologic change.

In the case of timing of annual minimum extremes (i.e., indicators under Group-3), the degree of deviations (P%) is negative in the future as well, i.e., the timing of 1-day minimum is moving backward from the 73rd day to the 18th while the 1-day maximum is also moving backward from 207th day to 206th and 204th days respectively from pre-impact to post-impact period. Thus, the delaying of the Julian date of minimum streamflow indicates that annual minimum values will appear early in the year negatively impacting the riverine ecology (Xue *et al.*, 2017). However, the hydrological alterations for the timing of 1-day minimum (Jmax) and 1-day maximum (Jul-min) are identified as moderate and low categories for RCP 4.5 whereas for RCP 8.5 both were altered moderately (Table 4.13; Annex 10). The overall degree of hydrologic alteration of IHAs under Group-3 is moderate. IHAs parameters in Group-3 have a moderate degree of hydrologic modification (D >33%).

Alterations in frequency and duration of high and low flow pulses

Among the Group-4 parameters, from the pre- to the post-impact period, the frequency and length of low (25th percentile) pulse count, as well as high (75th percentile) pulse count, increase insignificantly (Table 4.13). Such increases in flood duration may enhance the diversity of juvenile fish as well as an abundance of macroinvertebrates in the floodplain (Poff & Zimmerman, 2010). The degree of deviation (Table 4.13) for both low pulse and high pulse counts is high indicating an increased frequency of low and high flows in the post-impact period (Fig. 4.25). This suggests that dams may have effectively dampened the high-flow occurrence (Zhang *et al.,* 2017). However, the three-parameter of this group shows a low degree of hydrologic alteration except for high pulse count (i.e., frequency of high flow peaks) which shows moderate HA. Overall Group-4, parameters show a moderate degree of hydrologic alteration 59% under both RCPs excluding high pulse duration being an outlier. The change in group 4 parameters influence bed-load transport and channel sediment (Yuqin *et al.,* 2019).

Alterations in rate and frequency of flow conditions

All the parameters within Group-5, exhibit low hydrologic modification except for fall rate which was highly altered. The number of reversals decreases insignificantly (0.2 $m^3/s/y$) from the pre- to post-impact period (Table 4.13) indicating low intra-annual changes in water conditions of the downstream channel (Zhang *et al.*, 2017). The environment change generated by hydropower operations in the streamflow is effectively represented by such changes in the rate and frequency of the daily streamflow (i.e., rise and fall rate, and number of reversals) (Zhang *et al.*, 2017).

4.5.2 Future trends in hydrologic extremes

Future trends have been analyzed among the fourteen (14) hydrologic extremes indices which were altered moderately and high as revealed IHA tool and presented its results (i.e., trends, an average value of indices, and inter-annual variability) in Table 4.14. Some parameters such as 1-day (statistically insignificant) and 3-day maximum flows (statistically insignificant) show increasing annual trends of +0.7 $m^3/s/y$, and 1 $m^3/s/y$ respectively (Table 4.14). However, the minimum flow days parameters (1- 30- and 90-day) show an insignificantly increasing trend in the future with the same trend of 0.3 $m^3/s/y$ (Table 4.14). Hydrological extremes show inter-annual variability in the index value with an average value of 1, 535 m^3/s with a trend (statistically significant) of +0.67$m^3/s/yr$ from 1987-to 2053 for 1-day max indices. However, the index value varies from 162 to 2171 m^3/s for the aforementioned period, with a coefficient of variation of 0.2.

It is important to note that the future scenario under both RCPs shows high alteration in hydrologic regime except in group 3 (moderate, HA) however during baseline only the Group-5 parameter shows moderate HA. Such low alteration in group 1, group 2, and group 3 IHA parameters during baseline (Fig. 4.21) indicate that there is less dependence on water withdrawals for agriculture or domestic use as well as the construction of large reservoirs (Graff, 2006; Timpe *et al.*, 2017) in the Marshyangdi Watershed.

High hydrologic changes, particularly for group 4 and 5 IHA parameters, were observed under both RCPs as representations of dam operation for energy production, indicating that dams have a significant impact on pulse dynamism of the flood, river, and flood plain geomorphology and biological diversity (Timpe *et al.*, 2017).

Table 4.14: Trends in the hydrological extreme for (RCP 4.5)

S. N	Index name	Index value (mean)	Index value range	CV	Amount of trend
1	1daymin	98.5	48.9-199.3	0.1	0.31
2	30-day min	109.4	64.9-146.7	0.2	0.33
3	90-day min	128.1	101.7-188.5	0.1	0.31
4	1 day max	1535	162-2171	0.2	0.67
5	3day max	1121.4	811.7-1757	0.2	0.96
6	7daymax	938.4	705.9-1233	0.2	-0.63
7	30daymax	783.56	633.8-967.7	0.09	-0.64
8	90daymax	675.6725	577.4-810	0.08	-0.29
9	High pulse duration	150.1	3-193		-0.3
10	Date of minimum (Jmin)	99.1	1-366		1.4
11	Rise rate	6.78	3.5-11	0.22	-0.02
12	Fall rate	-5.92	-12- (5.92)	0.22	0.01
13	Reversals	119.1	89-161	0.1	-0.27
14	Baseflow	0.3	0.19-0.41	0.11	**0.001**

Note: Statistically significant trends at 95% confidence level are highlighted as bold.

4.6 Assessment of Current River Health

The river health status for baseline was calculated by using equations 9-14 and its results have been presented in (Annex 13; Fig. 4.26). Among the four components, the water quality plays a dominant role followed by hydrological components as indicated by their entropy weight (Annex 12) for the assessment of river health. In the Liao River of China also water quality component has contributed a major role in the integrated assessment of river health (Wei *et al.*, 2009).

The river health index score ranges from 0.28 at site M8 (Khudi River), to 0.59 at M21 (Muglin) indicating the river health category falls under the poor to moderate category (Annex 12). The integrated score for baseline at various sites reveals that 67% of sites fall under the moderate category, while 33% are under poor river health status with a mean value of 0.4±0.08 (Annex 12). In Huai River of China also reported a moderate state of river based on the integration of physical, chemical, and biological elements (Zhang *et al.*, 2018). The poor river health status at site M7 which is located at the downstream of the Upper Marshyangdi Hydropower, could be due to dominance of megalithic substrate type, frequent vehicle disturbance, prevalence of sand mining activities as well as devoid of riparian vegetation at its left bank (<18m). Similarly, site M16, which is one of the tributaries of the Marshyangdi River is located in a commercial area, has poor riparian vegetation on both banks of the river, which may contribute to poor river status. Poor river health status at site M8 one of the tributary rivers to Marshyangdi Watershed, was dominated by commercial activities, and poor riparian vegetation on its both river bank. Further its left bank was protected by gabion walls which may be one of the reasons for poor river health. Similarly, site M6 (Chudi River), lacks riparian vegetation on its both banks, and dominance of activities like bathing, washing caused this site in poor river health category. Further, site M5 (Tal Bazar) is also located near commercial areas (hotels), and is dominated by same type of substrate (mesolithal). In addition, due to lack of riparian vegetation, poor river health has been observed at this site. The watershed's moderate river health for the current status could be attributable to a change in water quality status as revealed by entropy weight and changes in flow regime.

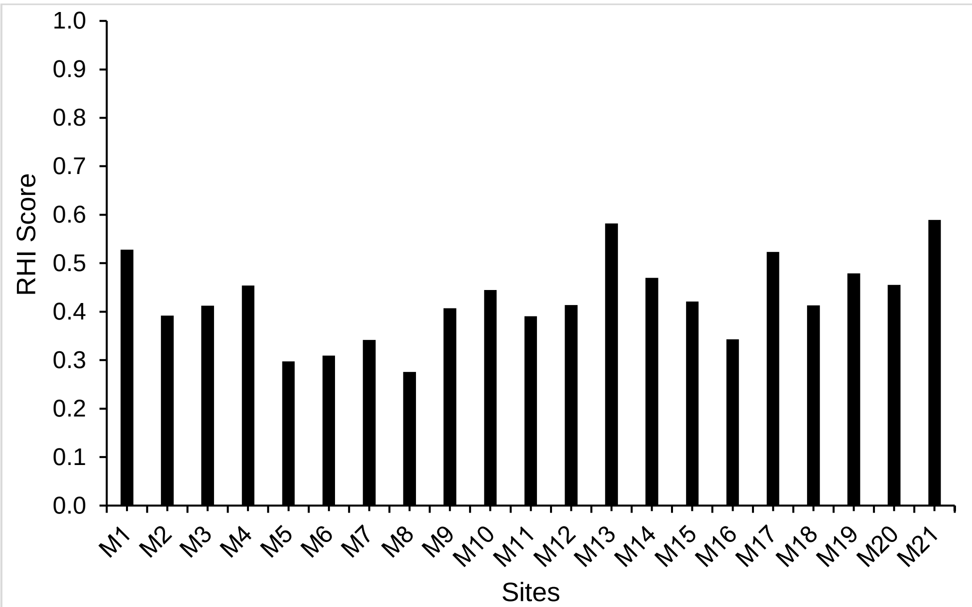

Figure 4.26: River health status of the Marshyangdi Watershed.

Seasonal variation in river health status

River health status varies among the four respective studied seasons for current condition (Annex13.1-Annex 13.4). For example, in post-monsoon 2018 it shows equal share of good and poor river health condition while in and in pre-monsoon 2019 it falls under poor category (48% sites) whereas in (post-monsoon 2019 and pre-monsoon

2021) it falls under moderate river health category (Annex 13.1-13.4). Overall, river health status shows much variation within the four seasons (Fig. 27a- Fig. 27d) in comparison to the river health scores based on the average of four seasons. Sites at the tributaries (M19, M16, M14, M13, M11, M8) shows similar deteriorating condition from current to future (NF & MF) under both RCPs except at site M14 and in post-monsoon 2018 and pre-monsoon 2019 which shows the moderate condition from current to future scenarios for both RCPs. Similarly, all the sites at the upstream region of the watershed (M1-M8) show poor river health status in all the seasons under both RCPs indicating deterioration in river health status from current scenarios. However, sites at the downstream region (M15-M19) shows moderate condition from current to future (NF & MF) for both RCPs with exception at site M16 (Chudi River). The deteriorating condition of the sampling sites located in the upstream region may be due to the high deviation in the flow health index scores based on nine flow health metrics (Annex 16).

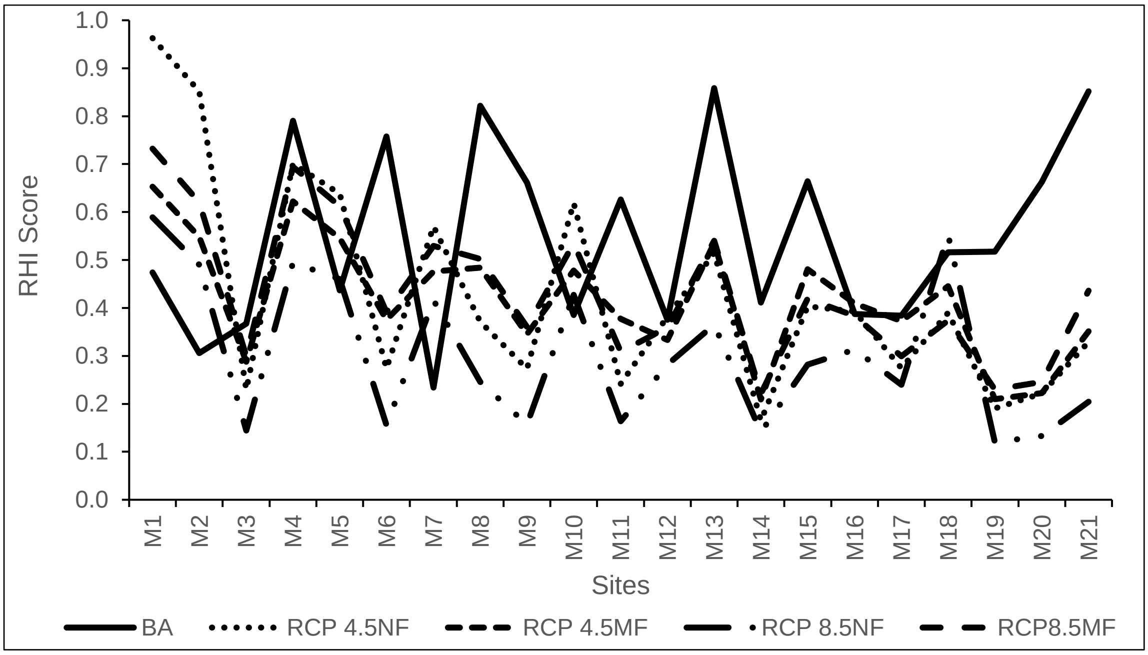

Figure 4.27a: Integrated assessment of river health for post-monsoon 2018

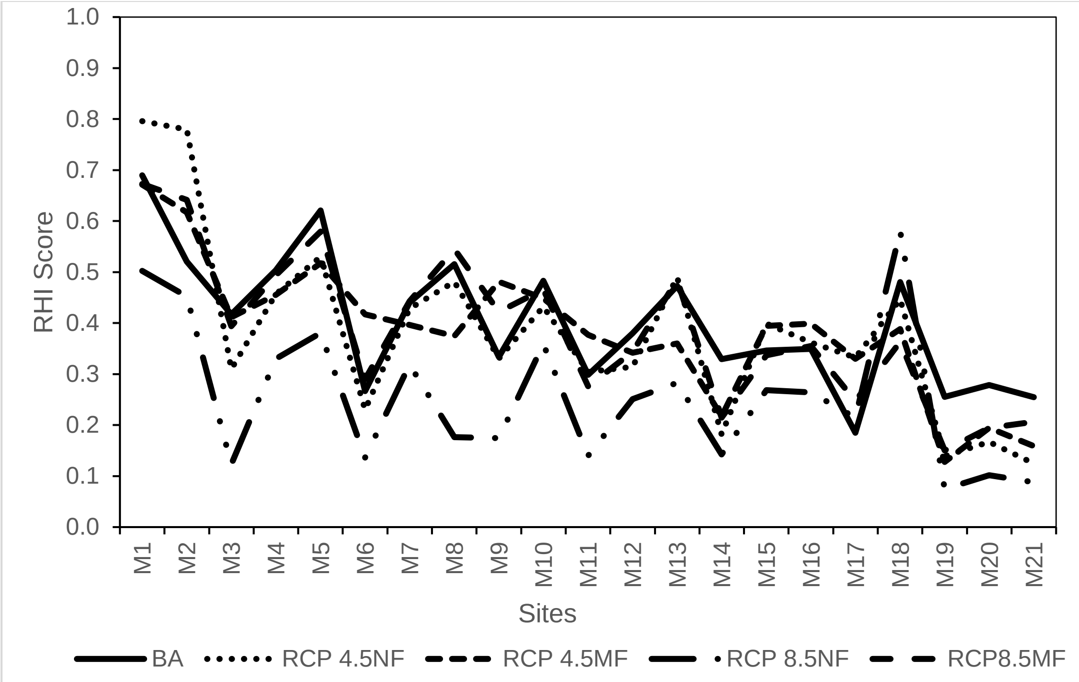

Figure 4.27b: Integrated assessment of river health for pre-monsoon 2019

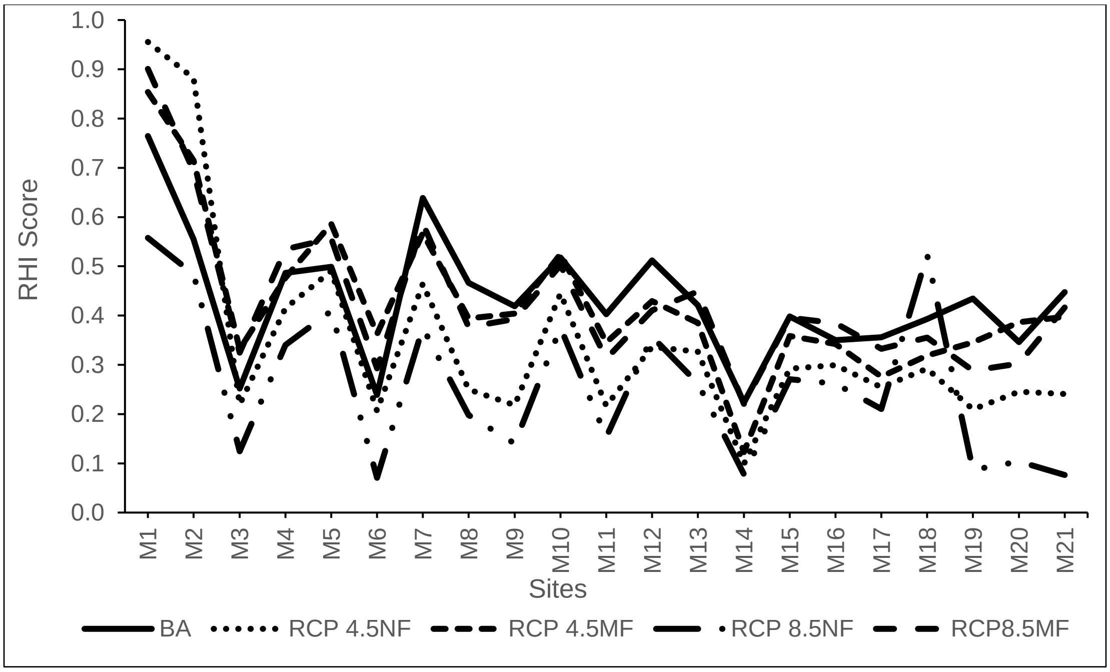

Figure 4.27c: Integrated assessment of river health for post-monsoon 2019

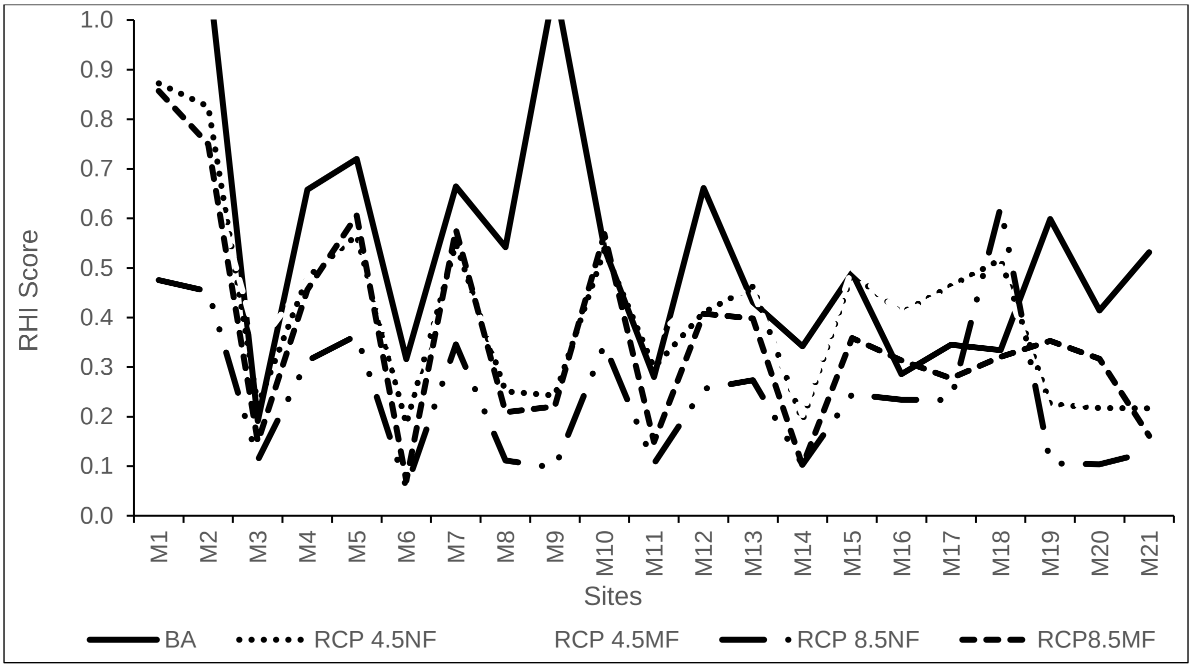

Figure 4.27d: Integrated assessment of river health for pre-monsoon 2021

4.6.1 Biological condition

The biological condition of the Marshyangdi Watershed based on four seasons is explained briefly hereunder in terms of composition, diversity, abundance, taxonomic richness as well as the biotic index (GRSbios) of macroinvertebrates (Table 4.16).

The total number of individuals was observed as 6452 in post-monsoon 2018, representing 8 orders and 25 families (Annex 14). Ephemeroptera family were found to be the highest among all the orders (4112) followed by Trichoptera (860) and Diptera (680) respectively. Similarly, 3021 individuals representing 9 orders and 44 families were documented in the pre-monsoon period of 2019 (Annex 14.1). The Ephemeroptera were found to be highest among all the orders (1596) followed by Trichoptera (770), and Odonata (166) respectively during this season (Annex 14.2). During the post-monsoon season of 2019, a total of 9728 individuals of macroinvertebrates representing 10 orders and 40 families were recorded (Annex 14.3). The highest number of macroinvertebrates was found in the order of Ephemeroptera (7626) followed by Trichoptera (798) and Diptera (686). Similarly, in pre-monsoon 2021 total number of individuals was found to be 2768 representing 28 families and 7 orders (Annex13.4). In this season also, the Ephemeroptera was the highest in number (91275) followed by Trichoptera (813) and Diptera (403), respectively. The dominancy of Ephemeroptera order in all four seasons reveals that the pollution-sensitive macroinvertebrate was dominant in the Marshyangdi Watershed.

In the post-monsoon of 2018, diversity ranged from 0.9 at site M9 to 1.9 at site M13 and M14which are tributaries river (Table 4.15) while abundance was highest at site M13 (1034 individuals) and lowest at site M21 (85 individuals). EPT index exceeded 50% at all sites, with the highest percentage at M6 (Upper Marshyangdi Upstream) Further, water quality class was dominated by class I category (not polluted state based on GRSbios index, however water quality class II at sites M12, M15, M17, and M19 indicated moderately polluted status of water (Table 4.15).

The diversity of the pre-monsoon 2019 season ranges from 0.4 (M5) in Tal Bazar to 1.9 (M1&M21). During this season, total abundance was observed to be high at (M4 , M5), (Table 4.16). Richness in terms of EPT also exceeded 50 percent at all the sites except at M19 (Daraudi River) and site M16 (Chudi River). Further scores of water quality in terms of the GRSbios index indicated that the water quality ranges from class II category at (M15, M18 and M20) to I at 48% of sites (Table 4.15).

However, for the post-monsoon 2019, diversity values ranged from 0.3 (M9, middle Marshyangdi Upstream) to 1.7 (M1and M4) (Table 4.16). Total abundance were found to be higher at M16 (1404 individuals) followed by 1193 individuals at M13. Further, all sites had EPT richness greater than 50%. Water quality class varies from I to I-II based on GRSbios biotic scores, indicating water quality status from not polluted to slightly polluted (Table 4.15). However, the water quality was dominated by class I category (57% of sites).

In pre-monsoon 2021, the diversity ranges from 0.6 at site M4 (Dharapani) to 2.1 at M14 (Khudi River) (Table 4.16). Abundance was the highest at site M20 (635 individuals) and the lowest at site M12(14 individuals). However, richness in terms of EPT percentage also exceeded 50% all the sites like other seasons. Furthermore, while comparing abundance across all seasons, it was shown that the number of macroinvertebrates was decreasing in the post-monsoon season of 2021. Based on GRSbios biotic index, water quality dominated by class I- II category (48% of sites), signifying slightly polluted state of water (Table 4.15).

In a nutshell, pollution-sensitive taxa such as Ephemeroptera, Trichoptera dominated faunal richness and composition of the watershed. An overall higher percentage of EPT taxa (>50% at all the sites) indicate the good biological state of water among the studied seasons. Further presence of macroinvertebrates such as Ephemeroptera, Trichoptera and Plecoptera suggests that water is well aerated in the watershed (Medupi, 2016). For the case of biological water quality based on the GRSbios biotic score, water quality is dominated by class I category in all the seasons except in pre-monsoon 2021meaning the non-polluted state of water (Table 4.15). Similarly, taxa richness in the watershed's tributaries was found to be higher in comparison to mainstream except in the pre-monsoon 2021. A similar case was also recorded in tributaries of the Karnali River located in the Western Himalayas (Shah *et al.*, 2020).

Table 4.15: Biological water class based on the transformation of GRS/ASPT

NEPBIOS/ASPT	**Class**	**Description**
6.5-10	I	Not Polluted
6-6.49	I-II	Slightly Polluted
5-5.99	II	Moderately Polluted
4-4.99	II-III	Critically Polluted
2.5-3.99	III	Heavily Polluted
1.01-2.49	IV	Very Heavily Polluted
1	V	Extremely Polluted

Sharma and Moog (2005)

Table 4.16: Biological water quality among all four seasons

Sites	Diversity				Abundance				EPT Index (%)				Taxa Richness				BWQ			
	PM1	PreM2	PM3	PreM4	PM1	PreM2	PM3	PreM4	PM1	PreM2	PM3	PreM4	PM1	PreM2	PM3	PreM4	PM1	PreM2	PM3	PreM4
M1	1.8	1.9	1.7	1.4	162	149	139	523	91	92	96	88	8	13	9	8	I	I	I	I-II
M2	1.7	1.4	1.4	1.3	157	23	68	80	86	87	100	96	6	6	5	5	I	I	I	II
M3	1.5	1.7	1.3	1.1	331	40	199	140	86	90	88	89	9	8	12	9	I	I	I	I-II
M4	1.8	1.0	1.7	0.6	318	498	242	185	89	98	93	91	9	16	15	4	I	I	I	II
M5	1.7	0.4	1.0	1.6	333	336	382	96	82	99	98	80	6	7	10	7	I	I-II	I	II
M6	1.5	1.1	1.3	1.6	436	138	498	110	96	97	97	50	8	7	13	7	I-II	I	I	I-II
M7	1.5	0.6	1.2	1.5	421	102	1118	92	85	100	99	71	11	5	7	5	I	I-II	I	II
M8	1.3	2.2	1.2	1.5	397	316	481	120	88	62	81	75	8	18	12	6	I-II	I	I	II
M9	0.9	0.5	0.3	1.4	254	64	164	80	98	94	99	76	8	6	6	7	I-II	I-II	I	II
M10	1.7	1.4	1.4	1.4	515	332	431	33	78	96	86	88	8	14	11	5	I	I-II	I	II
M11	1.8	1.7	1.0	1.4	367	55	493	16	83	66	96	69	8	12	13	4	I	I	I	II
M12	1.1	1.7	1.2	1.3	111	24	163	14	72	50	84	50	4	6	7	4	II	I-II	II	I
M13	1.9	0.9	1.6	1.1	1034	266	1193	79	74	83	74	65	11	8	13	6	I-II	I-II	II	II
M14	1.9	1.8	2.0	2.1	561	146	602	147	91	72	67	51	10	12	20	13	I-II	I	I-II	I
M15	1.5	1.7	0.8	1.0	381	31	420	97	86	77	94	52	9	6	11	5	II	II	I-II	I-II
M16	1.6	1.6	1.4	1.6	421	192	1404	88	80	45	92	52	9	11	13	9	I	I-II	I-II	I-II
M17	1.8	1.5	1.4	1.5	157	11	40	16	61	55	20	63	7	5	7	5	II	I	II	I-II
M18	1.8	1.7	1.2	1.3	289	15	269	17	87	67	94	53	9	6	9	4	I	II	I-II	I
M19	1.8	1.9	1.5	1.6	453	211	1045	182	79	29	93	72	13	14	16	7	II	I	I-II	I
M20	1.0	1.4	1.2	1.5	387	11	935	635	94	82	99	88	6	4	8	13	I	II	I-II	I
M21	1.8	1.8	1.2	1.6	85	96	181	30	88	89	95	67	8	11	8	8	I	I-II	I	II

Note: PM1 for2018 Post-monsoon; PreM2 for2019; Pre-monsoon; PM3 for Post-monsoon 2019; PreM 4 for Pre-monsoon 2021; BWQ is biological water quality

4.6.2 Water quality conditions

The study's findings are presented into two categories: descriptive statistics (based on 20 physicochemical characteristics) and the water quality index (WQI). The mean values of various measured physicochemical parameters are presented in Table (4.17-4.20) and the permissible limits for the sustenance of aquatic organisms are presented in (Annex 6). Although the mean and standard deviation of water quality vary from season to season, their concentrations are all within permissible limits, with the exception of ammonia in pre-monsoon 2021 at few sites. Another nutrient indicator, total phosphate, also surpassed its limit in the first three seasons (Table 4.17- 4.19), but only at a few sites in pre-monsoon 2021 (Table 4.20).

4.6.2.1 Characterization of physicochemical parameters

River temperature is a key physical parameter that influences river ecology (Medupi 2016; Webb & Walsh 2004) indirectly influencing the mobilization as well as the toxicity of pollutants. Water temperature affects the availability of oxygen in water bodies, as well as the composition and distribution of macroinvertebrate populations in stream systems, and helps to control the growth, condition, and survival of biota (Kannel *et al.,* 2007a; Morris *et al.,* 1989). Temperature ranges from 2^{o}C at Dhukurpokhari (M2) to 21^{o}C at Chudi River (M16) in the afternoon of post-monsoon 2018 (Table 4.17) which may be affected by different times in sampling, altitudinal and seasonal variation. The temperature variations at various sites are due to water flow, biotic and abiotic factors, and surface radiation (Singh *et al.,* 2017). Observing the temperature pattern among the seasons, the temperature at higher altitudes above site M1- M5) was found to be lower in comparison to lower altitudinal sites, resulting in thus decreasing temperature trend with the increasing altitudinal physio-geographically.

The hydrogen ion concentration (pH) influences the composition of aquatic macroinvertebrates as the biochemical, and the physicochemical properties are greatly dependent on this characteristic (Tadesse *et al.,* 2018). The higher pH values suggest that physicochemical conditions have been affected by carbon dioxide, carbonate-bicarbonate equilibrium as well as the probability of contamination by a strong base such as NaOH and Ca $(OH)_2$ (Tadesse *et al.,* 2014). pH has a strong influence on the concentration of ammonia, hydrogen sulfide, and heavy metals, and it becomes limiting and thus affect aquatic life if their concentration increased above permitted values (Klontz, 1993; Tadesse *et al.,* 2018). However, a low pH value (below 6.5) is also not desirable to many macroinvertebrate groups, for example, an abundance of mayflies (Ephemeroptera) is affected by low pH levels (below 4) (Courtney & Clements, 1998). The observed pH values in the studied sites of all four seasons are within the permissible limit (6.5-9), thus permitting all natural processes of aquatic life system in this Marshyangdi Watershed. The mean pH values were observed as 8.5 pH units among the studied seasons with maximum reaching 9 pH units at three sites in post-monsoon 2018 (Table 4.17) and two sites in pre-monsoon 2019 (Table 4.18) indicating alkaline water in the watershed. Such alkaline water has been reported by other studies conducted at the Marshyangdi River (Ghezzi *et al.*, 2019) as well

Total dissolved solids in freshwater are measured as the sum of the concentration of the dissolved major ions. The total dissolved solids (TDS) are found to be below the prescribed standard (Annex 6), indicating no effect on the aquatic ecosystem in all four seasons. It ranges from 40 mg/L at M13 during post-monsoon 2019 (Table 4.19) to 280 mg/L at M7 during pre-monsoon 2021(Table 4.20). However, if it surpasses the limit, it may interfere with freshwater osmoregulation in organisms, decrease the solubility of gases (such as oxygen), and limit the usability of water for various reasons (drinking, irrigation, and industrial) (Tadesse *et al.*, 2018). When combined with hazardous substances and heavy metals, a high concentration of total dissolved solids diminishes water clarity, reducing photosynthesis, and raising the water temperature, which affects the aesthetic value and physicochemical qualities of water (Tadesse *et al.*, 2018). As a result, the TDS concentration is unlikely to interact with the dissolved solid problem that is causing the water quality to worsen in the Marshyangdi River.

Conductivity (EC) is also one of the important physicochemical parameters which influence the macroinvertebrate community structures in riverine systems (Dorji, 2016). Several studies have shown that the assemblage of the macroinvertebrate community is strongly linked to the electrical conductivity of the aquatic ecosystems (Kefford, 1998; Pond *et al.,* 2008). The electrical conductivity of stream water is affected by the presence of anions with a negative charge or cations with a positive charge (USEPA, 2014). However, its concentration is within the permissible levels in all the seasons among the studied sites of the Marshyangdi Watershed. It ranges from 77µS/cm at M13 during post-monsoon 2019 to 531 µS/cm at M7 indicating no harmful levels of dissolved ions in the watershed (Table 4.19; Annex 6).

Dissolved oxygen (DO) has a significant role in the distribution and composition of freshwater communities (Dorji, 2016). It is an important water quality parameter to maintain due to its significant role in preventing the formation of undesirable amounts of hydrogen sulfide (WHO, 2003). The availability of DO depends on the rate and periods of its consumption by aquatic flora, fauna, and microorganisms, temperature, time of sampling, volume and velocity of flowing water, type and number of living organisms, altitude, climate, amount of nutrients in the water, etc. In general, freshwater should have 5-6 mg/L of DO to maintain healthy aquatic life, as evidenced by the fact that it ranged from 5 mg/L at M11 during post-monsoon 2019 to 9.4 mg/L at M1 during post-monsoon 2018 in the watershed (Table 4.16). DO values more than 5.1 mg/L indicate the optimum range at all sites, showing that the freshwater system is oxidized and unpolluted.

Total hardness (TH) as $CaCO_3$ in water occurs due to the occurrence of alkaline earth materials i.e., Calcium and Magnesium (Brown *et al.,* 1970). Though hardness has no known negative health effects, it can hinder soap from lathering and raise the boiling point of water. High TH can also induce encrustation of water supply distribution lines. In 2018 post-monsoon water was found to be moderately hard at 9 sites whereas at 8 sites it was hard and at the rest of the sites it was soft (Table 4.17). Similarly, hard water was dominated among all the sites during pre-monsoon 2019 (Table 4.18) while in post-monsoon 2019, moderately hard water dominated among the studies sites (Table 4.19). During pre-monsoon 2021 water was found to be hard (150-300 mg/L) at most of the sites except at sites, M8, M11, M13, M14 and M16 (Table 4.20). Overall water was found to be moderately hard in the watershed which ranges from 35 mg/L at M13 in post-monsoon 2019 to 366 mg/L at M1 in pre-monsoon 2019 (Table 4.18). This hardness of water in the watershed may be due to the mixing of (Ca^{2+}) and (Mg^{2+}) ions with bicarbonate, carbonate, sulphate, and other substances.

All living organisms require Calcium (Ca^{2+}) and Magnesium (Mg^{2+}) ions which are abundant in natural streams due to weathering of sedimentary carbonate rock. Calcium concentrations ranged from 12.0 mg/L at M2 during post-monsoon 2018 (Table 4.17) to 73.5 mg/L at M5 during post-monsoon 2019 (Table 4.19). In Marshyangdi Watershed its concentration was found within the permissible limit among the studied sites and seasons. Sodium (Na^{+}) was found in association with chloride ions and is present to some extent in most natural water. Its concentration ranges from 2.4 mg/L at M6 during pre-monsoon 2021 to 33.0 mg/L at M19 during post-monsoon 2019 (Table 4.19). Apart from sewage, fertilizers, and road salt, the most prevalent sources of sodium detected in river water are rocks containing NaCl (Barbatum & Ballance, 1996). Sodium concentration was found to be within the permissible limit among the studied sites and seasons indicating an absence of sewage and industrial effluents (Pasquini *et al.*, 2012). In a river, potassium (K^{+}) is the least common cation. Although potassium is a relatively abundant element, its concentration in natural freshwaters is usually less than 10 mg/L. Its value ranged from 0.5 mg/L at M15 during post-monsoon 2018 (Table 4.17) to 24.0 mg/L at M14 during pre-monsoon 2019. However, at a few sites during pre-monsoon 2019 (Table 4.18) the concentration of potassium was within limits at the sites of studied seasons indicating an absence of industrial discharges (Pasquini *et al.*, 2012).

Magnesium and calcium dominate the cation chemistry in the Marshyangdi Watershed, indicating that alkaline earth metals (Ca^{2+} and Mg^{2+}) predominate over alkalis (Na^{+}, K^{+}). The present result well matches the trend of ions found within the Tethyan series (predominance of Ca^{2+} and Mg^{2+} concentration) reflecting carbonate weathering. Similarly based on the ternary plot, Wolff-Boenish et al. (2009) observed the predominance of Ca and Mg in TSS and GHS drained watersheds, which was supported by Ghezzi et al. (2019) who had observed the dominance of $Mg^{2+}$and $Ca^{2+}$and, to a lesser extent, HCO_3^{-} at superficial water sites of THS and GHS domain except at two sites in THS domain (Mg-Ca-HCO_3-SO_4) respectively contradicting with our results. Looking at the anion composition water is dominated by bicarbonate (HCO_3^{-}) which is a weak acid type indicating the presence of the carbonate rock in the watershed. Evans et al. (2004) and Wolff-Boenish et al. (2009) also observed bicarbonate as an abundant anion thus indicating carbonate weathering in the watershed. Overall, the major ions in this area indicate natural origin. High concentrations of $Ca^{2+}$and Mg^{2+} ions in the water are present due to the weathering of crystalline dolomitic limestones and Ca-Mg silicates (Singh *et al.*, 2009).

Biological oxygen demand (BOD_5) value ranges from 0.7 mg/L at M2 during post-monsoon 2018 (Table 4.17) to 18.0 mg/L at M6 during pre-monsoon 2021 (Table 4.20). It determines the amount of dissolved oxygen utilized by aerobic bacteria in 5 days at $20^{\circ}C$, demonstrating the presence or absence of organic load in a specific area. It measures a load of biodegradable organic material, which was found to be within the acceptable range at all of the examined locations during all seasons, except for two sites M9 and M6 during pre-monsoon 2021, when BOD surpassed its limit (15mg/L).

Similarly, during all seasons, chemical oxygen demand (COD), which is determined chemically by acid digestion, was found to be within the acceptable limit at the sites analyzed. However, its value ranged from 1.1 mg/L at M2 during post-monsoon 2018 (Table 4.17) to 30.0 mg/L at M6 during pre-monsoon 2021 (Table 4.20). For COD also permissible to exceed its limit (>20 mg/L) at two sites, M16 during post-monsoon 2019 and M17 during pre-monsoon 2019. Based on BOD and COD values, there is an absence of oxygen demanding waste in the Marshyangdi River.

Chloride ions (Cl^-) primarily originate from weathering of rocks but other pollutants may also act as their sources. The value of chloride was observed low, compared to the permissible level (500 mg/L) for aquatic biota, in all the seasons ranging from 7.1 mg/L at M13 to 56.8 mg/L at M7during post-monsoon 2021. Chloride concentration was determined less than 40 mg/L in all the seasons among the studied sites indicating an unpolluted state of water. Chloride is found in low concentrations in all types of freshwaters, but higher chloride levels can corrode metal pipelines and buildings, as well as be detrimental to most trees and plants (Bartrum & Ballance, 1996).

Bicarbonate (HCO_3^-) in water may occur indirectly through the process of respiration, and weathering of the parent rocks. A high concentration of bicarbonate reflects high alkalinity and hardness in freshwater. However, in this watershed alkalinity exceeded (>200) at most of the sites except during post-monsoon 2018 (Table 4.16) indicating the alkaline nature of water in the watershed. Its value ranged from 38 mg/L at M13 to 306 mg/L at M16. Higher alkalinity in the Marshyangdi Watershed was also reported by different authors due to the weathering of carbonate rocks (Evans *et al.*, 2001, 2004; Galy & France Lanord, 1999; Ghezzi *et al.*, 2019; Tipper *et al.*, 2006; Wolff-Boenish *et al.*, 2009). Furthermore, Marshyangdi being situated along the TSS and GHS terrain carbonate dissolution dominates the cation budget in the watershed thereby increasing the alkalinity of water **(**Evans *et al.*, 2004**).** In addition, the presence of glacial meltwater at higher altitudes also enhances the solubility of carbonates due to low temperatures at the watershed (Wolff-Benish, 2009). Similarly, Tranter (2003) also reported that carbonate versus silicate weathering is favorable due to glacial activity in the upper Himalayan region. Thus, presence of hydrogen ion concentration, cations, and bicarbonates in the water, it can be concluded that the Marshyangdi River is alkaline.

Sulphate is one of the least harmful anions which is released from weathering of sedimentary rocks and pollutants such as fertilizers, wastes, and mining. Sulfate concentrations were found to be within the permissible limit among the sites studied during all seasons which ranges from 0.31mg/L at M15 during 2018 post-monsoon (Table 4.17) to 8.1mg/L at M2 (Table 4.20). Based on sulfate concentration, it can be concluded that the absence of anthropogenic influence (Pasquini *et al.,* 2012) in this watershed.

Nutrients are essential substances to living organisms as they are required for the growth and maintenance of their body (EPA, 2010). The concentration of nutrients in aquatic ecosystems are also important in determining anthropogenic disturbances, and the trophic status of rivers (Allan & Castillo, 2007; Flotemersch *et al.,* 2006; Hamid *et al.,* 2020). In this study, nutrients such as ammonia (NH_3-N) and nitrate (NO_3^-) were within the prescribed limit (Annex 6) except at a few sites during pre-monsoon 2021 ammonia exceeded its prescribed limit (>1.2 mg/L) at M19 M13, M8, and M4 respectively. Its value ranges from 0.01 mg/L during the first three seasons but at various sites to 11 mg/L at M16 during post-monsoon 2021(Table 4.20). Remarkedly, the concentration of ammonia exceeded its limit at site M16 (Chudi River) during other seasons as well which might be due to the contribution from the hotels, and settlement areas near the river. Generally, a high concentration of ammonia at some sites during pre-monsoon 2021 is possibly due to point sources of pollution, particularly sewage discharges (Kannel *et al.*, 2007b; Pasquini *et al.*, 2012). As those sites were near to the settlement and agricultural areas high amount of ammonia might have been released largely by the microbial-mediated breakdown of organic material. Ammonia may exist in the unoxidized form under alkaline conditions and once it mixes with freshwater it can deplete oxygen due to the formation of reduced nitrogen (Sharma & Ahlert 1997).

In alkaline waters, ammonia may exist in a toxic ionic form causing stress to the fish population (Kannel *et al.*, 2007b).

Phosphorus is one of the most important nutrients for plant and animal growth. Because it is available in small amounts in nature, even minor increases in its quantity can have a severe impact on water quality and biological conditions (USEPA,1986). Phosphorus, like nitrogen, is an essential nutrient for all living organisms. The most common form of phosphorus used by biological organisms is phosphate (PO_4^{3-}) which is essential for the formation of DNA, cellular energy, and cell membranes (USEPA, 1986). In the present study, nutrients like phosphate (PO_4^{3-}) were all within the prescribed limit (Annex 6) except at a few sites during pre-monsoon 2021 phosphates concentration exceeded (M8, M10, M12, M13 M15, & M21) (Table 4.20). The sites M21, M15, M13, and M8 are near the settlement area, also hotels were nearby as well as washing activities have been observed during the field visit whereas at sites like M10 agricultural activities were dominant. However, its concentration ranged from 0.01mg/L to 1mg/L at M13 during post-monsoon 2019 (Table 4.20). This site is the tributary of the Marshyangdi River and it is near commercial area like hotels.

Total Phosphorus (TP) includes all three forms of phosphorus i.e., orthophosphate, polyphosphate, and organic phosphate. As phosphorus changes from TP are measured instead of any single form to determine the number of nutrients that can feed the growth of aquatic plants such as algae. Its concentration should not exceed the prescribed limit to inhibit the growth of biological nuisances and to prevent rapid or cultural eutrophication. Total Phosphate (TP) in all the seasons among the studied sites exceeded its limit (>0.05) except at a few sites (M18-M21, M9, M13, M14) during pre-monsoon 2021 (Table 4.20). The highest amount of TP was reported at M8, (1 mg/L; Khudi River) in post-monsoon 2019 and at M9 in post monsoon 2018 (Table 4.18) while the lowest was 0.01 mg/L in pre-monsoon 2021 at most of the sites. Khudi River is one of the tributary rivers of Marshyangdi and is situated near the commercial area (hotels, houses) which might cause the highest increment in the TP.

Table 4.17: Physico-chemical parameters at Marshyangdi Watershed (post-monsoon 2018)

Site Code	Temp	pH	EC	TDS	DO	TH	Ca hardness	Mg hardness	COD	BOD	TA	Cl^-	NO_3^-	PO_4^{3-}	TP	$S0_4^{2-}$	NH_3-N	K^+	Na^+	Ca^{2+}
M1	4	9.0	404	203	9.4	182	24	2	2.6	1.6	90	5.0	0.44	0.01	0.12	7.6	0.08	1.1	6.7	61.2
M2	2	9.0	473	237	9.0	227	6	6	1.1	0.7	100	2.8	0.59	0.01	0.05	0.8	0.07	2.6	5.2	12.0
M3	8	8.8	366	185	7.5	168	9	5	9.7	5.8	83	7.0	1.11	0.01	0.3	0.8	0.11	1.7	4.6	22.5
M4	9	8.9	344	175	8.0	189	10	8	3.6	2.2	88	9.0	0.55	0.05	0.06	7.9	0.03	1.5	7.8	19.0
M5	9	8.9	363	182	7.9	147	8	6	8.9	5.3	75	11.4	0.52	0.01	0.08	0.9	0.3	1.9	5.6	17.0
M6	12	8.3	363	182	7.5	150	7	7	16.3	9.8	85	17.8	0.89	0.01	0.04	4.2	0.03	1.8	4.5	13.0
M7	11	8.4	374	60	7.9	161	6	6	2.8	1.7	75	17.4	0.89	0.01	0.08	7.2	0.11	2.2	6.5	51.0
M8	10	8.4	325	167	8.0	125	6	6	11.1	6.7	63	12.0	0.74	0.01	0.08	6.0	0.03	1.5	9.5	17.0
M9	15	8.4	124	62	8.5	69.3	7	7	10.8	6.5	40	2.6	0.59	0.01	1	4.5	0.03	1.9	6.7	52.7
M10	20	8.1	285	123	7.9	144	4	4	14.9	8.9	100	4.3	0.37	0.01	0.2	1.0	0.07	1.5	4.0	19.0
M11	13	8.5	163	81	6.1	77	3	3	12.8	7.7	55	9.2	0.59	0.01	0.05	0.8	0.09	2.5	7.0	18.0
M12	12	8.6	300	149	7.5	166	10	10	6.8	4.1	63	21.3	1.55	0.01	0.07	6.0	0.03	0.9	4.0	33.0
M13	19	8.5	84	42	5.6	48	6	6	1.9	1.1	38	4.3	0.03	0.04	0.7	4.4	0.03	1.5	4.0	22.0
M14	19	8.0	97	49	8.5	44.6	5	5	14.3	8.6	48	12.8	0.03	0.01	0.4	1.8	0.03	3.5	8.0	62.5
M15	14	8.2	278	139	7.2	158	8	8	12.0	7.2	75	16.5	0.66	0.01	0.05	0.3	0.06	0.5	4.0	15.0
M16	21	9.0	147	73	8.3	71	8	8	15.0	9.0	60	8.5	0.74	0.01	0.07	2.5	0.06	3.5	10.5	33.4
M17	13	8.7	139	139	7.9	155	4	4	6.6	4.0	70	12.8	0.44	0.02	0.22	7.6	0.02	5.0	7.5	30.5
M18	20	8.5	250	128	6.0	130	8	6	5.0	3.0	99	15.0	0.59	0.01	0.09	3.4	0.03	7.0	9.5	54.0
M19	19	8.5	242	129	8.0	126	10	8	15.7	9.4	93	9.2	0.15	0.01	0.1	2.9	0.03	3.0	5.6	31.1
M20	17	8.3	128	70	7.0	99	14	4	14.0	8.4	95	4.3	0.59	0.04	0.09	3.7	0.03	4.5	8.9	22.0
M21	15	8.2	273	137	7.5	119	9	9	3.0	1.8	80	11.4	0.74	0.04	0.05	2.6	0.03	2.7	3.6	19.0

Note: Unit is in mg/L except pH is in pH units, EC in µS/cm and Temp in (^{C}); E C is Electrical Conductivity; TA is Total Alkalinity; DO is Dissolved Oxygen; TDS is Total Dissolved Solids; NO_3^- is Nitrate, PO_4^{3-} is Phosphate; NH_3-N is ammonia, BOD is Biological Oxygen Demand; COD is Chemical Oxygen Demand, TH is Total Hardness; TP is Total Phosphate; Ca^{2+} & M^{2+} is Calcium and Magnesium hardness

Table 4.18: Physico-chemical parameters of water at Marshyangdi Watershed (pre-monsoon 2019)

Site Code	Temp	pH	EC	TDS	DO	TH	Ca hardness	Mg hardness	COD	BOD	TA	Cl^-	NO_3^-	PO_4^{3-}	TP	SO_4^{2-}	NH_3- N	K+	Na+	Ca^{2}+
M1	5	8.7	358	168	6.5	366	184	9	5.4	3.2	125	13.0	0.04	0.39	4	0.0	0.9	1.0	19.7	61.2
M2	12	8.9	249	128	5.9	347	174	5	5.1	3.1	205	13.0	0.04	0.18	3.9	0.0	4.1	1.8	19.8	12.0
M3	11	8.9	300	105	6.7	309	156	5	3.1	1.9	139	11.0	0.04	0.32	3.8	0.0	7.0	2.1	21.2	22.5
M4	22	8.9	312	153	5.6	273	138	3	8.3	5.0	120	12.0	0.04	0.06	3.8	0.0	0.8	18.0	35.0	19.0
M5	15	8.9	329	165	5.1	261	132	9	10.0	6.0	123	18.0	0.04	0.09	3.9	0.0	2.3	4.2	22.5	17.0
M6	16	8.8	360	176	5.9	268	135	5	2.6	1.6	138	23.0	0.02	0.11	4	0.0	1.5	27.6	22.7	13.0
M7	17	8.4	352	175	6.7	264	133	3	5.7	3.4	116	25.0	0.05	0.23	4.7	0.0	5.1	22.1	23.1	51.0
M8	19	8.5	100	50	6.5	72	37	13	7.7	4.6	58	10.0	0.1	0.07	3.8	0.0	15.0	3.8	21.7	17.0
M9	22	8.8	249	123	6.8	254	128	8	2.0	1.2	113	36.0	0.02	0.32	4.2	0.0	8.8	12.0	51.0	52.7
M10	30	8.5	295	149	7.3	241	122	12	7.4	4.4	123	19.0	0.01	0.16	4.5	0.1	3.3	3.2	20.7	19.0
M11	19	8.3	148	40	7.1	102	52	8	3.1	1.9	80	11.0	0.01	0.10	4	0.0	2.4	1.3	19.6	18.0
M12	24	8.5	280	145	7.2	249	126	18	5.1	3.1	159	20.0	0.01	0.06	4.3	0.0	1.1	3.2	21.0	33.0
M13	30	9.0	123	61	5.7	69	36	12	6.0	3.6	53	12.0	0.02	0.06	3.7	0.1	19.5	2.9	25.1	22.0
M14	27	8.5	106	52	6.4	60	31	11	2.0	1.2	45	7.0	0.01	0.37	4.5	0.1	24.0	28.0	56.0	62.5
M15	21	8.7	298	97	7.4	206	104	12	4.0	2.4	78	16.0	0.01	0.55	4	0.1	14.5	17.4	21.1	15.0
M16	29	9.0	187	94	5.2	70	36	12	2.3	1.4	78	9.0	0.01	0.15	3.7	0.1	21.6	10.6	15.8	33.4
M17	23	8.8	308	153	6.9	110	56	18	23.1	13.9	86	19.0	0.01	0.09	4.1	0.2	1.0	12.7	33.4	30.5
M18	26	8.9	317	159	6.6	124	63	14	6.3	3.8	100	20.0	0.01	0.23	4.3	0.1	1.5	19.6	30.5	54.0
M19	26	8.9	226	114	6.4	84	43	15	6.9	4.1	104	12.0	0.02	0.39	3.9	0.0	1.1	17.4	31.1	31.1
M20	26	8.7	252	122	7.1	97	50	7	3.4	2.0	120	25.0	0.06	0.09	3.8	0.1	3.0	1.3	26.6	22.0
M21	25	8.8	287	144	6.1	102	52	7	13.4	8.0	103	33.0	0.03	0.33	3.4	0.0	8.0	12.1	21.5	19.0

Table 4.19: Physico-chemical parameters of water at Marshyangdi Watershed (post-monsoon 2019)

Site Code	Temp	pH	EC	TDS	DO	TH	Ca hardness	Mg hardness	COD	BOD	TA	Cl^-	NO_3^-	PO_4^{3-}	TP	$S0_4^{2-}$	$NH_{3-}N$	K^+	Na^+	Ca^2+
M1	3	8.9	395	201	6.9	262	43	14	5.7	3.4	111	14.2	0.66	0.04	0.12	3.7	0.09	0.9	22.2	72.2
M2	8	8.7	469	247	6.7	293	40	22	14.9	8.9	211	8.5	0.79	0.01	0.05	4.6	0.12	4.1	16.6	73.2
M3	8	8.9	388	201	6.5	150	41	26	10.3	6.2	210	14.2	0.71	0.02	0.62	4.3	0.07	7.0	17.5	73.4
M4	10	8.7	332	174	6.2	200	45	12	5.1	3.1	178	11.2	0.95	0.04	0.06	4.0	0.03	0.8	17.6	73.0
M5	8	8.7	332	173	5.3	190	41	16	11.4	6.8	221	29.1	0.94	0.01	0.08	4.0	0.04	2.3	17.1	72.7
M6	16	8.4	328	172	5.5	149	37	17	10.6	6.4	221	25.6	1.1	0.01	0.04	4.0	0.03	1.5	20.2	73.0
M7	15	8.5	300	156	5.4	149	33	28	18.3	11.0	188	26.3	0.9	0.01	0.1	4.0	0.05	5.1	19.9	73.5
M8	16	8.4	160	119	5.6	64	12	13	4.0	2.4	116	13.5	1.05	0.09	1.38	3.8	0.03	6.5	19.4	43.9
M9	16	8.5	291	152	5.5	128	32	23	13.1	7.9	200	30.5	1.04	0.02	1.05	3.8	0.08	8.8	18.9	73.4
M10	16	8.6	265	138	5.3	128	37	22	12.0	7.2	180	17.0	0.74	0.08	0.05	3.8	0.03	3.3	19.9	72.4
M11	16	8.4	153	75	5.1	85	18	16	15.7	9.4	126	25.6	0.7	0.02	0.43	3.8	0.1	2.4	18.5	57.0
M12	16	8.3	256	132	6.5	123	41	20	18.6	11.2	189	18.5	0.92	0.04	0.1	3.7	0.06	1.1	18.5	71.5
M13	25	8.6	77	40	5.3	35	6	7	2.9	1.7	190	17.8	0.37	0.13	0.62	3.9	0.07	8.5	16.6	26.9
M14	21	8.4	82	48	6.5	40	8	8	15.7	9.4	180	12.1	0.59	0.03	0.12	3.8	0.07	9.5	18.0	32.8
M15	18	8.6	241	140	6.3	106	27	19	9.4	5.6	210	24.9	0.85	0.07	0.05	3.8	0.08	5.5	17.5	72.7
M16	25	8.3	149	75	5.9	67	15	12	22.9	13.7	175	14.2	0.7	0.04	0.12	3.9	0.27	8.6	14.3	41.3
M17	20	8.2	240	129	6.8	109	27	20	26.6	16.0	240	28.4	0.89	0.04	0.38	3.7	0.06	1.0	18.5	70.4
M18	19	8.3	258	134	6.7	100	29	17	8.6	5.2	120	28.4	0.96	0.06	0.18	3.7	0.03	1.5	22.1	70.4
M19	11	8.1	219	115	6.2	105	24	9	18.3	11.0	122	15.6	0.78	0.11	0.2	3.9	0.05	1.1	33.0	67.9
M20	21	8.2	236	121	6.8	105	28	14	16.0	9.6	198	14.2	0.88	0.11	0.11	3.8	0.06	3.0	22.7	68.4
M21	21	8.4	252	132	6.4	102	28	18	4.0	2.4	201	32.0	0.55	0.08	0.11	3.7	0.17	8.0	24.9	70.3

Table 4.20: Physico-chemical parameters of water at Marshyangdi Watershed (pre-monsoon 2021)

Site Code	Temp	pH	EC	TDS	DO	TH	Ca hardness	Mg hardness	COD	BOD	TA	Cl^-	NO_3^-	PO_4^{3-}	TP	$S0_4^{2-}$	$NH_{3-}N$	K^+	Na^+	Ca^{2+}
M1	11	8.9	353	183	6.7	225	32	19	4.0	2.4	268	21.3	0.66	0.06	0.01	3.8	0.53	2.6	3.5	42.1
M2	9	8.5	441	226	7.0	279	49	14	17.2	10.3	297	10.7	0.79	0.1	0.01	8.1	0.18	2.7	4.1	45.5
M3	10	8.7	393	202	6.2	250	40	15	1.6	1.0	288	8.5	0.71	0.04	0.01	6.5	0.73	3.4	6.0	45.6
M4	19	8.6	366	186	6.0	231	40	13	15.2	9.1	276	14.2	0.95	0.04	0.01	4.1	1.62	2.8	6.3	44.8
M5	11	8.8	382	199	6.1	244	40	22	7.6	4.6	290	17.0	0.94	0.06	0.01	5.8	0.28	3.3	8.4	46.1
M6	18	8.6	405	206	5.7	256	36	15	30.0	18.0	306	42.6	1.1	0.04	0.01	3.4	0.19	1.4	2.4	20.0
M7	20	8.6	531	280	6.8	343	48	15	8.0	4.8	230	56.8	0.9	0.1	0.01	2.2	0.16	9.0	30.4	53.8
M8	21	8.7	148	77	7.1	95	16	16	6.0	3.6	113	11.4	1.05	0.53	0.01	5.5	1.7	4.7	3.6	28.5
M9	28	8.6	369	190	5.8	235	37	16	28.4	17.0	280	28.4	1.04	0.14	0.31	4.4	0.44	5.4	16.6	45.0
M10	24	8.5	294	152	5.3	188	34	11	4.0	2.4	223	17.0	0.74	0.16	0.01	6.9	0.31	4.5	9.9	40.3
M11	22	8.2	195	99	6.0	123	22	13	5.2	3.1	147	8.5	0.7	0.04	0.01	6.0	0.24	4.2	3.3	33.8
M12	19	8.0	336	176	6.1	216	32	24	3.0	1.8	256	28.4	0.92	0.61	0.01	3.7	1.2	5.3	14.4	43.9
M13	28	8.7	120	62	5.6	77	8	12	10.4	6.2	91	7.1	0.37	1	0.39	3.9	1.5	2.9	6.1	16.6
M14	27	8.4	123	63	5.9	78	10	14	5.0	3.0	93	9.9	0.59	0.06	0.74	3.8	1.7	2.6	2.6	22.8
M15	23	8.4	249	140	5.7	167	29	8	4.0	2.4	195	14.2	0.85	0.22	0.01	3.8	6.27	4.8	9.0	36.7
M16	29	8.2	145	75	5.4	92	25	18	6.8	4.1	110	10.7	0.7	0.1	0.03	4.0	10.5	2.6	5.4	13.1
M17	21	8.4	263	138	5.7	169	26	18	2.4	1.4	201	29.8	0.89	0.04	0.01	3.6	7.69	5.1	8.9	38.8
M18	22	8.2	352	179	6.5	222	33	13	19.2	11.5	265	21.3	0.96	0.08	0.07	5.0	8.9	5.4	8.8	41.0
M19	23	7.9	316	163	5.5	201	142	9	18.8	11.3	239	14.2	0.78	0.1	0.1	2.0	1.78	7.4	7.3	38.0
M20	24	7.9	304	156	5.7	193	28	11	12.8	7.7	230	15.6	0.88	0.1	0.06	5.0	0.77	7.2	7.6	38.6
M21	24	7.9	447	198	6.0	260	52	16	8.0	4.8	222	32.0	0.55	0.35	0.15	5.0	0.68	3.5	7.9	38.7

4.6.2.2 Assessment of water quality based on water quality index

The Water Quality Index (WQI) of the Marshyangdi River was calculated as per the equation 18 mentioned in the methodology section 3.6.2 and presented in Table 4.21. The water quality objectives utilized in the computation of WQI are listed in Annex 6, which shows that the majority of the parameters were within acceptable limits of the water quality standard for the sustenance of aquatic living organisms. Water quality based on WQI averaged for all the seasons as well as for the observed data for the respective four seasons indicated an excellent condition of water quality class in the watershed with the exception at the sites M17, M18, and M16 (very poor) in pre-monsoon 2021. While water quality has been observed as poor at sites M8, M12, M13, M15, 9 and (Table 4.21) in the same season. Such poor water quality class may be due to the exceedance limit of nutrient parameters like ammonia (>1.2 mg/L) at those sites. In this season at 57% of sites, the limit of ammonia and phosphate for aquatic life exceeded its permissible limit. Previous WQI-based investigations in Nepal's Jhimruk Watershed have shown good to excellent water quality during the pre- and post-monsoon seasons (Thapa *et al.,* 2020). Furthermore, good water quality was also observed based on WQI in streams of Bhalu Khola, a tributary of the Budhigandaki River (Rana and Chettri, 2015). Similarly, Gurung et al. (2019) reported that the quality of water originating from spring sources in the rural watershed of western Nepal ranged from bad to good, indicating that the water can be used for household purposes with proper treatment.

Table 4.21: Seasonal variation in water quality index during baseline

Sites	Post M1	Remarks	Pre M2	Remarks	Post M3	Remarks	Pre M4	Remarks	Avg	Remarks
M1	47	Excellent	43	Excellent	44	Excellent	51	Good	45	Excellent
M2	47	Excellent	40	Excellent	42	Excellent	50	Excellent	45	Excellent
M3	42	Excellent	42	Excellent	41	Excellent	52	Good	43	Excellent
M4	46	Excellent	40	Excellent	40	Excellent	71	Good	45	Excellent
M5	45	Excellent	39	Excellent	35	Excellent	44	Excellent	41	Excellent
M6	40	Excellent	39	Excellent	35	Excellent	39	Excellent	39	Excellent
M7	41	Excellent	45	Excellent	35	Excellent	51	Good	43	Excellent
M8	41	Excellent	46	Excellent	40	Excellent	141	Poor	57	Good
M9	38	Excellent	40	Excellent	36	Excellent	58	Good	42	Excellent
M10	39	Excellent	40	Excellent	40	Excellent	56	Good	43	Excellent
M11	33	Excellent	34	Excellent	32	Excellent	37	Excellent	35	Excellent
M12	39	Excellent	38	Excellent	39	Excellent	141	Poor	57	Good
M13	33	Excellent	33	Excellent	42	Excellent	199	Poor	63	Good
M14	37	Excellent	33	Excellent	35	Excellent	72	Good	40	Excellent
M15	38	Excellent	39	Excellent	42	Excellent	200	Poor	60	Good
M16	39	Excellent	33	Excellent	38	Excellent	277	Very poor	65	Good
M17	39	Excellent	40	Excellent	40	Excellent	207	Very poor	60	Good
M18	34	Excellent	39	Excellent	42	Excellent	243	Very poor	64	Good
M19	39	Excellent	37	Excellent	44	Excellent	81	Good	45	Excellent
M20	37	Excellent	47	Excellent	46	Excellent	58	Good	45	Excellent
M21	41	Excellent	40	Excellent	44	Excellent	93	Good	51	Good

Note: PM1: Pre-monsoon 2018; PreM2: Pre-monsoon 2019; P ostM3: Post-monsoon 2019; PreM4:Pre-monsoon;Avg:average

4.6.3 Physical habitat condition

Physical habitat condition was evaluated using the Rapid Bioassessment procedure (Barbour *et al.,* 1999) to determine the current status of physical habitat in the watershed. A qualitative health evaluation index (QHEI) was specifically developed to measure the physical factors influencing the life of aquatic organisms including fishes (Gazendam *et al.,* 2011). This habitat assessment approach which is based on the weighted method emphasizes the most biologically significant parameters and plays an important role in supporting bio survey (USEPA,1993). Habitat assessment score ranges from 0.4 to 0.8 (Mean- 0.7; SD-0.1) representing two categories of habitat good and fair among all the studied three seasons whereas in post-monsoon 2018 it falls under three categories namely excellent, fair as well as good. Out of the 21 surveyed sites, more than 95% of the sites scored above 100 during all the seasons indicating suitable habitat conditions in the Marshyangdi River. For the post-monsoon 2018, 52% of sites were in good condition whereas during post-monsoon 2019 only 48% of sites were in good condition while for the pre-monsoon 2019 and 2021, 57% of sites were in good condition with an HA score higher than 0.65 (Table 4.22).

Table 4.22: Habitat assessment based on Rapid Bioassessment Protocol among four seasons

Sites	Score	Remarks	Score	Remarks	Score	Remarks	Score	Remarks
M1	0.84	Excellent	0.65	Fair	0.65	Good	0.7	Good
M2	0.82	Excellent	0.7	Good	0.75	Good	0.79	Good
M3	0.77	Good	0.67	Good	0.64	Fair	0.84	Good
M4	0.61	Fair	0.65	Fair	0.62	Fair	0.75	Good
M5	0.8	Excellent	0.47	Fair	0.49	Fair	0.48	Fair
M6	0.6	Fair	0.65	Good	0.66	Good	0.68	Good
M7	0.74	Good	0.66	Good	0.59	Fair	0.51	Fair
M8	0.8	Excellent	0.7	Good	0.68	Good	0.66	Good
M9	0.64	Fair	0.65	Fair	0.61	Fair	0.65	Fair
M10	0.81	Excellent	0.58	Fair	0.57	Fair	0.55	Fair
M11	0.77	Good	0.77	Good	0.72	Good	0.64	Fair
M12	0.77	Good	0.68	Good	0.68	Good	0.75	Good
M13	0.8	Good	0.76	Good	0.72	Good	0.68	Good
M14	0.83	Excellent	0.81	Good	0.79	Good	0.71	Good
M15	0.74	Good	0.57	Fair	0.54	Fair	0.63	Fair
M16	0.69	Good	0.64	Fair	0.58	Fair	0.52	Fair
M17	0.78	Good	0.71	Good	0.65	Fair	0.7	Good
M18	0.78	Good	0.53	Fair	0.4	Fair	0.35	Fair
M19	0.7	Good	0.77	Good	0.67	Good	0.66	Good
M20	0.59	Fair	0.56	Fair	0.56	Fair	0.58	Fair
M21	0.84	Good	0.77	Good	0.67	Good	0.75	Good

4.6.3.1 River velocity

The hydraulic characteristics like depth, velocity, wetted stream width, and substrates of the Marshyangdi Watershed were studied as per the methodology mentioned in the section 3.6.2.4 and presented in (Table 4.23; Annex 15 - Annex 15.2). The average values of streamflow between sites varied from 0.1m/s at M21 & M15 to 1.4 m/s at M4 in post-monsoon 2018 with an average velocity of 0.7 m/s among the sites (Annex 15). For pre-monsoon 2019 velocity ranged from 0.2 m/s at M18 to 0.9 m/s at M12 with average velocity of 0.5 m/s (Table 4.23). For the post-monsoon 2019 velocity among the sites also varied from 0.2 m/s (M18, M15, M10) to 0.9 m/s (M1) but at different sites with the mean velocity of 0.6 m/s (Annex 14.1). Similarly, for pre-monsoon 2021 velocity ranged between 0.2 m/s at M18 to 1.2 m/s at M4 with an average velocity of 0.7 m/s. Water flow was observed at all the sampling sites during the field visit with lesser flow downstream of the hydropower dam (M18, M120 & M7) because of human activity. Streamflow is a major component that affects the biodiversity of macroinvertebrates. Korte (2010), for example, found that fifty taxa from various taxonomic groups had distinct preferences for current velocities and substrate types in his study. He further mentioned that moderate or distinct velocities of 11- 50 cm/s were found to be the most favorable for aquatic macroinvertebrates, which were also observed at the Marshyangdi Watershed.

4.6.3.2 River depth and width

The breadth and width of a river are also major factors for macroinvertebrate diversity. (Baumgärtner *et al.,* 2008; Kłonowska-Olejnik & Skalski, 2014 ;). Water depth is an important aspect to consider since habitat stability, substrate particle size, and macroinvertebrate habitat availability all change with water depth (Baumgärtner *et al.,* 2008). The average river depth varied from 14 m during pre-monsoon 2019 to 63 m at M9 during pre-monsoon 2021(Annex 14.2). Minimum depth was observed at Chudi River (M6) which is a tributary river located in the commercial area. Maximum depth was observed at the upper Marshyangdi upstream region (M13). Baumgärtner et al. (2008) observed significantly different community patterns between the depth zones, due to different dominance structures and partly because of species turnover in Upper Lake Constance of Central Europe.

Table 4.23: Hydraulic conditions of pre-monsoon 2019

Sites	Depth avg	Velo. avg	Megalithal%	Substrates in %			wetted width(m)
				Macrolithal %	Mesolithal %	Microlithal %	
M1	24.0	0.8	80	20	-		3
M2	36.3	0.7	30	70	-		16
M3	30	0.5	75	25	-		6
M4	36.0	0.4	60	20	20		22
M5	38.0	0.5	10	40	50		19
M6	39.1	0.5	95	5			42
M7	30.2	0.8	35	20	15	30	9
M8	31.3	0.6	50	20	30		14
M9	40.4	0.3	80	20	-		42
M10	24.7	0.2	30	70	-		9
M11	44.0	0.5	75	20	5		14
M12	60.1	0.9	80	20	-		50
M13	34.4	0.4	20	10	70		7
M14	54.5	0.8	10	70	20		13
M15	59.1	0.5	90	10	-		29
M16	14.1	0.3	10	20	70		13
M17	36.9	0.4	70	10	20		9
M18	40.5	0.2	70	10	20		12
M19	20.1	0.4	40	10	50		25
M20	61.3	0.4	50	30	20		26
M21	50.3	0.3	-	60	40		25

Note: Velo avg: average velocity in m/s; Depth in meter (m)

4.6.4 Current hydrological condition

Flow health generates a preliminary regime that can be used as an interim measure to ensure environmental protection. The metrics of hydrological flow health evaluate the frequency and magnitude of high flows and low flows and compare them against flows that occur under undisturbed conditions thereby assisting in the management of flow regimes in the form of flow health score (FHI). A flow health score close to 0 indicates that the flow considerably deviates from the virgin condition while close to 1 indicates that the flow is similar to the virgin condition. The status of flow health at the watershed and sampling sites obtained from the flow health tool is explained hereunder.

4.6.7 Current condition of flow health

Flow health was analyzed based on nine metrics for the reference period (1987-1999) and test period (anthropogenic influence) from 2000-to 2010 at the Bimalnagar Station. The observed data from DHM of 1987-2015 as well as for simulated data at the same station from 2000 to 2010 were used to study flow health. The flow health scores observed no differences and the deviation was very small for both observed and simulated discharge (Fig. 4.28; Annex 16).

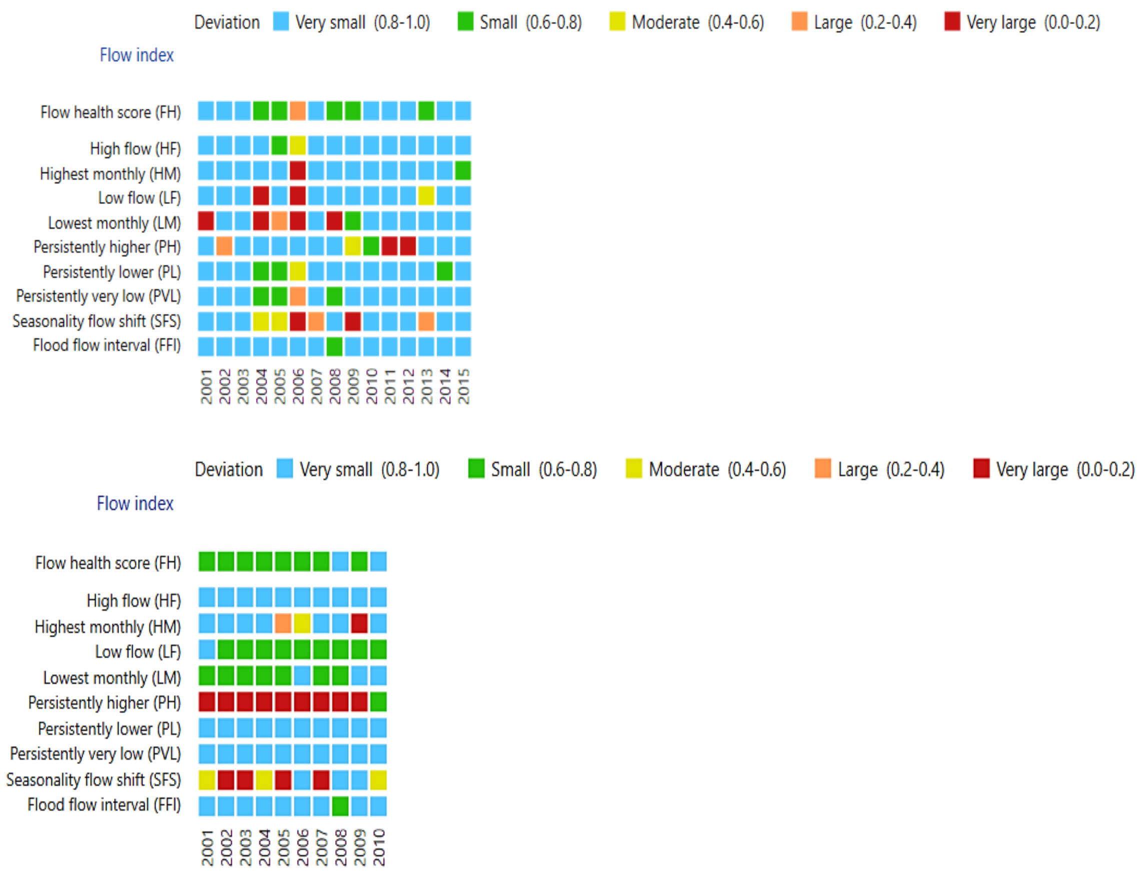

Figure 4.28: Hydrological flow health at Bimalnagar Hydrological Station for observed and simulated discharge respectively

4.6.8 Current condition of flow health at sampling sites

The average annual Flow Health Index score (FHI) ranged from 0.06 to 0.71 among the sampling sites indicating high deviation at the sites located in the upstream region (M12-M21) of the watershed as well as at the tributaries (M3, M6, M8, M9, M14). Such high deviation at the sampling sites in the upstream region of the watershed might have caused the poor river health condition of the watershed (Annex-13).

4.7 Assessment of Future River Health

Climate change along with the various anthropogenic activities has serious implications on river health. River health is affected by changes in various components like biological, physical, and hydrological factors. The river health index is the overall effect of its components with the weight value that drives the overall functional ecosystem. This section explains the status of future river health for RCP4.5 and RCP8.5 based on an integrated approach (Annex 13; Fig 4.29).

Among the various components of river health, the hydrological component plays an important role in the assessment of river health under future scenarios (NF & MF), followed by water quality as revealed by entropy weight (Annex 11). Integrated score based on the average of four seasons (Fig. 4.29; Annex 13) across the sampling sites showed the moderate river health conditions in the future under both scenarios but with varying percentages, except for NF8.5 which falls under the very poor category (43% of sites) with a mean value of 0.31± 0.15. For NF8.5, the river health conditions were found to be very poor which is unlikely because of the asymmetric (skewed) data distribution, while the rest of the baseline and other future scenarios (NF 4.5, MF 4.5, and MF 8.5) RHI scores were normally distributed in the histogram. In the future scenarios, it was observed that the last two sites (M20 & M21) fall under good and excellent categories respectively in comparison to moderate conditions with baseline. The observed better river health status at those sites from current o the future may be due to more water availability (basin outlet) and lesser human interferences. The river health status from sites M1-M3 was found to be deteriorated in the future compared to the baseline from moderate to poor and very poor; Annex 13), which could be attributable to changes in the upstream area of the watershed's flow health conditions (Annex 15.1 & Annex 15.2). Further sites from M6 to M9 indicated an improvement from baseline to future for both RCPs scenarios except for RCP8.5NF and at site M8 (Khudi River). Tributaries river showed deterioration in river health status from baseline to near and mid future with exception of M14 and M19 which falls under moderate category during MF8.5.

Further, statistical analysis (t-test) was performed between baseline and future scenario in river health index assuming equal and unequal variances among two sample with for the normally distributed data (Annex 13.5)

Statistical analysis performed between the river health index score (RHI) between the baseline and RCP4.5NF scenarios at 95% confidence interval assuming unequal variances reveals no significant difference between these two periods (p=0.4). Thus, it can be concluded that the moderate condition of river health in baseline period continues to be in same condition in the NF for RCP4.5.

Assuming equal variances between the RHI score for baseline and RCP 4.5MF, two sample t-test assuming equal variance, the null hypothesis can be retained at the 95% confidence level meaning that any difference between the baseline and RCP4.5MF is due to chance. Thus, it can be concluded that there is insignificant difference in RHI score between these two periods.

Similarly, the t-test between baseline and RCP8.5MF, assuming equal variances the null hypothesis can be retained, i.e., at the 95% confidence level any difference between the baseline and RCP8.5MF is due to chance. So, it can be concluded that there is no significant difference between RHI score for baseline and future period.

Hence statistically (95% confidence interval) moderate river health condition in the baseline period will remain in the same condition in future period for both RCPs.

This study assumed that emissions of pollutants and anthropogenic activities will remain constant in the future, thereby not deteriorating river quality which could contribute to some uncertainty in the results. As a result, more research into river health in the context of various pollutant emissions as a result of climate change could be explored to minimize such uncertainty (Zhao *et al.*, 2019)

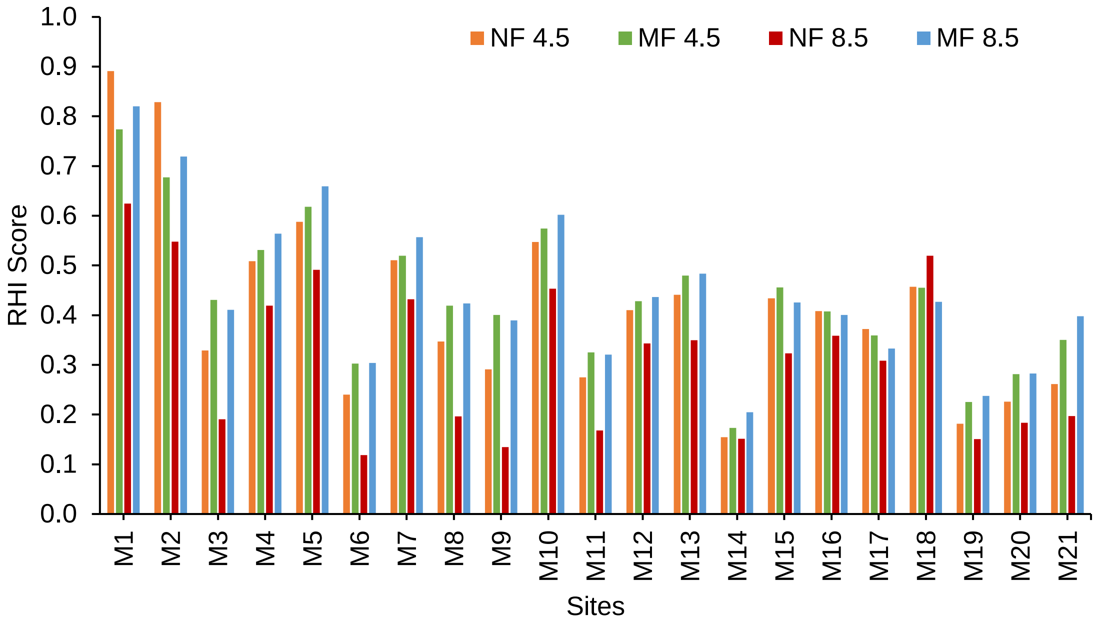

Figure 4.29: Future River health status based on an integrated score

4.7.1 Water quality condition

4.7.1.1 Characterization of physicochemical parameters

The concentration of physicochemical parameters of water quality at each sampling site under both scenarios (RCP 4.5 and 8.5) was predicted for near (NF) and mid-future (MF) with the help of equation-19 mentioned in the methodology section for all the observed seasonal data and averaged data. In this section, the status of future (NF &MF) water quality of Marshyangdi River based on the concentration of physio-chemical parameters and water quality index (WQI) as presented in (Table 4.24a & Table 4.24b; Annex 17) for both RCPs (4.5 & 8.5). Overall, water quality was predicted to be in good status in the future as most of the physicochemical parameters of water were within the limit required for the sustenance of aquatic life except for a few parameters at a few sites only which are elaborated hereunder.

Near Future (RCP 4.5 & 8.5)

The concentration of most of the water quality physicochemical parameters in the near future under both RCPs predicted to be within the acceptable limits of sustenance of aquatic living organisms (Annex 6). However, some parameters like pH, TP, and NH_3 exceed their limit at a few sites under RCP4.5 and RCP8.5 scenarios for the near future (Table.4.24a) while DO was found to be below the acceptable limit at a few sites. For example, pH exceeded its limit at four sites (M13, M16, M20 & M21) which ranges from 6.0 pH units at sites (M5-M7) for RCP 8.5 NF to 12.4 pH units for RCP 4.5 NF at sites (M12, M17, M18). While chemical parameters like DO range from 4 mg/L at M16 for RCPs 4.5 to 10 mg/L (M1 & M2) for RCP 4.5NF.

Similarly, chemical parameters like ammonia exceeded their limit at M15-M18 which ranges from 0.05 mg/L at M6 to 3.1 mg/L at M16 for both RCPs. Also, its values exceeded at site M48 for RCP 8.5NF. Further nutrients parameter like total phosphate have been predicted to exceed their limit at 8 sites (38%) in near future but the situation seems to be improved in the mid future for this parameter (Table 4.24a).

Mid Future (RCP 4.5 & 8.5)

The concentration of physicochemical parameters averaged for all four seasons was predicted to have the same magnitude for RCP 4.5 and RCP 8.5. For example, dissolved oxygen at sites M6 and M5 ranges from 4.3 mg/L which is slightly less than the limit required for aquatic organisms (5mg/L). Similarly physical parameters like pH of Marshyangdi Watershed for both RCPs. However, some chemical parameters like ammonia range from 0.05 (M16) to 3.2 mg/L at M6 thereby indicating exceeding its limit (>1.2mg/L) at these sites. Also, nutrient parameters like total phosphate exceeded its limit (>0.1mg/L) at M13 & M8 for RCP 4.5MF while for RCP 8.5 MF it exceeded at sites M8, M12 & M13 (Table 4.24b).

Ammonia is higher (exceeded its limit; Annex 6) during current scenarios (only during pre-monsoon 2021) as well as in the future under both RCP (4.5&8.5). Higher ammonia at these sites (M15-M18-) may be a due breakdown of organic matter and excretion by the fishes as a nitrogenous compound. Though it is hazardous to aquatic life at elevated temperatures and pH levels, its toxicity may decrease in some cases due to increased hardness in the ambient water (Wicks *et al.*, 2002). Hence, as pH in the future has not exceeded its limit and water is hard in the watershed, the toxicity of ammonia might not be problematic in future water quality thereby not affecting the aquatic organisms. As a result, based on current pollution-discharge conditions, increasing runoff at all the sampling sites (Table 4.9) helps to lower the concentrations of the pollutant in the river water, hence improving the quality of water (Zhao *et al.*, 2019) in the future

Table 4.24a: Concentration of physico-chemical parameters for near-future (RCP4.5)

Sites	pH	TDS	DO	Cl^-	COD	BOD	Ca^{2+}	Na^+	K^+	TA	TH	SO_4^{2-}	NO_3^-	TP	$NH_{3\text{-}N}$	PO_4^{3-}
M1	9.2	197	7.7	7.7	13.9	4.6	2.8	50.9	8.7	155	155	269.8	0.66	0.17	0.19	0.04
M2	9.2	218	7.5	7.5	9.3	10.0	6.0	39.3	7.2	212	212	298.9	0.87	0.08	0.1	0.04
M3	8.4	165	6.4	6.4	9.8	5.9	3.5	38.8	7.2	196	196	209.2	0.94	0.3	0.22	0.03
M4	6.6	129	4.9	4.9	8.7	6.1	3.6	32.3	9.3	143	143	167.8	0.72	0.04	0.32	0.03
M5	6.6	135	4.6	4.6	14.2	7.1	4.3	29.8	6.6	171	171	158.2	0.69	0.05	0.12	0.02
M6	6.0	130	4.3	4.3	19.2	10.5	6.3	22.7	9.6	150	150	145.0	0.66	0.04	0.05	0.01
M7	6.3	124	5.0	5.0	23.2	6.4	3.9	37.2	14.6	131	131	169.3	0.7	0.08	0.06	0.03
M8	7.5	91	6.0	6.0	10.3	6.3	3.8	24.4	8.0	120	120	78.0	0.9	0.34	0.39	0.16
M9	6.5	100	5.1	5.1	18.5	10.3	6.2	42.3	10.3	120	120	130.7	0.77	0.51	0.11	0.04
M10	6.4	107	4.9	4.9	10.9	7.3	4.4	29.0	7.0	138	138	133.4	0.51	0.08	0.1	0.05
M11	8.2	72	6.0	6.0	13.4	9.0	5.4	31.5	7.4	125	125	95.0	0.71	0.14	0.11	0.02
M12	6.7	121	5.5	5.5	17.6	6.7	4.0	33.9	8.0	133	133	151.0	0.58	0.05	0.26	0.14
M13	9.5	56	6.1	6.1	11.2	5.8	3.5	24.8	8.1	102	102	62.5	0.28	0.48	0.46	0.32
M14	8.4	53	6.9	6.9	10.6	9.3	5.6	43.9	14.3	117	117	56.0	0.84	0.41	0.46	0.03
M15	7.1	108	5.6	5.6	14.9	6.2	3.7	30.5	10.0	117	117	133.3	0.73	0.14	1.35	0.06
M16	10.1	93	7.3	7.3	12.3	13.8	8.3	30.3	11.9	160	160	87.7	0.88	0.11	3.19	0.05
M17	7.3	119	5.8	5.8	19.1	12.5	7.5	36.8	10.1	127	127	115.5	0.68	0.15	1.69	0.02
M18	7.2	127	5.5	5.5	17.9	8.3	5.0	41.7	12.8	188	188	122.6	0.73	0.12	1.93	0.03
M19	8.3	129	6.5	6.5	12.7	14.8	8.9	41.8	15.7	188	188	128.0	0.43	0.2	0.47	0.06
M20	12.4	175	9.9	9.9	22.1	17.3	10.4	58.1	15.1	277	277	184.5	1.15	0.13	0.35	0.12
M21	12.4	228	9.7	9.7	40.3	10.6	6.4	55.8	18.1	226	226	217.7	1.09	0.24	0.34	0.19
Max	12.4	228	9.9	9.9	40.3	17.3	10.4	58.1	18.1	277	277	298.9	1.2	0.5	3.2	0.3
Min	6.0	53	4.3	4.3	8.7	4.6	2.8	22.7	6.6	102	102	56.0	0.3	0.0	0.1	0.0

RCP 8.5NF																
SITES	**PH**	**TDS**	**DO**	**Cl^-**	**COD**	**BOD**	**Ca^{2+}**	**Na^+**	**K^+**	**TA**	**TH**	**SO_4^{2-}**	**NO_3^-**	**TP**	**NH_3-N**	**PO_4^{3-}**
M1	7.8	167	6.5	11.8	3.9	2.3	43.1	7.4	1.2	131	229	4.2	0.64	0.16	0.19	0.04
M2	7.8	185	6.3	7.8	8.5	5.1	33.3	6.1	3.0	180	253	3.8	0.84	0.07	0.1	0.04
M3	7.5	147	5.7	8.7	5.2	3.1	34.5	6.4	4.0	174	186	3.2	0.94	0.3	0.22	0.03
M4	49.1	961	36.1	64.9	45.0	27.0	240.1	69.5	8.2	1065	1247	27.7	0.68	0.03	0.3	0.03
M5	6.0	121	4.1	12.8	6.4	3.8	26.7	6.0	1.7	153	142	2.5	0.65	0.05	0.12	0.02
M6	6.1	131	4.4	19.3	10.6	6.4	22.9	9.7	1.1	151	146	2.8	0.7	0.04	0.05	0.01
M7	6.3	125	5.0	23.5	6.5	3.9	37.6	14.7	4.0	132	171	3.4	0.74	0.08	0.07	0.03
M8	7.6	92	6.0	10.4	6.4	3.8	24.7	8.1	6.2	122	79	4.2	0.93	0.35	0.4	0.16
M9	6.6	101	5.1	18.7	10.5	6.3	42.8	10.4	4.8	122	132	3.3	0.81	0.54	0.11	0.04
M10	6.5	108	5.0	11.1	7.4	4.4	29.3	7.1	2.4	140	135	3.1	0.53	0.08	0.1	0.05
M11	8.1	72	5.9	13.3	8.9	5.4	31.2	7.3	2.8	123	94	3.5	0.71	0.15	0.11	0.02
M12	6.7	121	5.5	17.8	6.8	4.1	34.2	8.1	1.7	134	152	3.6	0.6	0.05	0.27	0.15
M13	9.3	55	5.9	10.9	5.7	3.4	24.3	7.9	8.7	99	61	4.3	0.28	0.48	0.46	0.32
M14	8.3	52	6.8	10.4	9.2	5.5	43.2	14.0	9.8	115	55	3.5	0.84	0.41	0.47	0.03
M15	7.1	108	5.6	14.9	6.2	3.7	30.6	10.1	5.3	117	134	2.5	0.75	0.14	1.4	0.07
M16	9.8	90	7.1	12.0	13.4	8.0	29.6	11.6	10.3	156	85	4.0	0.89	0.11	3.25	0.05
M17	7.3	119	5.8	19.1	12.5	7.5	36.9	10.1	2.6	127	116	4.1	0.71	0.15	1.75	0.02
M18	7.2	128	5.5	17.9	8.3	5.0	41.7	12.8	3.3	188	123	3.5	0.75	0.13	1.99	0.03
M19	8.2	128	6.4	12.5	14.7	8.8	41.3	15.5	3.1	186	126	3.1	0.43	0.2	0.47	0.06
M20	7.2	102	5.8	12.9	10.1	6.0	33.9	8.8	3.9	162	108	3.5	0.69	0.08	0.21	0.07
M21	7.2	133	5.7	23.5	6.2	3.7	32.5	10.6	4.8	132	127	3.2	0.65	0.14	0.21	0.11
MAX	49.1	961	36.1	64.9	45.0	27.0	240.1	69.5	10.3	1065	1247	27.7	0.9	0.5	3.3	0.3
Min	6.0	52	4.1	7.8	3.9	2.3	22.9	6.0	1.1	99	55	2.5	0.3	0.0	0.1	0.0

Table 4.24b: Concentration of physico-chemical parameters for mid-future (RCP 4.5)

Sites	pH	TDS	DO	Cl^-	COD	BOD	Ca^{2+}	Na^+	K^+	TA	TH	SO_4^{2-}	NO_3^-	TP	NH_3-N	PO_4^{3-}
M1	9.0	191	7.5	13.5	4.5	2.7	49.5	8.5	1.4	151	262	4.8	0.64	0.16	0.19	0.04
M2	8.9	212	7.3	9.0	9.7	5.8	38.2	7.0	3.4	206	291	4.4	0.84	0.07	0.1	0.04
M3	8.3	163	6.3	9.7	5.8	3.5	38.3	7.1	4.5	193	206	3.6	0.94	0.3	0.22	0.03
M4	6.2	121	4.5	8.2	5.7	3.4	30.3	8.8	1.0	134	157	3.5	0.68	0.03	0.3	0.03
M5	6.2	126	4.3	13.3	6.7	4.0	27.9	6.2	1.7	160	148	2.6	0.65	0.05	0.12	0.02
M6	6.2	133	4.4	19.6	10.7	6.4	23.2	9.9	1.1	153	148	2.8	0.7	0.04	0.05	0.01
M7	6.4	126	5.1	23.7	6.6	3.9	38.0	14.9	4.0	134	173	3.4	0.74	0.08	0.07	0.03
M8	7.6	92	6.0	10.4	6.4	3.8	24.7	8.1	6.2	122	79	4.2	0.93	0.35	0.4	0.16
M9	6.7	102	5.2	18.9	10.5	6.3	43.1	10.5	4.8	123	133	3.3	0.81	0.54	0.11	0.04
M10	6.5	109	5.0	11.2	7.4	4.5	29.6	7.2	2.4	141	136	3.1	0.53	0.08	0.1	0.05
M11	8.3	73	6.0	13.5	9.1	5.5	31.7	7.4	2.8	125	96	3.6	0.71	0.15	0.11	0.02
M12	6.8	123	5.6	17.9	6.8	4.1	34.5	8.2	1.7	136	154	3.6	0.6	0.05	0.27	0.15
M13	9.5	56	6.1	11.2	5.8	3.5	24.8	8.1	8.9	102	63	4.4	0.28	0.48	0.46	0.32
M14	8.4	53	6.9	10.6	9.3	5.6	43.9	14.3	10.0	117	56	3.5	0.84	0.41	0.47	0.03
M15	7.2	109	5.7	15.1	6.2	3.7	30.9	10.2	5.4	118	135	2.5	0.75	0.14	1.4	0.07
M16	10.3	94	7.4	12.5	14.0	8.4	30.9	12.2	10.8	163	89	4.2	0.89	0.11	3.25	0.05
M17	7.4	120	5.9	19.4	12.7	7.6	37.4	10.3	2.6	129	117	4.1	0.71	0.15	1.75	0.02
M18	7.3	129	5.6	18.2	8.4	5.1	42.3	12.9	3.3	191	124	3.5	0.75	0.13	1.99	0.03
M19	8.3	130	6.5	12.8	14.9	8.9	42.0	15.8	3.1	189	128	3.2	0.43	0.2	0.47	0.06
M20	7.3	104	5.9	13.1	10.2	6.1	34.4	9.0	3.9	164	109	3.6	0.69	0.08	0.21	0.07
M21	7.4	135	5.8	23.9	6.3	3.8	33.1	10.7	4.9	134	129	3.3	0.65	0.14	0.21	0.11
MAX	10.3	212	7.5	23.9	14.9	8.9	49.5	15.8	10.8	206	291	4.8	0.9	0.5	3.3	0.3
Min	6.2	53	4.3	8.2	4.5	2.7	23.2	6.2	1.0	102	56	2.5	0.28	0.03	0.05	0.01

RCP 8.5MF																
Sites	**PH**	**TDS**	**DO**	**Cl^-**	**COD**	**BOD**	**Ca^{2+}**	**Na^+**	**K^+**	**TA**	**TH**	**SO_4^{2-}**	**NO_3^-**	**TP**	**NH_3-N**	**PO_4^{3-}**
M1	9.0	192	7	14	4	3	50	8	1	151	263	5	0.64	0.16	0.19	0.04
M2	8.9	212	7	9	10	6	38	7	3	206	291	4	0.84	0.07	0.1	0.04
M3	8.4	165	6	10	6	4	39	7	5	196	209	4	0.94	0.3	0.22	0.03
M4	6.2	122	5	8	6	3	30	9	1	135	158	5	0.68	0.03	0.3	0.03
M5	6.3	127	4	13	7	4	28	6	2	161	149	4	0.65	0.05	0.12	0.02
M6	6.4	137	5	20	11	7	24	10	1	158	153	4	0.7	0.04	0.05	0.01
M7	6.6	130	5	24	7	4	39	15	4	138	178	5	0.74	0.08	0.07	0.03
M8	7.7	93	6	11	7	4	25	8	6	124	80	5	0.93	0.35	0.4	0.16
M9	6.8	105	5	19	11	6	44	11	5	126	137	4	0.81	0.54	0.11	0.04
M10	6.7	112	5	11	8	5	30	7	3	145	140	4	0.53	0.08	0.1	0.05
M11	8.3	73	6	14	9	5	32	7	3	126	96	4	0.71	0.15	0.11	0.02
M12	7.0	125	6	18	7	4	35	8	2	139	157	4	0.6	0.05	0.27	0.15
M13	9.5	56	6	11	6	3	25	8	9	102	63	4	0.28	0.48	0.46	0.32
M14	8.4	53	7	11	9	6	44	14	10	117	56	3	0.84	0.41	0.47	0.03
M15	7.3	112	6	15	6	4	31	10	5	121	138	3	0.75	0.14	1.4	0.07
M16	10.3	94	7	12	14	8	31	12	11	163	89	4	0.89	0.11	3.25	0.05
M17	7.5	123	6	20	13	8	38	10	3	131	119	5	0.71	0.15	1.75	0.02
M18	7.4	132	6	19	9	5	43	13	3	194	127	4	0.75	0.13	1.99	0.03
M19	8.3	129	6	13	15	9	42	16	3	188	128	3	0.43	0.2	0.47	0.06
M20	7.4	105	6	13	10	6	35	9	4	167	111	4	0.69	0.08	0.21	0.07
M21	7.5	137	6	24	6	4	34	11	5	136	131	4	0.65	0.14	0.21	0.11
MAX	10.3	212	7.0	24.0	15.0	9.0	50.0	16.0	11.0	206	291	5.0	0.9	0.5	3.3	0.3
Min	6.2	53	4.0	8.0	4.0	3.0	24.0	6.0	1.0	102	56	3.0	0.3	0.03	0.05	0.01

4.7.1.2 Assessment of water quality based on water quality index

The water quality index for future scenarios (NF, MF) under both RCPs has been predicted based on the concentration of water quality and the results are shown in (Fig.4.30; Annex 17). Water quality based on WQI falls under the excellent water quality class (Annex 16) in the future (NF & MF) under both RCPs scenarios. However, in a similar study on the New Brunswick Rivers of Canada's Atlantic coast, water quality was also not projected to deteriorate under climate change based on WQI (El-Jabi *et al.*, 2014).

Seasonal variation at the studied sites also revealed the excellent condition of water quality in the watershed in all seasons except for pre-monsoon 2021 (Annex-17.1). However, water quality at these sites was found to be very poor (M13 & M18), poor (M8, M12, M15, &M17), and unfit for drinking (M4 &M16)in the future (NF & MF) for both RCPs compared to baseline. The exceedance limit in the concentration of ammonia (Table 4.20) at these sites might be the cause of the degraded water quality class at these sites.

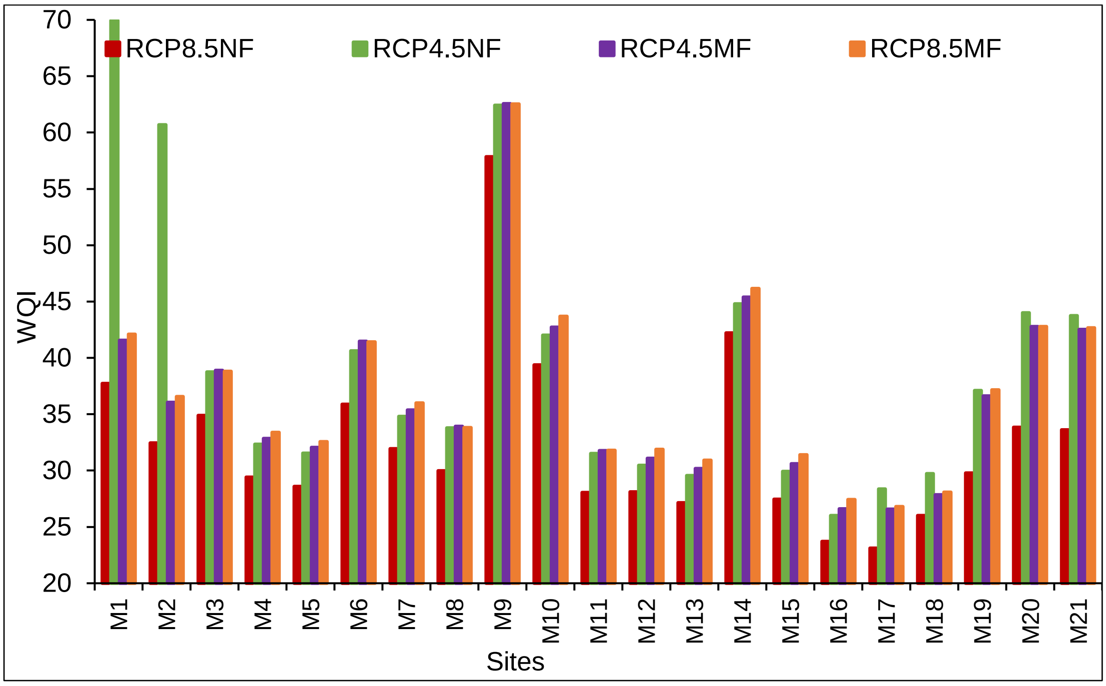

Figure 4.30: Future water quality index of Marshyangdi Watershed

4.7.2 Biological condition

The MaxEnt model was used in predicting the probability distribution of macroinvertebrates based on existing occurrence data for six families (Baetidae, Leptophlebiidae, Heptageniidae, Ephemeridae, Perlidae and Hydropsychidae belongin g to the EPT order (>15 species in each site). Distribution for some families is shown in Fig. 4.33- 4.35 and the details of environmental and spatial variables contributing to the SDM are presented in (Annex 7). Overall mean AUC ranged from 0.75±0.32 (Leptophlebiidae) to 0.86±0.15 (Hydropsychidae, Fig. 4.32). As the AUC value is equal to or more than 0.75 results of SDMs are considered to be good, indicating the credibility and accuracy of the model (Araujo *et al.,* 2005). The model performed well in matching the distribution of the occurrence records. Furthermore, variable importance by the jackknife method revealed the annual mean temperature (Bio1), temperature seasonality (SD; Bio 4), and Precipitation of Driest Quarter (Bio17) as the common climate factors influencing the distribution of macroinvertebrates in the Marshyangdi Watershed for both RCPs. However, the percentage contribution of each variable varies for Ephemeroptera, Plecoptera, and Trichoptera respectively for e.g., all the three families belonging to Ephemeroptera order Bio 1 contributes the highest percentage followed by slope, Bio17, and Bio04 respectively (Fig.4.31a) thus indicating climate parameter; mean annual temperature plays a dominant role in the distribution of this family (Montebrand *et al.,* 2019). But for the Trichoptera order, slope (Fig.4.31b) contributes the highest percentage followed by Bio 1, Bio17, and Bio 4 while for the Plecoptera family too percentage contribution of the variables followed the same trend as that of the Trichoptera order. In the Rhone catchment, upstream of Lake Geneva in Switzerland, the slope of the variable and Bio 1 were found to be dominant variables in the distribution of EPT orders (Montebrand *et al.,* 2019). It is interesting to note that for all the species, the aspect contributes least as variable importance for macroinvertebrates.

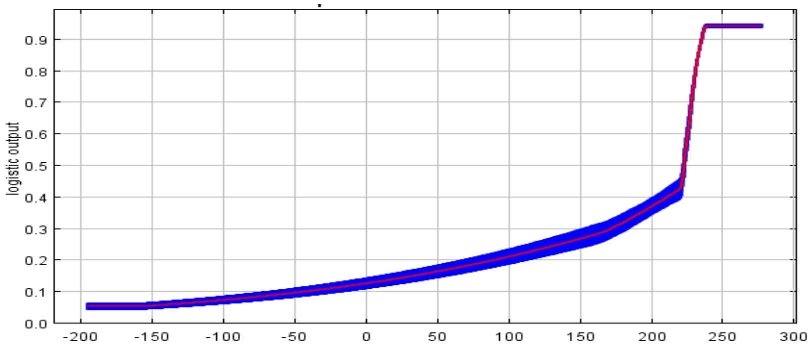

Figure 4.31a: Response of Baitedae to mean annual temperature

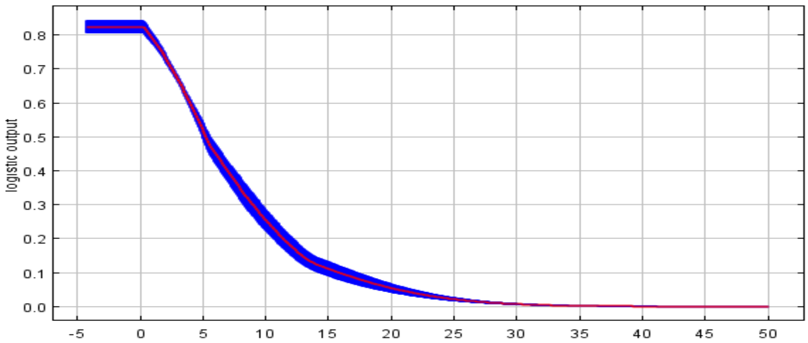

Figure 4.31b: Response of Hydropsychidae to slope

4.7.2.1 Current scenarios of species distribution and model quality

In the Marshyangdi Watershed, the predictive distribution map for macroinvertebrates generated through the MaxEnt model showed an increase in area per kilometers square under both RCPs 4.5 & 8.5 during 2050 for all the modeled families for current scenarios. However, for the Trichoptera order increase in area was more for RCP 4.5 in comparison to RCP 8.5 and the same was the case for the Leptophlebiidae family representing the Ephemeroptera order. Thus, an increase in the area in the future suggested no effects on the species distribution in comparison to baseline (Fig. 4.33-4.35). In other words, there is no effect of climate change on modeled families in the future under both RCPs i.e., habitat suitability showed a positive response to climate change among the modeled families of Marshyangdi Watershed.

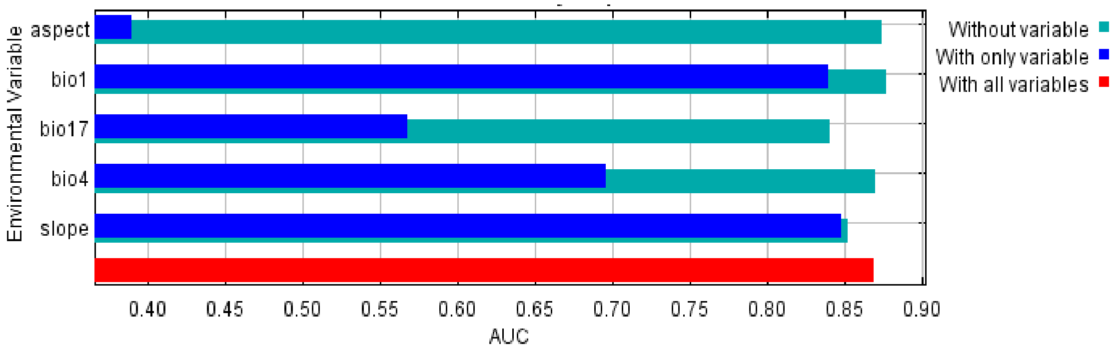

Figure 4.32: The results of the jackknife procedure on AUC for Hydropsychidae

4.7.2.2 Future species richness under climate change scenarios (RCP 4.5 and 8.5)

This study projected the distribution of EPT order with MaxEnt models based on ensembled of three RCMs available from CMIP5 under medium and high emission climatic scenarios RCPs 4.5 and 8.5 for the years 2050. The family richness pattern of macroinvertebrates was predicted to be similar from sites M10 to M21 except at M11 (Table 4.25) for both RCPs 4.5 and 8.5 scenarios. However, family richness pattern have been predicted to be better for RCP 8.5 scenarios in comparison to RCP 4.5 from sites M1 to M9 except at site M8 (similar richness) (Table 4.25). Family richness is found to be lower at the sites located at higher altitudes for both RCPs scenarios which might be due to increase in elevation (Table 4.25). However, in comparison to the current scenario species richness was found to be increased from site M12 to M20 except at site M11.

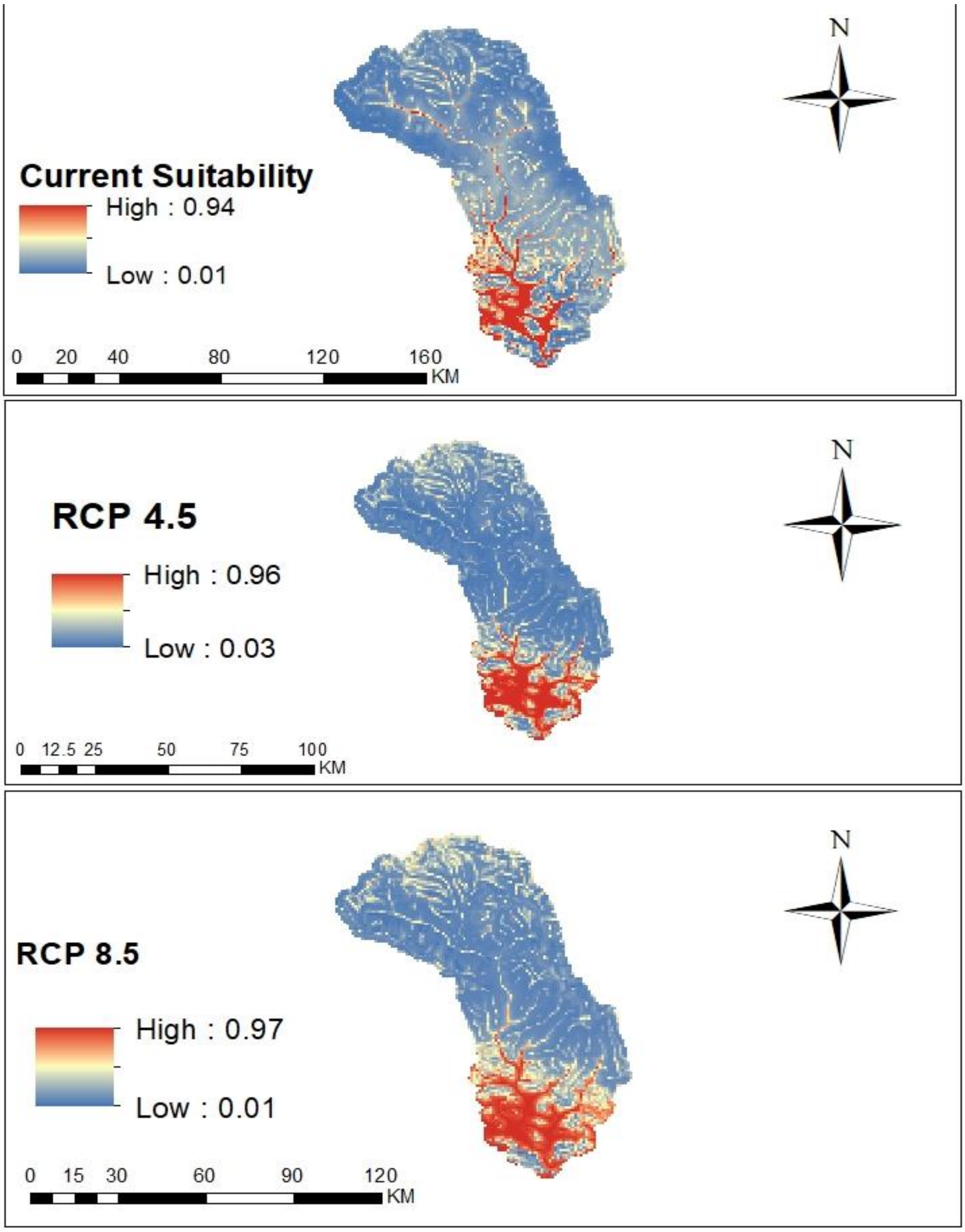

Figure 4.33: Future distribution of Baetidae w.r.t current at Marshyangdi Watershed

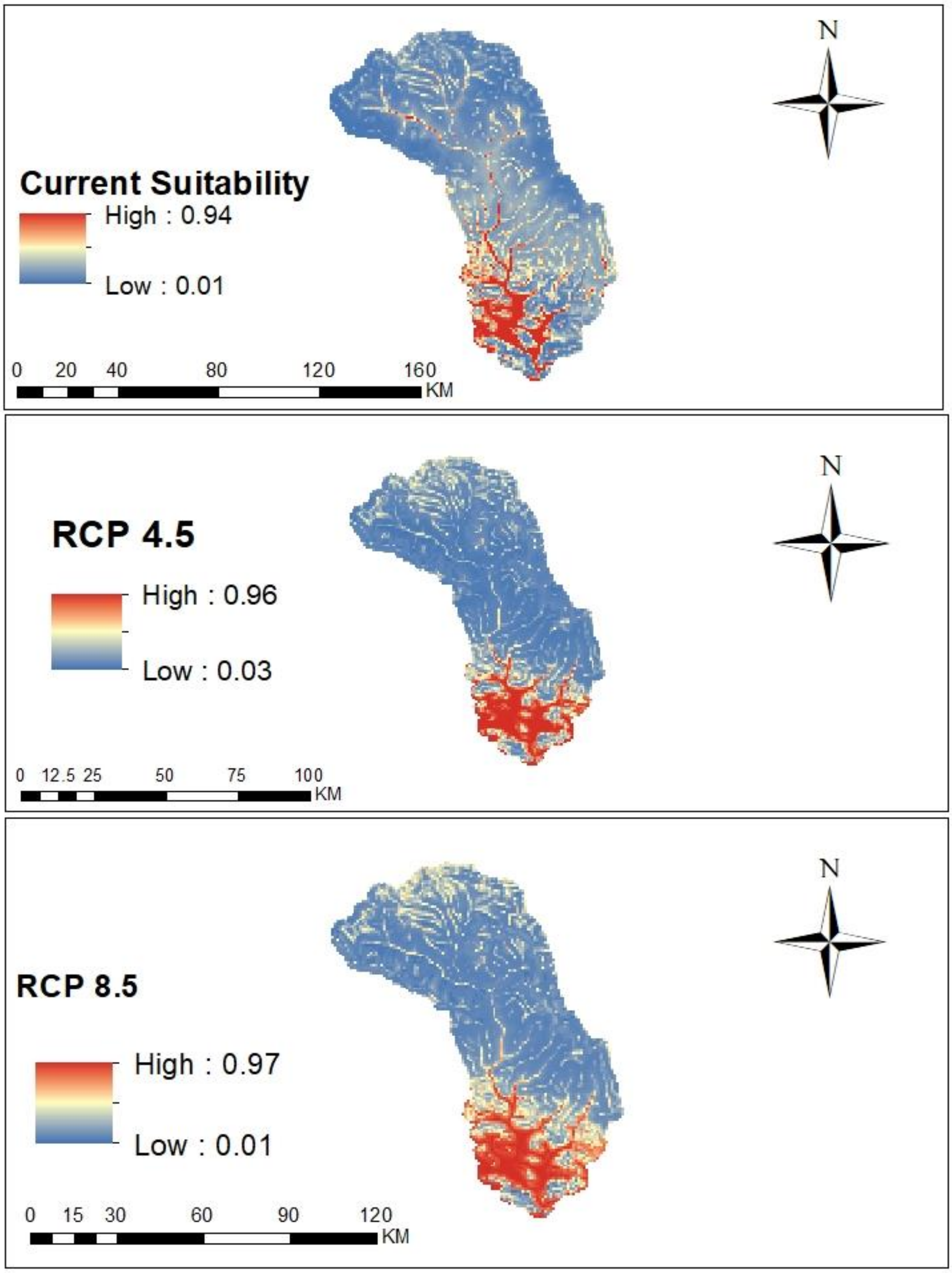

Figure 4.34: Future distribution of Perlidae w.r.t current at Marshyangdi Watershed

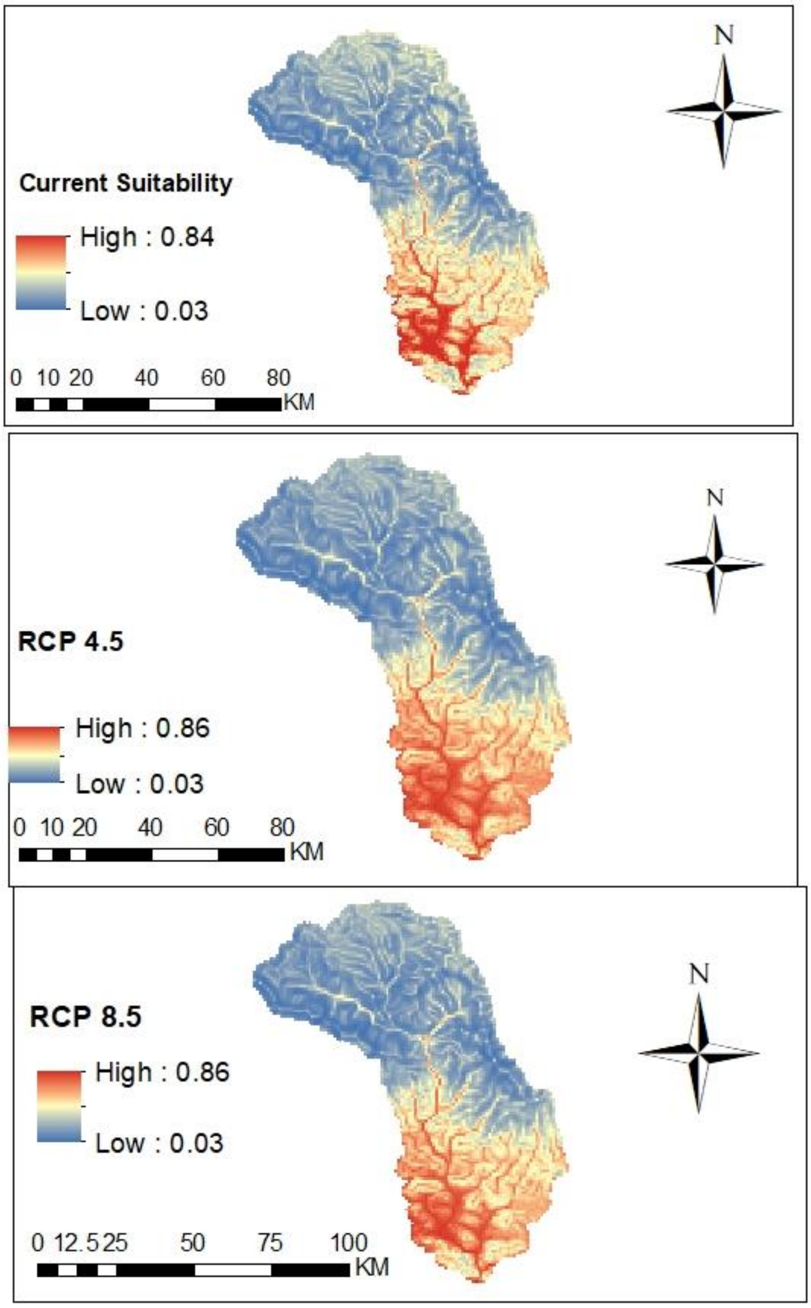

Figure 4.35: Future distribution of Leptophlebiidae w.r.t current at Marshyangdi Watershed

Table 4.25: Taxonomic richness at Marshyangdi Watershed

Sites	Altitude	Baseline	RCP 4.5	RCP 8.5
M1	3714	6	0	3
M2	3156	5	0	0
M3	2604	5	0	0
M4	1813	5	1	1
M5	1675	4	1	4
M6	861	5	4	6
M7	851	5	1	3
M8	798	4	6	6
M9	610	6	5	6
M10	582	5	6	6
M11	640	6	1	5
M12	492	3	6	6
M13	477	5	6	6
M14	490	5	6	6
M15	368	4	6	6
M16	378	5	6	6
M17	335	3	6	6
M18	286	5	6	6
M19	271	5	6	6
M20	227	5	6	6
M21	216	6	6	6

4.7.3 Hydrological condition

4.7.3.1 Flow health at watershed under (RCP 4.5 & 8.5)

The deviation of flow parameters of Marshyangdi River within the test period from 2000-2053 against the reference period 1987-1999 within five flow deviation classes as shown in Fig. 4.36. The annual average flow health score (FHI) depicted the small deviations at the Bimalnagar Watershed in the future under both RCPs (FHI=0.7). As depicted in Fig. 4.36 below flow health scores showed a large deviation from the beginning of the year 2000 till the end in the future 2053 in two flow health metrics;

seasonality flow shift and persistently higher flow thus indicating disturbance for some biota in the future (Narasimhan *et al.*, 2014).

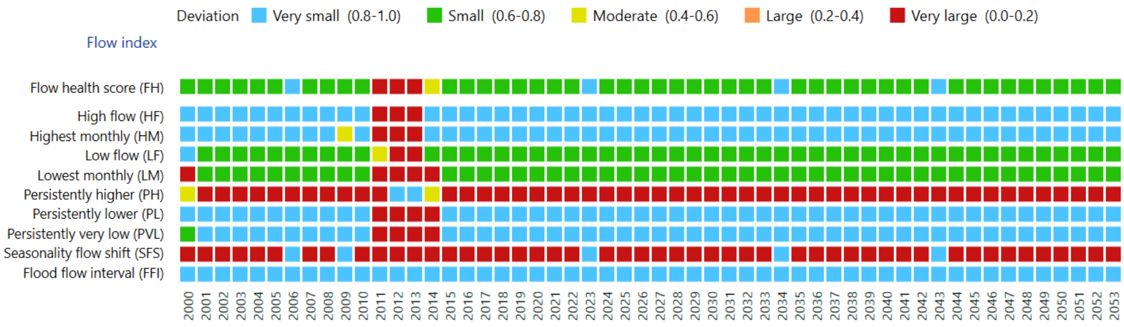

Figure 4.36: Flow health at watershed under RCP 4.5 scenario

4.7.3.2 Flow health across the sampling sites (RCP 4.5 & 8.5)

Annual average flow health scores varied from 0.001 at M11(Fig.4.41) to 0.7 at (M21, Fig 4.37) (Annex 15) indicating a very large to small deviation in the future under both RCPS. Flow health status at all the sampling sites showed similar conditions (deviations) to baseline i.e., annual average scores of flow health metrics at sampling sites seemed to have highly deviated from the mid to upstream region of the watershed (M12-M21) as well as at the tributaries (M8, M11, M13, M14, M16, M19),M in comparison to less deviation at the sampling sites located at the downstream region of the watershed. For example, at M11 (tributary) and M2 (upstream part of the watershed) flow health metrics show similar deviation from baseline to future (Fig.4.38; Fig 4.39). The flow index of the Marshyangdi watershed at outlet point M21 in confluence with the Trishuli River was found to be very small and deviated in comparison to its tributaries and upstream study areas as a result of higher discharges.

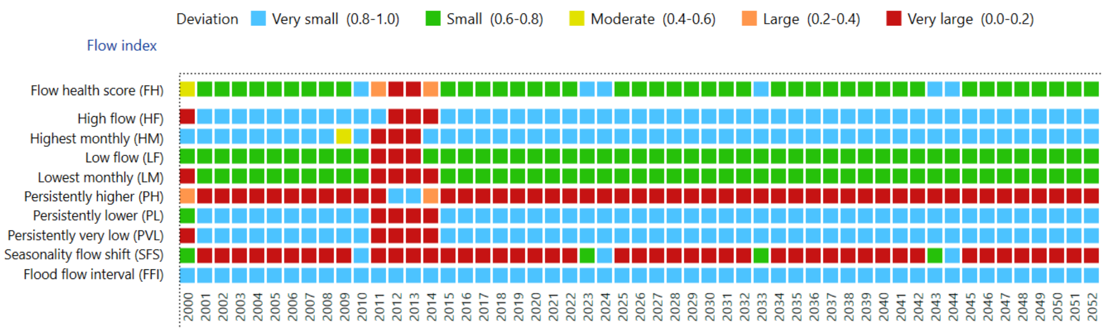

Figure 4.37: Flow health at M21 sampling site under RCP4.5 scenario

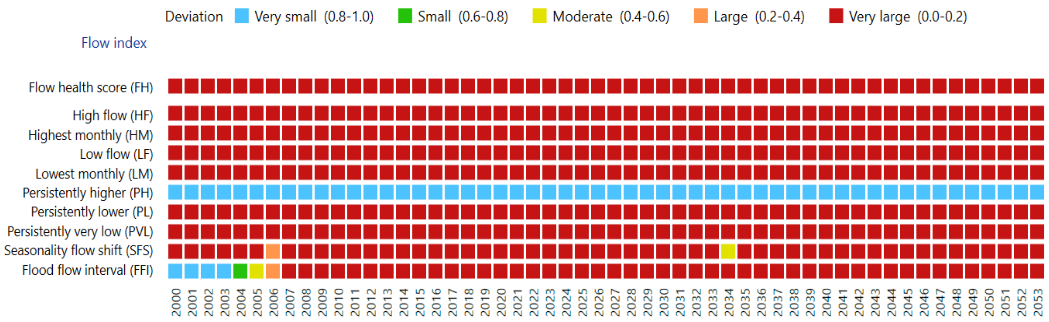

Figure 4.38: Flow health at M11 sampling site under RCP4.5 scenario

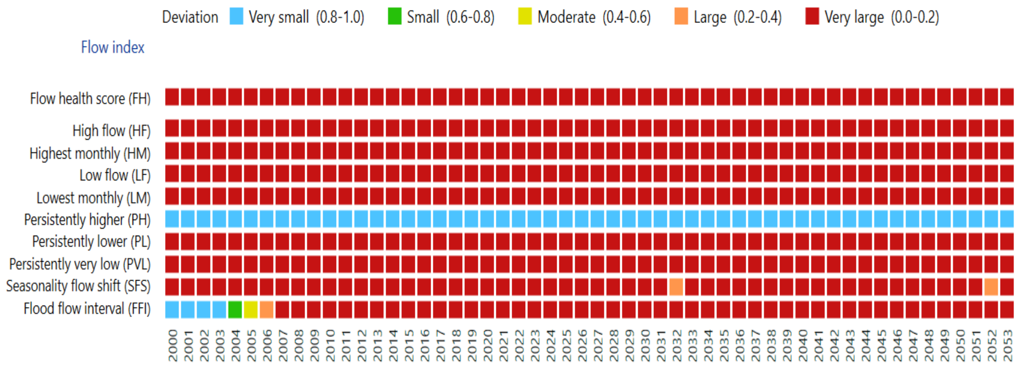

Figure 4.39: Flow health at M2 sampling site under RCP4.5 scenario

CHAPTER 5
SUMMARY AND CONCLUSIONS

5.1 Summary

Freshwater resources are crucial for ecological, economic, social and environmental development and sustainability of the basin. However, climate change has impacted these resources and are expected to increase in coming days. Climate change coupled with an ever-increasing population and limited availability of freshwater has exacerbated water security challenges all over the world. Such changes in climate due to variability in its parameters (precipitation, temperature) have direct or indirect hydrological effects in terms of quantity, quality, and duration of streamflow. Thus, impacts in various sectors are primarily translated through changes in streamflow and associated alterations in water availability and river health. Thus, a widely used hydrological model was used to assess the hydrological and water availability conditions in one of the snow-fed Himalayan watersheds, Marshyangdi. In assessing the climate change scenarios, multiple RCMs with bias correction methods, and various other tools like Rclimdex were used. Indicators of hydrologic alteration and flow health tools were used to evaluate the climatic and hydrologic extremes in the watershed. The river health was evaluated based on an indicator-based framework prepared based on a thorough literature review.

The first and second objective are interlinked as it is related to studying the historical (1983-2013) trends of climate and projecting the future (2014-2053) climate for medium (RCP 4.5) and high (RCP 8.5) emission scenarios. The climatic trend revealed an increasing trend in an annual average as well as extreme indices related to temperature and but for annual average precipitation and its extremes it shows decreasing trend, indicating a hotter and dry climate in both medium RCP (4.5) and high climate change scenarios (RCP8.5). Similarly, annual average precipitation, as well as precipitation-related extreme indices, shows increasing trend revealing a wetter condition in the future under both RCPs (4.5 & 8.5). Streamflow is expected to alter highly in the future from low alteration in the current situation. Trends in maximum flow extreme indices of flow regime tend to increase significantly indicating the possibility of flood in the watershed during the historical period. Hydrological status based on the SWAT model reveals an increasing amount of flow indicating no threat to water availability in the projected period at this watershed.

Among the various studied components of river health, all of them were found to be within the acceptable standard for the sustenance of aquatic organisms. For example, water quality based on the water quality index and various physicochemical parameters were found to be within the permissible level, thus revealing the suitability of water for the sustenance of aquatic life in the Marshyangdi Watershed except for a few chemical and nutrients parameters at a few sites. Similarly, habitat conditions of the watershed ranged from excellent to fair conditions among the studied seasons. The biological condition of the Marshyangdi River based on selected metrics (e.g., EPT and Taxonomic richness) also reveals good status in the current and future scenarios for both RCPs. However, the flow health index score reveals a small deviation for the current scenarios at the watershed but at the sampling sites located at higher altitudes and the tributary's river of Marshyangdi River, flow health index scores show a very high deviation from the natural state. Finally, an integrated assessment based on the above four components of an ecosystem revealed statistically significant moderate condition of river health in the watershed which will continue to be in the moderate condition (statistically significant) in the future scenarios.

5.2 Conclusions

This study assessed the water availability and river health under current and future scenarios (NF-near future, and MF- mid-future) for two representative concentration pathways RCP 4.5 and RCP 8.5 in one of the Himalayan watersheds, Marshyangdi. An ensemble of three regional climate models (RCMs) was used to project future climate, and hydroclimatic extremes and assess projected trends in the climatic extremes under RCP 4.5 and RCP 8.5 scenarios for two future periods. Key conclusions specific to the respective objectives of this study are listed hereunder.

- In the climatic study, the maximum temperature (Tmax) is increasing significantly, while minimum temperature (Tmin) has mixed trends (i.e., increasing at two stations which are located in the lower part of the watershed and decreasing at stations located at higher altitudes) over the historical period

(1983–2013). Similarly, Tmax-related climatic extremes (e.g., warm spell duration index and warm days) are also increasing while Tmin-related extremes indices (e.g., warm nights and cool days) are decreasing, thus revealing that the watershed is getting warmer over the years. Furthermore, decreasing trends in average annual precipitation at all the stations and an increasing trend in precipitation related extreme (e.g., consecutive dry days) reveal that the watershed is gradually getting drier over the historical period.

- In the future for both RCP (4.5 and 8.5) scenarios, maximum (Tmax) and minimum (Tmin) temperatures are expected to increase in the watershed Similarly, some extreme indices related to Tmax show significant increasing trends e.g., warm nights and warm days whereas Tmin-related extremes, such as cool nights and cool days, shows a significant decreasing trend in future with respect to baseline. Such increases in temperature and temperature-related extremes suggest that the watershed's climate will continue to be warm in the future. Similarly, average annual precipitation is projected to increase for all the scenarios and future timeframes considered (July & August) whereas only few precipitation-related extreme indices exhibit increasing trend (e.g., PRCPTOT). In addition, decreasing trends in consecutive dry days have been observed suggesting that the watershed would be wetter in the future. Water availability in terms of river flow is likely to improve in the future, with an increase in volume (MCM) of up to 15% for NF 4.5 and 11% for RCP 8.5 MF compared to the baseline scenario. Further significant low alteration in the baseflow index for both RCPs scenarios also suggest that low flow periods will not be affected thereby improving the water availability condition in the watershed. However, the flow regime based on 32 hydrologic extreme indices calculated from the IHA tool reveals low alteration during the historical period. However, increases in trend amount in indices like 1-day and 3-day flow in future scenario and its high alteration in the natural flow regime reveals variation in streamflow for both RCPs considered resulting in severe ecological consequences in the future.
- An integrated score based on four major components of river health reveals the continuation of the moderate condition (statistically significant) of the river compared to baseline for both RCPs in the future. The hydrological component plays a dominant role as indicated by an entropy weight for the integrated

assessment of river health in future scenarios. Thus, alteration of flow regime and deviations which have been observed within the metrics of flow health index suggest devising and implementing strategies to protect river health of Marshyangdi Watershed.

5.3 Recommendations

- Future river health is projected to be moderate which may deteriorate with local development activities in the watershed, and this should be accounted for by formulating river health management policies.
- To minimize impact of hydrological alterations in river health, it is recommended to characterize the drivers of hydrologic alteration and design appropriate interventions
- Water quality are generally expected to be deteriorated after mixing with tributaries. But in this case such characteristics are reflected at only few locations. Therefore, it is recommended to monitor water quality at (M1) locations (one for pristine condition at headwater), one nearby outlet to reflect overall condition of the watershed health (M21) and at intermediate points (M8). Further seasonal monitoring is recommended.
- Future studies may consider non-climatic factors like landuse, urbanization, industrialization, economic growth etc. for river health assessment.

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APPENDIX

Annex-1 Frameworks used for river health assessment in different countries

S.N	Country	Indicators	Sub-indicators	Reference
1.	Australia/FARWH 2010	• Catchment Disturbance Infrastructure	• Land cover change • Land use	Storer et al. (2011)
		• Hydrological Changes (Flow stress ranking)	• Low/High flow • Proportion of zero flow • Monthly variation • Seasonal period	
		• Physical form	• Longitudinal connectivity: Major/minor dams, Gauging stations, Road-rail crossings • Erosion: Erosion extent, Bank stabilization Artificial channel	
		• Fringing zone	• Extent of fringing zone: Fringing vegetation width, Fringing vegetation length • Nativeness	
		• Aquatic biota	• Fish and crayfish • Macroinvertebrates	
2.	China/ACED 2011	• Hydrology	• Flow Stress Ranking indicators: Mean Annual FlowSeasonal Amplitude; Seasonal Period; Low Flow Magnitude(Q90): High Flow Magnitude (Q10) Flow Duration Curve, Low Flow Spells, High Flow Spells • Flow Variability	Leigh et al. (2012)
		• Physical form	• bank stability (resistance to fluvial scour • channel form variability (Planform, Bed material particle size, channel cross-section) • connectivity (lateral and longitudinal) • direct disturbance (sand/gravel and gold mining).	
		• Water quality	• Physical: water temperature EC, TDS, suspended solids (SS), • Chemical: DO, Cations of K^+ and Na^+, Cl^-, Bicarbonate (HCO_3) , CODMn, ammonium (NH_4), nitrite(NO_2), nitrate , (NO_3^-) BOD_5, chemical oxygen demand (COD_{Cr}), volatile phenols , heavy metals:(Pb), Chromium (Cr), Aluminium (Al), Zinc (Zn), Copper (Cu), Mercury (Hg) and Arsenic (As) calcium and magnesium (Ca, Mg), alkalinity (Alk) silicate (SiO4),	

			• Nutrients: PO_4^{3-}, NH_4, TP, TN, $SO_4{}^{2-}$ • Ecoli	
		• Riverine vegetation	• Riparian vegetation: Longitudinal extent (continuity), its width and structural composition and abundance (i.e., cover abundance of trees, shrubs and herbs) • Landuse • Instream vegetation: macrophytes	
		• Biological	• Macroinvertebrates • Algae • Fish	
3.	RH & Eflows in Chinese rivers	• Physical form	• Channel Physical form: Bankfull capacity • Delta Physical Form • Annual sediment load • High flow events • concentrations, and growth rate of the delta area,	Speed et al. (2012)
		• Water quality	• Physical: pH, Oxygen balance • metal and non-metal toxicants, • Nutrients: TP, TN • Fecal coliform	
		• Biological	• Fish • Benthic macroinvertebrates • Riverine vegetation Composition • Vegetated buffer width • Vegetation buffer continuity	
		• Socioeconomic indicator	• Water consumption • Hydropower generation • Flood risk • Drought risk • Navigation	
4.	Yufu river China	• Hydrological indices	• Runoff • fulfillment rate of ecological water demand • Flow velocity	Condon et al. (2011)
		• Water quality indices	• Physical: • Chemical: BOD, COD, DO, COD_{Mn}, Fluoride, Ionic Surfactants, NH_3-N, S, • Nutrients: TP, TN, SO_4^{2-}	
		• Biological indices	• fish diversity • zoobenthos diversity • algal biodiversity	
		• Habitat indices	• embankment stability • river meandering coefficient	

			• the riparian vegetation coverage • the habitat complexity • riverbed substrate • type of riparian land use • a combined characteristic of rate and depth • riparian zone width • embankment rebuilding • non-point source pollution intensity	
5.	US-EPA/841/D-13/001, 2013	• Biological quality	• Multiple biological assemblage (periphyton,Fish, Benthic macroinvertebrates)	USEPA (2013)
		• Chemical stressors	• Physical: Salinity Acidification • Nutrients: Total phosphorus, Total nitrogen	
		• Physical habitat stressors	• Excess streambed sediments, • Riparian vegetative cover • In-stream fish habitat, • Riparian disturbance	
		• Human Health indicators	• Mercury in fish tissue • Eenterococci (bacteria)	
		• Changes in stream condition		
6.	Ecological condition: Tanana River basin, interior Alaska 2008	• Physicochemic l	• Physical: pH, specific conductance, turbidity, total solids, total suspended solids, color • Chemical: alkalinity, dissolved inorganic and organic carbon • Nutrients: nitrogen and phosphorus, Chla, ammonium, nitrate	Rinella et al. (2008)
		• Physical habitat	• channel form: channel slope, wetted width, thalweg depth, • substrates :(% sand or fines, log mean substrate diameter) • riparian vegetation: riparian woody cover (sum of all layers), mid-channel canopy shade • Fish habitat: LWD volume in bank full channel, fish cover all types, pools (% of reach) • riparian disturbance: riparian disturbance	
		• Biological	• Fish • Macroinvertebrate • Periphyton	
		• Physical Habitat	• Embeddedness • Relative bed stability • Riparian vegetative cover • Riparian disturbance	Wolff & Koch (2011)

7.		• Water quality	• Physical: TSS • Chemical: Sulphate • Nutrients: TP, TN	
		• Biological	• Benthic Macroinvertebrates	
8.	Evaluation of river health China PSRmodel	• Ecological environmental factors	• The rate of erosion • The degree of equilibrium between precipitation and evaporation	Su et al. (2019)
		• Human Factors	• The rate of water resources development • Human activity Intensity • The rate of basin land development	
		• The situation of river ecological environment	• Biodiversity • Vegetation cover • Cleaning situation • Water quality • River Connectivity	
		• The water condition of river	• The rate of flood guarantee • The rate of Irrigation maintenance • The capacity of flood storage	
		• The situation of human society	• The degree of public participation • The sense of river health	
		• River protection	• The amount of pollutant reduction • The degree of protecting measures' implementation	
		• River management • innovation	• The ability of Technological innovation • Other abilities of innovation	

		• Hazard prevention	• Health risk identification • The rate of health risk control	
9.	Klamath Network.Natural Resource Report NPS/KLMN/NRR—2013/669	• Water chemistry	• Physical: pH, EC, Temp, acid neutralizing capacity • Chemical: Dissolved Oxygen, Dissolved organic carbon; Anions (Cl^-, $SO4^{2-}$), Cations (Na^{2+}, Ca+, K+, Mg^{2+}) • Nutrients: TN, TP	Dinger et al. (2013)
		• Stream Environment	• Riparian • Dominant tress • Channel morphology • shading, • Substrate • Discharge	
		• 3.Aquatic Community	• Algal biomass • Benthic macroinvertebrates • Amphibians • Fish	
10	RHA Poudre River	• Flow regime	• Peak flow • Base flow • Rate of change	Jared et al. (2015)
		• Sediment	• Land Erosion • Channel erosion • Transport	
		• Water quality	• Temperature • Nutrients • Dissolved oxygen • pH	
		• Riparian condition	• Vegetation structure and complexity • Habitat Connectivity • Contributing area	
		• Debris	• Large wood • Detritus	
		• River Form	• Planform • Dimension • Profile	
		• Channel resilience	• Dynamic Equilibrium • Channel recovery	
		• Physical Structure	• Coarse scale • Fine scale	

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		Aquatic and Riparian	• Aquatic insects • Fish • Trout • Aquatic habitat Connectivity • Birds	
11.	Ecological assessment of Colorado stream	• Biological indices	• Aquatic Vertebrates and Crayfish • Benthic Macroinvertebrates • Periphyton	Condon et al. (2013)
		• Water chemistry	• Physical: Specific conductivity, pH, Turbidity, SS • Chemical: Dissolved oxygen, TP, TN, Hg	
		• Physical habitat	• Streambed stability • Habitat complexity • Riparian vegetation cover complexity • Riparian disturbance	
12	Integrated assessment of Alabama watershed	• Biological Condition	• Fish • Macroinvertebrate	USEPA (2014)
		• Water Quality	• Nutrients: Nitrate -Nitrite, TP • Physical: SS, EC	
		• Habitat Condition/Geo morphology	• Stream habitat condition • Dam Presence/Absence	
		• Landscape Condition	• Percent natural Landcover • Percent Intact Hydrologically Active Zone (HAZ) Land Cover • Percent Hubs and corridors	
		• Hydrologic Condition	• Dam storage ratio	
13.	Eastern Cape RHP	• 1.Biological Indicators	• Macroinvertebrates • Fish • Riparian Vegetation	Scherman et al. (2004)
		• Physical indicators	• Habitat • Instream habitat • Geomorphology (Location, altitude, channel gradient and longitudinal profile, Quaternary catchment code) • Flow/Hydrology (current speed, water depth, and (in • the longer term) substratum characteristics	
		• Water quality Indicators	• Inorganic salts: $MgSO_4$, Na_2SO_4, $MgCl_2$, $CaCl_2$, NaCl $CaSO_4$ • Nutrients: SRP, TIN	

			• Toxic: NH_3, F, Al	
14.	Ecological health assessments using a Dongjin River	•		
		• Water quality	• Physical: pH, Temperature, Conductivity, SS • Chemical: DO, BOD, COD • Nutrients: Nitrite, Nitrate, phosphate, TN, TP, NO_3-N, NH4-N, TDN, TDP, • Bacteria • CHL-a	Jang & An (2016)
		• Biological	• Fish	
15	The Freshwater Health Index (Ecosystem Vitality indicators)	• Water quantity • Water quality • Drainage-basin condition • Biodiversity	• Deviation from natural flow regime: measures the degree to which current surface water flows have shifted from historic, natural flows • Groundwater storage depletion: changes in the availability of water stored in aquifers • Physical: TSS • Nutrient: TN TP • Bank modification • Flow connectivity • Landcover naturalness • Changes in number (i.e., species number) and population size of species of concern • Changes in number and population size of invasive and nuisance species	Souter et al. (2018)
	. Ecosystem services (Governance & Stakeholders indicators)	• Provisioning • Regulation and Support	• Water Supply Reliability Relative to Demand • Biomass for Consumption Sediment Regulation Deviation of Water Quality Metrics from Benchmarks • Flood Regulation Exposure to Water-Associated Diseases	
		• Cultural/Aesthetic	• Recreation • Conservation of Cultural heritages site	
		• Governance & Stakeholders • Enabling Environment	• Water resource management • Rights to resource use • Incentives and regulations • Financial capacity • Technical capacity	

		• Stakeholder Engagement	• Information access and knowledge • Engagement in decision-making processes	
		• Vision and Adaptive • Governance • Effectiveness	• Strategic Planning and Adaptive Governance • Monitoring and Learning Mechanisms • Enforcement and Compliance • Distribution of Benefits from Ecosystem Services • Water-Related Conflict	
16	Biological evaluation of Michigan's non-wadeable rivers	• Water quality	• Physical: temperature, pH, conductivity, turbidity, and suspended chlorophyll • Chemical: DO, TN, TP	Wessell et al. (2018)
		• Habitat quality	• riparian width, large woody debris, aquatic vegetation, bottom deposition, bank stability, thalweg substrate, and off-channel habitat	
		• Biological	• Macroinvertebrates	
17.	Manual for FRHA Thailand, 2018	• Biological	• Fish	Babel (2018)
		• Physical habitat	• Flow: Long-term stability in flow (%), • Assurance that environmental flow is available (%) • Erosion Control in the riverine ecosystem • Riparian vegetation along the river	
		• Water quality	• Chemical: Dissolved Oxygen, Heavy metals • Nutrients: Total nitrogen, Total Phosphorous	
		• Socioeconomic	• Ecosystem provisioning services for human activities • Economic value of water • Investment in river protection and • enhancement work • Citizen awareness of river health issues	
18.	National water-quality assessment program water-resources investigations report 00-4125	• Biological	• Macroinvertebrate	Brown &May (2000)
		• Physicochemical	• Physical: Specific conductance, pH, Temperature • Chemical: Dissolved Oxygen, Alkalinity	
		• Habitat	• Elevation • Discharge • Mean width, Mean depth, Mean dominant substrate, Mean velocity, Agriculture and urban landuse, Gradient, Basin area, Open canopy, Percent canopy	
19.	Sustainable Rivers Audit (Murray-	• Biological	• Macroinvertebrates • Fish	Sheldon & Leigh (2012)

	Darling Basin), 2012	• Water quality	• Physical: flow, pH, Temp, SS, TP, TN, salinity • Chemical: TOC and composition, DO, and Chlorophyll a, alkalinity • Residual nutrient: NOx, NH_4, DRP	
		• Hydrology (FSR)	• Mean Annual Flow • Flow Duration Curve Difference Index • Seasonal Amplitude Index • Seasonal Period	
		• • Physical Form condition	• Bed Dynamics (Channel Sediment ratio, Channel sediment depth) • Channel Form (Mean Channel width, Channel mean depth, Channel Width Coefficient of Variability, Channel depth, Coefficient of Variability, Channel Sinuosity, Channel Meander Wavelength, Channel Slope) • Bank Dynamics (Longitudinal Bank Variability, Mean Bank Complexity) • Floodplain Form (Floodplain Sediment Deposition)	
20.	EHMP, 2012	• Water quality	• Physical: Electrical Conductivity, pH, Diel change in Temp (includes max & min) • Chemical: Diel change in DO (includes max & min), δ15N(plants) • Algal bioassay	EHMP, (2000)
		• Biological	• Macroinvertebrates • fish	
		• Ecosystem processes	• Gross Primary Production • R24 • δ13C (aquatic plants)	
		• Hydrology	• Flow volume (use of gauge data) • Wetted Area (surveying, satellite data) • Current velocity (hydraulic current meters) • Channel Morphology (surveying)	
21	ISC	• Hydrology (an assessment of flow)	• Hydrologic deviation (comparison of monthly flows with • those that would have existed under natural conditions) • Percentage of catchment urbanized • Presence of any hydropower stations that cause water surges	Ladson (1999)
		• Physical form	• Bank and bed stability • Presence and influence of artificial barriers • Density and origin (i.e., exotic or native species) of coarse • woody debris (only assessed in plains streams)	

			• Stream side zone	
		• Water quality	• Physical: turbidity, salinity, Conductivity, pH • Nutrients: TP	
		• Aquatic life	• Macroinvertebrate's diversity	
		• Streamside zone	• Width of streamside vegetation • Longitudinal continuity of vegetation • Structural intactness • Cover of exotic vegetation • Presence of Regeneration of indigenous species • Conditions of Billabong condition	
22	Biophysical Ecosystem Health Report :3194 New Zealand (2018)	• Aquatic life	• Microbes • Plants • Invertebrates • Fish • Water birds	Clapkott et al. (2018)
		• Physical habitat	• Form • Extent • Connectivity • Substrate • Riparian	
		• Water quality	• Physical: Temperature, Clarity, Suspended sediments, Turbidity, • Chemical: Dissolved Oxygen, Toxicants • Nutrients, TN, Nutrient loads, dissolved P • Toxicants: Ammonia, Nitrate, Metals	
		• Water quantity	• Hydrological variability (Mean, Mean annual low flow variability, Flood magnitude, Flood Frequency) • Extent (Wetted area, velocity, depth) • Connectivity (Floodplain, groundwater)	
		• Ecological processes	• Biogeochemical Processes (GPP, ER, Cotton strip, assay, OM processing, OM, Delta 15N, Algal bioassay, Denitrification) • Biotic Interactions (Connectance, Rel ascendency, Path length, Parasitism)	
23	SDGs based RHA (2020)	• Clean Water	• Nemerow comprehensive pollution index • Water quality standard ratio of centralized drinking water sources	Xue et al. (2020)
		• Sanitation	• Centralised water supply ratio • Scale of sewage treatment facilities per • 10, 000 people	

		• Present status of Biodiversity	• Biodiversity index of phytoplankton, zooplankton, benthic animal and Fish	
		• Threats to Biodiversity	• Endemic or Indicative species retention • Disturbance index of aquatic habitat • Proportion of water reduced river reach • River connectivity • COD emissions • TP emissions	
24		• River water quality	• Chemical: Dissolved Oxygen, COD, Mn, SD, TP, NH_3-N • Chla: Chlorophyll	Xu et al. (2020)
		• Ecosystem	• P-IBI • B-IBI • Water indicator species • River bank Ecology • Emergent plant Coverage • Submergent Plant Coverage • Aquatic plant diversity • Coefficient of terrestrial vegetation	
		• Ecological Landscape	• Ecological landscape condition • Harmony with the surroundings	
25	River health index	• River Hydrology	• Flow velocity • Water yield	Peng & Su (2011)
		• River Morphology	• River change • Degree of Crook • Bank stability • Riverbed stability • Form of river revetment	
		• Condition of Riparian zone	• Width of riparian zone • Structural integrity • Longitudinal connectivity	
		• Water environment	• ratio of water up to the quality standards	
		• Aquatic organisms	• Changing rate of fish species • phytoplankton species	
26	Urban river health Analysis	• Pressure	• Ammonia emission intensity (P1) • Pesticide application intensity (P2) • Fertilizer application intensity (P3) • Water consumption per unit of GDP(P4) • Water consumption of industrial output (P5) • Water consumption of agricultural output (P6) • COD emission (P7)	Zhang et al. (2019)

			• Sewage Discharge(P8)	
		• State	• Riparian vegetation coverage rate (S1) • Stability of riverbed (S2) • Water quality compliance rate (S3) • Phytoplankton Shannon index (S4) • Fish diversity index (S5) • Longitudinal continuity (S6)	
		• Response	• Wastewater treatment rate (R1) • Daily ecological flow supplement rate (R2) • Rain and sewage diversion rate (R3) • Green space construction rate (R4) • Annual construction rate of ecological embankments (R5) • Rate of environmental protection investment to GDP (R6)	
27	River Health Status Model	• Response	• Macroinvertebrates • EPT proportion • Water Quality: pH, Cadmium (Cd), Lead (Pb), and Chlorophyll a (Chl a) Total Dissolved Solids (TSS), Surfactant's air and water temperature difference, Dissolved Oxygen (DO), Electrical Conductivity (EC), Biological Oxygen Demand (BOD), Phosphorus (P), Total Kjeldahl Nitrogen, (TKN), and oil and grease (OG).	Baltazar et al. (2016)
		• Pressure	• land use, infrastructure, and riparian vegetation	
28	Integrated Ecological River Health Assessments (Nakdong river)	• Biological health	• Fish	Kim &An (2015)
		• Chemical health	• Nutrients:TN:TP ratio, TP, TN • Physical: EC, TSS • Chlorophyll-a • Chemical: BOD, COD	
		• Physical habitat health	• epifaunal substrate/available cover, pool substrate characterization, channel flow status, existence of small-scale dams, channel alteration, sediment deposition.	
29	Integrated assessment of river health/ Liao River	• Water quality index	• Chemical: DO, CODCr, COD_{Mn}, BOD5, petroleum • hydrocarbon, volatile phenols, sulfide, lead, mercury, cadmium, TN, TP, NH_4+N, NO_3–-N, NO_2—N, • Physical: pH value, suspended solids (SS), and conductivity	Wei et al. (2009)
		• Biotic index	• hygienic parameters: includes fecal coliform • and total bacterial • attached algae	

			• benthic	
		• Physical habitat index	• substrate, habitat complexity, velocity-depth, combination, bank stability, bank conservation, vegetation cover, vegetation diversity, the intensity of human activities, water cognition, and riverside land use	
30	Integrated Approaches of Water quality for RH	• Water quality	• Physical: Temp, pH, conductivity, • Chemical: dissolved oxygen (DO), biochemical oxygen demand (BOD5), (TSS), NH_3-N, COD	Salmiati &Salim (2017)
		• Biological	• Macroinvertebrates	
		• River habitat	• Physical characterization: land use, description of the stream origin and type, • riparian vegetation • instream parameters: width, depth, flow, and substrates • Channel dimension	
31	Ecological Status of Wyoming Streams	• Chemical Stressors	• P, pH	Peterson et al. (2007)
		• Physical Stressors	• Channel dimensions • Channel gradients • substrate size and type • riparian zone components, such as riparian vegetative cover and anthropogenic alterations	
		• Biological Stresors	• Fish • Macroinvertebrate	
32.	Index of River Health	• Ecological functions	• Habitat integrity: pool variability, channel sinuosity, bank vegetation protection and channel alteration • ecosystem community structure: primary productivity of planktonic plants (*P*) and the nature reserve area (*N*)	Zhang et al. (2009)
		• Environmental functions	• Water chemistry: pH, Temp transparency • Nutrients:NO_3^-, NO_2^-, $PO4^{3-}$, DO, Chla • Chemical: COD_{Cr}, COD_{Mn}, TN, TP, NH_4^+	
		• Landscape function	• Condition of aquatic/terrestrial ecotones • Width of riparian vegetation • Aesthetics of the river/lake bank.	
		• Social service function	• Surface water ratio • Channel connectivity index • Navigability	

33.	Aquatic ecosystem health	• Biological	• Benthic macroinvertebrates	Chen et al. (2019)
		• Water quality	• TP, NH_4^{+},N, COD, BOD_5, DO	
		• Physical habitat quality	• Fow velocity and state, • water quantity, quantity of sediment in riverbed, • sediment coverage rate of silt • riparian type, • erosion degree of riparian, • riparian width, • vegetation coverage, • vegetation structural integrity, • Riparian land use pattern	
		• Biodiversity	• Macroinvertebrates • Phytoplankton • Zooplankton • Floristic diversity of riparian zone • Fish • Birds, • Dolphin • Turtles • Butterfly	
		• People livelihood		
34	Ecological health og Gin-Gin Brook	• Hydrology	• CLFT	Galvin & Storer (2012)
		• Water chemistry	• Physical: temperature, pH, specific conductivity, turbidity • Chemical: dissolved oxygen	
		• Stream Connectivity	• longitudinal surface water flow • fish movement • lateral connectivity.	
		• Biological	• Fish • Crayfish	
		• Additional Environmental data	• aquatic habitat condition (e.g., woody debris, substrate characterization, macrophytes) • catchment condition (e.g., land use, impact of cattle, sources of pollution) • physical form (e.g., erosion, channel form) • riparian vegetation (e.g., width, presence of weeds, vegetative cover) • fish passage (barrier assessments)	
35	AIM National	• Water quality	• Physical: Acidity (pH), Conductivity, Temperature, Turbidity	USEPA (2014)

	Aquatic Monitoring Framework		• Nutrients: TN, TP,	
		• Water shed functions and instream habitat quality	• Residual pool depth • Streambed particle sizes • Bank stability and cover • Large woody debris • Floodplain connectivity	
		• Biodiversity and riparian habitat quality	• Macroinvertebrate biological integrity • Ocular estimate of riparian vegetative type, cover, and structure • Canopy cover	
36	Environmental health in Yarra catchment	• Biological	• Macroinvertebrates	Bessel-Browne (2000)
		• Physicochemical sampling	• Physical: Temperature, Electrical conductivity Turbidity • Chemical: Dissolved Oxygen, Alkalinity • Nutrients: Total Phosphorus, Total Kjeldahl Nitrogen, Nitrate and Total Organic Carbon	
		• Habitat	• slope, altitude, discharge area • substrate composition, abundance of filamentous algae • riparian vegetation and river shading.	
37	Ecological Health Assessments	• Biological	• Fish	Kim et al., (2019)
		• Physical habitat	• Epifaunal; Embeddedness; Sediment deposition, Channel alteration, Channel flow status, Velocity depth ratio, Freq of riffles, Bank stability, Vegetative protection; Riparian vegetation, Dam construction	
		• Physiochemical water quality	• Physical: EC, TSS • Chemical: BOD, COD • Nutrients: TP, T N • Chla	
38	Analysis in Streams and Rivers	• Chemical Analysis	• Physical: suspended solids, specific conductivity • Nutrients: TP • Chemical: BOD	Lee et al. (2017)
		• Biological	• Fish	
		• 3Physical Habitat analysis	• Epifaunal; Embeddedness; Sediment deposition, Channel alteration, Channel flow status, Velocity depth ratio, Freq of riffles, Bank stability, Vegetative protection; Riparian vegetation; Existence of small-scale dams	

39	ICIMOD	• Biological	• Macroinvertebrate Assemblages	Rai et al. (2019)
		• Physico-chemical parameters	• Physical: temperature, turbidity, pH • chemical: nitrates, orthophosphates, TH, DO	
		• Habitat Assessment	• Epifaunal; Embeddedness, Sediment deposition, Channel alteration, Channel flow status, Velocity depth ratio, Feq of riffles, Bank stability, Vegetative protection; Riparian vegetation	
		• Socio-economic stressor		
40	Future river health	• Hydrological indices	• Runoff • fulfillment rate of ecological water demand	Zhao et al. (2019)
		• Water quality indices	• Physical: conductivity • Chemical: BOD, COD, COD_{Mn} Cl^-, DO fluoride, anionic surfactant • Nutrients: NH_3-N, sulfide, SO_4^{2-}, TP, TN	
		• Habitat Indices	• embankment stability; river meandering coefficient, • the riparian vegetation coverage, the habitat complexity; riverbed • substrate, types of riparian land use, a combined, characteristic of rate and depth, riparian zone width, embankment, rebuilding degree, and non-point source pollution intensity	
41	Star project WFD	• Biological quality elements	• aquatic flora: phytobenthos (Diatoms), macrophyte • benthic invertebrate fauna • fish fauna	Furse et al. (2006)
		• Hydromorphological quality element	• Flow type, Flow types only found in sweeps up • Channel substrate, Channel feature(s) (spot-checks), Channel features only found in sweep-up, Marginal & Bank features (spot-checks) • Bank features only found in sweep up, Vegetation structure (Bank-face) • Vegetation structure (Bank-to top), Point bars, Channel vegetation types, Land-use within 50 m of banktop (Sweep-up), Extent of trees (Sweep-up) Associated features, Features of special interest	
		• Physico-chemical quality elements	• Physical: pH, Conductivity • Chemical: BOD_5, Dissolved Oxygen • Nutrients: Ammonium Nitrite, Nitrate, Ortho-phosphate, Total phosphate, Source pollution	

			(Y/N), Non-source pollution ((Y/N), Eutrophication (Y/N)	

NOTE: *COD_{Mn}: Permanganate salt index; Chla : chlorophyll ; TP: Total phosphorus ; NH_3-N: ammonia nitrogen; SD: water; IBI: index of biological integrity; P-IBI :Phytoplankton index of biological integrity; TN:Total Nitrogen; Large woody debris (LWD), ammoniacal nitrogen (NH_3-N); COD_{Cr} chemical oxygen demand ; Soluble Reactive Phosphate (SRP); HAZ: Hydrologically Active Zone*

Annex-2 Climatic models and scenarios used in climate change-related studies in Nepal

S. N	River Basin/Watershed	Climate model(s)	Scenarios	Time period	Focus	References
1	• Bagmati	• HadCM3	• SRES - A2; B2	B:1970–1999 NF: 2010–2039 MF:2040–2069 FF:2070–2099	• Climatic models and scenarios used in climate change-related studies in Nepal	Babel et al. (2013)
2	• Bagmati	• HadCM3	• SRES - A2; B2	Future decades:2020; 2050; 2080	• Climate change impact on irrigation water requirement	Shrestha et al. (2013)
3	• Chamelia	• ACCESS_CCAM • CNRM_CCAM • MPI.ESM_CCAM • MPI.E.MPI_REMO • ICHEC_RCA4	• RCP - 4.5; 8.5	B: 1980-2005 NF: 2021–2045 MF:2046–2070 FF: 2071–2095	• Climate Change impact on hydrology	Pandey et al. (2019)
4	• Dudhkoshi	• PRECIS	• SRES - A1B	B: 2000–2010 NF:2040–2050 FF:2086–2096	• Climate change impact on hydrological regime	Nepal (2016)
5	• Hindukush Himalaya	• PRECIS	• SRES - A1B	NF:2011-2040, MF:2041–2070 FF:2071–2098	• Climate change	Kulkarni et al. (2013)

6	• Hindukush Himalaya	• CMIP3 • CMIP5	• SRES - B1, A1B and A2 for CMIP3 • RCP 8.5 for CMIP5	B:1970-1999 MF:2020–2049 FF: 2070–2099	• Change and trends of temperature and precipitation indices	Panday et al. (2015)
7	• Indrawati	• ECHAM4/OPYC3 • HadCM3 model	• SRES - A2; B2	B: 1961-1999 Future decades: 2020; 2050; 2080	• Climate change impact on Flow regime	Bhatta (2016)
8	• Indrawati	• HadGEM3-RA • MIROC-ESM • MRI-CGCM3	• RCP – 4.5; 8.5	B: 1995–2004 Future decades: 2020; 2030; 2040; 2050; 2060; 2070; 2080; 2090	• Climate change impact on hydrology and water availability	Shrestha et al. (2016d)
9	• Kaligandaki	• GCM • CMCC-CMS	• RCP - 4.5; 8.5	B:1981–2010 F: 2041–2070 FF: 20712100	• Climate change impact on hydrological regime and water balance	Bajracharya et al. (2018)
10	• Karnali	• GCM from CanESM2	• RCP - 2.6; 4.5; 8.5	NF:2011-2040 MF:2041-2070 FF:2071-2100	• Climate change	Shrestha et al. (2016b)
11	• Koshi	• CNRM-CM3 • CSIRO-Mk3.0 • ECHam5 MIROC 3.2	• SRES - A2; B1	B: 1971-2000 F: 2016-2045	• Climate change imp act on hydrological regime	Bharati et al. (2012)

12	• Koshi	• GCMs (10)	• SRES - B1; A1B; A2	Three future periods: 2020s; 2055s; 2090s	• Precipitation projection	Agarwal et al. (2014)
13	• Koshi	• CSIRO-Mk3.5 • ECHam5 • MIROC3. • CNRM-CM3	• SRES - A2; B1	B: 971–2000 NF:2016-2045 FF:2036–2065	• Climate change impact on water availability	Bharati et al. (2014)
14	• Koshi	• PRECIS-HADCM3Q • PRECIS-ECHAM05	• SRES - A1B	B:1976-2000 F:2040–2060	• Climate change • Hydrological regime.	Devkota and Gyawali (2015)
15	• Koshi	• CNRM-CM3 • CSIRO-Mk3.5 • ECHam5 MIROC3.2	• SRES - A2; B1	B:1971-2000 NF:2030 FF:2050	• Climate change impact on hydrological regime	Bharati et al. (2016)
16	• Koshi	• GCMS (10)	• SRES - B1; A1B; A2	NF:2011–2030 MF:2046–2065 FF:2080–2099	• Climate projection	Agarwal et al. (2016)
17	• Koshi: Tamor, Arun, Dudhkoshi, Tamakoshi, Sunkoshi	• PRECIS-ECHAM05 • PRECIS-HadCM3	• SRES – A1B	B: 2000-2008 F: 2041-2060	• Climate change • Snowmelt hydrology	Khadka et al. (2016)
18	• Koshi	• CMIP5 GCMs (8)	• RCP - 4.5; 8.5	B:1961-1990 F: 2021-2050	• Projection of future climate	Rajbhandari et al. (2016)
19	• Koshi	• PRECIS	• SRES - A1B	NF:2011-2040 MF:2041-2070 FF: 2071-2098	• Project future extreme climate	Rajbhandari et al. (2017)

20	• Kulekhani	• CCSR/NIE • CGCM3 • CSIROECHM4 • HadCM3	• SRES - A2; B2	B:2010–2039 NF:2040-2069 FF:2070–2099	• Climate change impact on future river discharge	Shrestha et al. (2014)
21	• Marshyangdi	• GCM SDSM (4.2)	• SRES - A1B	Future decades: 2030-2050, 2080	• Future water availability • Change in rainfall pattern	Parajuli et al. (2015)
22	• Marshyangdi	• CanESM2	• RCP - 2.6; 4.5; 8.5	NF:2011–2040 MF:2041–2070 FF: 2071–2100	• Climate change projection	Khadka and Pathak (2016)
23	• Narayani	• HadCM3 • PRECIS RCM	• SRES - AIB	B: 1970-2000 F: 2030-2060	• Climate change impact on hydrology • Future flood magnitude	Bhattarai et al. (2018)
24	• Sunkoshi	• PRECIS • ECHAM5 • RegCM4 • ECHAM4	• SRES - A1B; A2	NF:2041-2050 FF:2051- 2060	• Climate change impact on hydrology	Magar et al. (2016)
25	• Tamakoshi	• HADCM3 • CGCM3	• SRES - A2 &B2; A2 &A1B	B:2000-2009 F:2000 -2059	• Future change in climate	Khadka et al. (2014)
26	• Tamakoshi	• MIROC-ESM, MRI • CGCM3 • MPI-ESM M	• RCP - 4.5; 8.5	NF:2015–2039 MF:2040–2069 FF:2070–2099	• Climate change impact in hydropower	Shrestha et al. (2016c)

27	• West Seti	• ECHAM5 • HadCM3 in PRECIS • Era40, CCSM • ECHAM5 GFDL • HadCM3 in WRF	• SRES - A1B	B: 1971 -2000 F: 2031 -2060	• Climate change impact on water balance and crop yields	Gurung et al. (2013)
28	• West Seti	• WRF/ GRADS	• RCP - 4.5	B:1996-2013 F: 2050	• Impact of climate change on water availability and future flow	Maharajan et al. (2016)
29	• West Seti	• MPI-ESM-LR • PRECIS-1 • NorESMI1-M • ICHEC-EC-EARTH • CCM4 • CNRM-CM5 • MPI-M-MPI • ESM-LR	• RCP- 4.5; 8.5	B:1976-2005 F :2071-2100	• Streamflow projection	Shrestha (2017)

Note: B: Baseline; F: Future; FF: Far Future; MF: Mid Future; NF: Near Future; RCP: Representative Concentration Pathway; SRES: Special Report on Emission Scenarios

Annex-3 River health assessment framework adopted in this study

Component	Indicator (s)	Metrics	Significance to River Health	Method	Reference
C1: Hydrology	Flow Health Index (FHI)	High Flow Volume (HFV)	• Reflects prevailing natural hydrological conditions, particularly highlighting dry years; indicates major reductions in total flow volume and availability of gross habitat area due to flow regulation	Flow Health Index is calculated by aggregating nine sub-indices, after normalizing them in a range of 0-1. The FHI ranges from 0-1; with 1 indicating a low degree of deviation from the reference hydrology, and therefore better river health condition.	• Leigh et al. (2012) • Speed et al. (2012)
		Highest Monthly Flow (HMF)	• Higher value (near to 1) refers to the potential for inundating wetlands, cuing fish spawning behavior, facilitating fish migration and mobilizing sediment for creation of physical habitat		
		Low Flow Volume (LFV)	• Occurrence of a month of very low flow can be problematic for the biota for its survival at any time of the year		
		Lowest Monthly Flow (LMF)	• Minimum flows are required for survival and critically important to river health especially during the time of lowest flow		
		Persistently Higher Flow (PHF)	• Relates to the situation of artificial regulation of flows. PHF reduces penetration of light to the bed and reduces primary production of benthic algae. It also means that invertebrates are not stressed seasonally thus maintaining diversity.		

		Persistently Lower Flow (PLF)	• PLF would potentially allow colonization of the stream bed by invasive vegetation, or accumulation of fine sediments that settle out during periods of low flow. It has implications for gross habitat area availability for fish and macroinvertebrates		
		Persistently Very Low (PVL)	• PVL is often associated with loss of riffle habitats, crowding in pools and degraded water quality, such as temperature extremes and increased risk of hypoxia and high salinity.		
		Seasonality Flow Shift (SFS)	• Higher value (~1) indicates disruption of natural timing of flow pulses and baseflows that stimulate the behavior of aquatic organisms whose life cycle has adapted to a particular seasonal pattern of flow.		
		Flow Flood Interval (FFI)	• FFI refers to a period over which there would be no negative ecological impacts. Higher value (~1) of FFI indicates better river health.		
C2: Water Quality	Chemical	Dissolved oxygen (DO)	• Adequate supply of dissolved oxygen (5mg/L) is important for the sustenance of aquatic life. It influences microbial activity and chemical oxidation state of various metals, such as iron	In-situ/field measurement Lab	• USEPA (2014); • Rinella et al. (2008) • Furse et al. (2006) • Galvin &Storer (2012) • Dinger et al. (2013) • Jang &An (2016) • Leigh et al. (2012) • Speed et al. (2012) • Storer et al.(2011)
		Chloride ($Cl^{-)}$	• Higher(>500mg/L) chloride content may cause corrosive effect on metal pipes, structures and is harmful to most trees and plants		

		COD	• It is an estimate the organic pollution in water. Low COD values is required to sustain aquatic life		• Su et al. (2019) • Condon et al. (2007) • Wolf & Koch (2019) • Wessell et al. (2008) • USEPA (2013) • Souter et al. (2018) • Babel (2018) • Brown &May (2000) • Sheldon & Leigh (2012) • Clapkott et al. (2018); • Wei et al. (2009) • Salmiati et al. (2017) • Peterson et al. (2007) • Miller et al. (2015) • Bessel-Browne (2000) • Kim & An (2019) • Lee et al. (2017) Rai et al. (2019) • Ladson et al. (1999) • Zhao et al. (2019)
		BOD	• The decay of organic matter in water is measured as biochemical oxygen demand. Higher its value lower DO thus affect aquatic life.		
		Calcium ions (Ca^{++})	• These are essential element for organism, its concentration may rise up to 100ml/l in areas of carbonate rich rocks.		
		Sodium ions (Na+)	• Exceeding 200mg/L in water may indicate the possibility of sewage effluents or industrial discharges effecting the aquatic organisms.		
		Potassium ions (K)	• Its concentration in natural water is below 10mg/L, therefore higher concentration in water indicates heavy weathering in the region		
		Total Alkalinity (TA)	• Lower alkalinity may result change in pH even with small addition of acid. Higher (>300 mg/L) will not adversely affect fish, but such high values will render some commonly used chemicals, such as copper sulfate, ineffective.		

		Total Hardness	• It represents total calcium and magnesium ions concentration present in the water. • Animals may suffer from mobidity/ mortality when there is sudden change in hardhness of water from hard (>120mg/L) to soft (<60mg/L).		
		Sulphate (SO_4^{2-})	• Causes hardness in water therefore high levels (>250mg/L) are not recommended.		
		pH	• pH affects biological and chemical processes in water body. The pH>8.5 increases the toxicity of ammonia to fish, whereas low pH<6.5 increases toxicity of aluminum and copper		
		Total dissolved solids (TDS)	• TDS (<500mg/L) ensure safety from almost all inorganic constituents; higher TDS reduces amount of light penetrating the water thus affecting photosynthetic activity and may increase water temperature combining with toxic compound and heavy metals.		
		Conductivity (EC)	• Conductivity is a good and rapid measure of the total dissolved solids hence any changes in conductivity (>1000 µs/cms) indicates discharge or some other source of pollution in a water body and also affect the aesthetic value of water due to mineral taste of water.		
	Nutrients	Nitrate (NO_3^-)	• Higher (> 45 mg/L) nitrate could deplete amount of DO in water which in turn affects biomass and species diversity of aquatic organism. It may also cause eutrophication.		

		Total phosphate (TP)	• Higher TP (>0.05mg/L) affect algae growth and water clarity, in turn affecting swimming, boating, fishing and aesthetic enjoyment.		
		Ammonia (NH_3)	• Ammonia in high pH (i. e., more alkaline water) is more toxic to aquatic biota and are detrimental to the ecological balance of water bodies. Higher value (>1.2mg/L) causes eutrophication in water.		
		Phosphate (PO_4^{3-})	• Excessive phosphate (>0.1mg/L), an important plant nutrient, may cause eutrophication.		
C3: Biological Condition	Macroinvertebrates	Diversity index	• Diversity includes measures of both richness and evenness, as well as evenness of species and values, ranging between 0 and 5, with a higher value representing better diversity and therefore better river health.	Multi-metric indices	• Jared et al. (2015) • USEPA, (2014) • Rinella et al. (2008) • Furse et al. (2006) • Denger et al. (2013) • Jang et al. (2016) • Leigh et al. (2012) • Scherman et al. (2004) • Speed et al. (2012) • USEPA, (2013) • Wolff & Koch (2019) • Wessell et al. (2008)
		Biotic index	• It indicates taxon's sensitivity to organic pollution and is expressed in terms of water quality class (I –V); with class I indicate better river health.		
		EPT Richness	• Composition measure is reflected in terms of EPT index. EPT are intolerant to pollutants, therefore, higher EPT index indicates clean (or less polluted) water and therefore better river health.		
		Total richness	• Higher the total number of taxa (or tax richness), there is better interaction among themselves and can be considered as better health.		
		Total abundance	• Abundance represents a total number of individuals; higher abundance indicates better river health.		

					• Brown & May • (2000) • Sheldon & Leigh (2012) • Clapkott et al. • (2018) • Peng &Su (2018) • Kim & An (2015) • Chen et al. (2019) • Salmiati et al. (2017) • Jared et al. (2015) • Peterson et al. (2007) • Bessel-Browne (2000) • Kim &An • (2019) • Lee et al. (2017)
C4: Physical Condition	Habitat condition	Epifaunal substrate/ available cover	• A wide variety and/or abundance of submerged structures in the stream provides macroinvertebrates with many niches, thus increasing habitat diversity and improving river health.	RBP Protocol (Barbour et. al (1999)	• Kim et al. (2015) • Wei et al. (2009) • Kim & An (2019 • Lee & An (2017) • Rai et al. (2019)
		Embeddedness	• Provides a surface area to macroinvertebrates for shelter, spawning, and egg incubation and improves river health		

		Sediment deposition	High levels of sediment deposition indicate an unstable and continually changing environment which becomes unsuitable for many organisms and deteriorates river health		• Zhao et al. (2019)
		Channel alteration	• Disrupts the natural habitat of the macroinvertebrates and deteriorates river health		
		Channel flow status	• Provides status of the biological condition under abnormal or lowered flow conditions; wide variation in channel flow status deteriorates river health		
		Velocity depth ratio	• The presence of all flow patterns (slow/shallow to fast/deep) provides and maintains a stable aquatic environment and improves river health		
		Frequency of riffles	• Increased frequency of riffles occurrence greatly enhances the diversity of the stream community and improves river health		
		Bank stability	• The unstable bank may result in high turbidity, more deposition, loss of riparian vegetation, and alteration of hydrological regime, and therefore deteriorates river health		
		Vegetative protection	• Well-protected vegetative banks stabilize the bank, protect against soil erosion, and therefore, control instream scouring, and provide stream shading. It improves river health.		

		Riparian vegetation	• Serves as a buffer to pollutants entering a stream from runoff, controls erosion, and provides habitat and nutrient input as well as breeding grounds for macroinvertebrates. It improves river health.		

Notes: DO is Dissolved Oxygen; COD is Chemical Oxygen Demand; EC is electrical conductivity; Cl is Chloride, E: Ephemeroptera; P: Plecoptera; T: Trichoptera

Annex-4 Score for classification of river health

Score	Description	Remark
0.80 - 1.0	Largely ummodified	Excellent
0.60 - 0.79	Slightly modified	Good
0.40 - 0.59	Moderately modified	Moderate
0.20 - 0.39	Substantially modified	Poor
0.00 - 0.19	Severely modified	Very Poor

Annex-5.1 Correlation between water quality indices for the pre-monsoon 2019

	pH	EC	TDS	DO	TH	Ca Hard	Mg Hard	COD	BOD	TA	Cl^-	NO_3^-	PO_4^{3-}	TP	$S04^{2-}$	NH_3	K	Na^+	Ca^{++}
pH	1																		
EC	.17	1																	
TDS	.21	.93**	1																
DO	-63**	.06	-.09	1															
TH	.05	.68*	.60**	.00	1														
Ca hard	.05	.68**	.60**	.00	1.0**	1													
Mg	-.05	-.25	-.17	.28	-.47*	-.47*	1												
COD	.14	.24	.32	-.03	-.16	-.16	.35	1											
BOD	.14	.24	.32	-.03	-.16	-.16	.35	1.0**	1										
TA	.14	.60**	.61**	-.01	.77**	.77**	-.35	-.08	-.08	1									
Cl-	-.03	.46*	.52*	.23	.17	.17	-.17	.16	.16	.28	1								
NO_3^-	-.13	.21	.09	.02	.39	.39	-.37	.10	.10	.24	.15	1							
PO_4^{3-}	-.11	-.10	-.05	-.12	.09	.09	-.33	.01	.01	.08	-.02	.39	1						
TP	.03	.14	-.03	.28	.12	.12	-.05	-.22	-.22	-.11	.05	-.12	-.22	1					
$S0_4^{2-}$	-.56**	.18	.21	.46*	.20	.20	.15	-.14	-.14	.05	.10	-.08	-.27	.10	1				
NH_3	.11	.07	.12	.25	-.36	-.36	.54*	.63**	.63**	-.25	.04	-.25	-.35	-.18	.18	1			
K	.05	-.69**	-.68**	-.22	-.49*	-.49*	.10	-.30	-.30	-.65**	-.34	-.13	-.03	.20	-.11	-.06	1		
Na^+	.02	.16	.19	-.11	-.15	-.15	-.08	-.03	-.03	-.25	.11	-.18	-.29	.32	.35	.04	.15	1	
Ca^{++}	.00	-.23	-.14	.07	-.20	-.20	.05	-.03	-.03	-.30	.14	-.12	-.19	.22	.35	.12	.22	.50*	1

Annex-5.2 Correlation between water quality indices for the post-monsoon

	pH	EC	TDS	DO	TH	Ca Hard	Mg Hard	COD	BOD	TA	Cl^-	NO_3^-	PO_4^{3-}	TP	SO_4^{2-}	NH_3	K	Na^+	Ca^{++}
pH	1																		
EC	0.54**	1																	
TDS	0.54*	0.98**	1																
DO	-0.06	0.29	0.28	1															
TH	0.59**	.92**	0.90**	0.26	1														
Ca Hard	0.46*	0.90**	0.87**	0.22	0.83**	1													
Mg Hard	0.28	0.60**	0.60**	-0.02	0.40	0.58**	1												
COD	-0.53	-0.09	-0.14	0.13	-.10	-0.05	0.21	1											
BOD	-.0.53	-0.09	-0.14	0.13	-.10	-0.05	0.21	1.00**	1										
TA	0.11	0.24	.22	0.02	.12	0.25	0.38	0.25	0.25	1									
Cl-	-0.22	-0.03	-.06	-0.29	-.18	0.05	0.35	0.04	.04	0.25	1								
NO_3^-	-0.19	0.36	.43	-.06	.23	0.41	0.34	0.15	0.15	0.08	0.23	1							
PO_4^{3-}	-0.34	-0.50*	-0.47*	.07	-0.49*	-0.46*	-0.52*	-0.30	-0.30	-0.29	-0.18	-0.35	1						
TP	0.00	-0.26	-.17	-.29	-.33	-0.39	-.008	-.24	-.24	-0.22	0.03	0.15	0.17	1					
SO_4^{2-}	0.43*	0.53*	.52*	.00	.536*	0.30	0.22	0.03	0.03	0.35	-0.40	-.02	-0.40	-0.10	1				
NH_3	-0.07	-.014	-0.19	0.11	-0.09	-0.02	-0.07	0.24	0.24	0.06	-.06	-.44	-0.07	-0.13	.10	1			
K	0.10	-.42	-.39	-.21	-0.46*	-0.56**	-0.05	-0.15	-.15	.17	-.04	-.43	0.10	0.41	.09	.47*	1		
Na^+	-0.42	0.02	0.01	.21	-0.04	0.03	-0.17	-0.04	-0.04	-0.42	0.10	.01	0.44*	-.10	-.29	-.22	-.33	1	
Ca^{++}	0.18	0.81**	0.79**	0.24	0.66**	.88**	.68**	.08	.08	.24	.32	.52*	-.35	-.33	.12	-.28	-.58	.27	1

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Annex-6 Standard values of water quality parameters for aquatic ecosystem

Parameters	Permissible limit	Reference
DO	**5**	DoI/GoN (2008); CCME, (2001)
pH	6.5-9	; CCME, (2001)
EC	1000	BBWMSIP (1994) in Regmi *et al.*, (2017); BIS, (2012)
NH_3	1.2	DoI/GoN (2008)
NO_3^-	45	CCME, (2001)
PO_4^{3-}	0.1	BBWMSIP (1994) in Regmi et al. (2017); USEPA (1986)
Cl^-	500	BBWMSIP (1994) in Regmi et al. (2017)
COD	<20	Chapman, (1996), DoI/GoN (2008)
SO_4^{2-}	200	BIS, (2012)
TA	200	BIS, (2012)
BOD	<15	DoI/GoN (2008)
TH	>180	DoI/GoN (2008)
TP	<0.05	CCME, (2001)
Mg Hardness	30	BIS, (2012)
Ca Hardness	70	BIS, (2012)
TDS	1000	BBWMSIP (1994) in Regmi et al. (2017)
Ca^{++}	100	BIS, (2012)
Na	200	BIS, (2012)
K +	<10	BIS, (2012)

Annex-7 Environmental variables for prediction of the potential distribution of macroinvertebrates in Marshyangdi Watershed

Type of variables	Variable	Description	Source	Unit
Bioclimatic	Bio 1	Annual mean temperature	WorldClim	ºC
	Bio 4	Temperature seasonality (standard deviation* 100)	WorldClim	Dimensionless
	Bio17	Precipitation of driest quarter	WorldClim	mm
Topographic				
	SLO	Slope	Calculated from elevation	%
	ALT	Elevation	SRTM	m
	ASP	Aspect	Calculated from elevation	^{0}C

Annex 8: Projected seasonal variation in climate at Gorkha Station with respect to baseline

		Tmax (°C)				Tmin (°C)					PPT (average annual,mm)				
Variable		**RCP4.5**		**RCP8.5**			**RCP4.5**		**RCP8.5**			**RCP4.5**		**RCP8.5**	
Period	**BA**	**NF**	**MF**	**NF**	**MF**	**BA**	**NF**	**MF**	**NF**	**MF**	**BA**	**NF**	**MF**	**NF**	**MF**
Annual	26.7	25.9	26.6	26.3	26.9	16.0	0.2	16.8	16.6	17.2	1698	1747	1777	199	1789
DJF	20.2	20.1	20.4	20.0	20.9	9.2	0.5	10.3	10.0	10.6	1230	72	98	30	82
MAM	29.0	28.0	28.1	28.2	28.6	16.7	6.2	17.5	17.3	17.9	2567	330	346	52	358
JJAS	30.2	30.0	30.3	30.1	30.5	21.2	11.1	22.0	21.6	22.5	5573	1271	1254	86	1263
ON	25.6	25.3	25.9	25.6	26.0	14.6	4.8	15.4	15.2	15.8	9473	73	79	30	86

Annex 8.1: Projected seasonal variation in climate at Chame Station with respect to baseline

Variable		Tmax (^{0}C)				Tmin (^{0}C)					PPT (average annual,mm)				
		RCP4.5		RCP8.5			RCP4.5		RCP8.5			RCP4.5		RCP8.5	
Period	**BA**	**NF**	**MF**	**NF**	**MF**	**BA**	**NF**	**MF**	**NF**	**MF**	**BA**	**NF**	**MF**	**NF**	**MF**
Annual	17.2	17.3	17.7	29.8	17.7	4.5	6.1	6.5	6.2	7.0	1193	1219	74	219	219
DJF	11.7	12.0	12.5	12.0	12.5	5.1	0.5	0.6	0.5	0.8	2346	139	1	40	426
MAM	18.5	18.4	18.7	18.5	18.7	5.6	6.3	6.5	6.2	7.2	4633	258	19	59	838
JJAS	20.5	20.7	21.0	20.8	21.0	5.8	10.9	11.7	11.1	12.4	9170	738	44	85	1660
ON	16.9	16.8	17.3	17.3	17.3	5.8	4.4	5.0	4.8	5.3	18265	84	10	35	3300

Annex 8.2: Projected seasonal variation in climate at Thakmarpha Station with respect to baseline

Variable		Tmax (^{0}C)				Tmin (^{0}C)					PPT (average annual,mm)				
		RCP4.5		RCP8.5			RCP4.5		RCP8.5			RCP4.5		RCP8.5	
Period	BA	NF	MF	NF	MF	BA	NF	MF	NF	MF	BA	NF	MF	NF	MF
Annual	17.2	17.5	26.6	17.5	18.4	5.4	6.5	7.3	6.6	18.4	410	456	485	484	466
DJF	11.9	12.4	20.4	12.2	13.8	-1.3	0.6	1.0	0.6	13.8	322	39	49	52	49
MAM	17.6	18.1	28.1	17.9	19.1	4.8	5.8	6.7	5.7	19.1	644	105	132	109	116
JJAS	21.3	21.4	30.3	21.5	21.9	12.1	12.74	13.7	12.9	21.9	1306	260	251	266	242
ON	16.1	16.1	25.9	16.6	17.1	3.2	4.0	4.7	4.1	17.1	2330	52	54	57	59

Annex-9 Average annual precipitation (mm) at all the stations within and surrounding of a Marshyangdi Watershed

Year	802	809	816	604	806	807	808	823	820	608	824
1983	3175	2070		488	968	2428	2378	2850	488	171	3572
1984	3736	1827		338	1073	2362	2915	3016	384	362	4209
1985	4133	2003		464	1126	2203	1823	2889	627	487	3507
1986	3595	1870		406	0	2490	1867	3183	581	394	4025
1987	3519	1684		480	1140	2999	721	3709	510	173	3709
1988	3523	1140		409	1976	2276	1732	4433	459	300	4433
1989	3346	1976		405	1976	1665	2486	3720	518	175	3720
1990	3480	1798	956	362	1798	2012	2037	4419	312	147	4419
1991	3257	1368	1004	315	1368	1310	982	3201	360	185	3201
1992	2667	1005	796	288	1005	979	537	2666	243	172	2666
1993	3259	1448	798	417	1448	1390	2111	3328	333	202	3328
1994	3194	2190	749	344	2190	1397	1148	3465	519	249	3465
1995	3486	2282	1320	0	2282	1889	1339	4449	473	181	4449
1996	4436	1936	1165	484	1936	1414	969	3809	328	235	3809
1997	3327	1512	1221	612	1362	1930	1013	3714	649	167	3714
1998	3549	842	3198	433	728	522	1114	3899	433	165	3899
1999	3436	1942	751	374	1942	2020	720	3484	2254	364	3484
2000	3545	1685	593	293	1685	2263	714	4575	248	145	4575
2001	3140	1872	530	382	1872	1770	734	3741	371	221	3741
2002	3304	1743	909	430	1743	1500	537	3724	379	178	3724
2003	3849	1729	899	475	1729	1883	577	4316	491	125	4316
2004	4141	1613	974	316	1613	1739	490	3795	325	232	3795
2005	2838	1277	1174	430	1277	814	2	3331	400	126	3331
2006	2852	1114	947	360	1114	1618	649	3410	275	246	3410
2007	3372	1763	1683	458	1763	2700	672	3707	446	246	3707
2008	3690	1473	1017	422	1473	1949	522	4192	393	394	4192
2009	2642	1476	482	347	1476	2020	612	3001	208	157	3001
2010	3281	1900	1235	436	1900	2148	819	4309	280	349	4309
2011	3338	1999	901	319	1999	2251	0	3716	233	333	3716
2012	3099	1896		419	1896	1684	910	4341	244	269	4341
2013	2668	1983		506	1983	1598	457	3641	0	392	3641

Note: 802 is Khudi; 809 is Gorkha; 816 is Chame;604 is Thakmarpha; 806 is Larke Sambdo;807 is Kunchha; 808 is Bandipur;823 is Gharedunga;820 is Manang Bhot;608 is Ranipauwa; 824 is Siklesh Stations respectively

Annex-10 Seasonal streamflow at the Marshyangdi Watershed (mm)

	Annual (%)	DJF	MAM	JJAS	ON
Baseline	296	86	142	573	280
RCP 4.5 NF	342(16)	133	187	608	350
RCP 4.5 MF	334(13)	132	186	595	332
RCP 8.5 NF	340(15)	135	180	608	345
RCP 8.5 MF	330(12)	135	180	592	325

Note:NF is near future; MF is mid future; RCP is Representative Concentration Pathways

Annex-10.1 Seasonal streamflow at sampling sites in future with respect to baseline (m^3/s)

	RCP4.5NF				**RCP8.5NF**			
Site	**DJF**	**MAM**	**JJAS**	**ON**	**DJF**	**MAM**	**JJAS**	**ON**
M1	1.5	1.3	2.2	2.0	1.5	2.7	2.3	0.5
M2	5.9	5.0	8.3	7.5	5.7	10.4	8.8	1.8
M3	10.3	9.6	16.2	13.1	10.4	18.7	15.5	3.1
M4	62.3	91.0	127.2	76.2	9.6	16.2	13.1	15.1
M5	63.2	92.3	129.1	77.3	97.8	146.3	93.0	15.3
M6	79.0	117.7	192.2	101.6	110.5	193.1	108.8	23.2
M7	89.5	134.8	258.0	133.9	125.7	259.4	140.3	30.8
M8	5.2	9.6	34.7	17.6	8.6	34.7	17.8	4.7
M9	98.5	148.4	307.5	177.9	136.6	310.2	183.9	39.2
M10	99.1	149.5	309.6	179.1	137.5	312.3	185.2	1.6
M11	8.2	16.5	83.7	20.9	16.8	85.5	20.9	7.7
M12	108.5	164.5	399.1	215.8	151.8	404.6	221.9	48.4
M13	1.6	3.4	14.5	2.9	3.9	14.7	3.0	2.1
M14	7.1	11.5	66.6	19.6	11.9	68.8	19.0	8.1
M15	109.7	164.3	450.3	239.8	154.2	457.7	244.7	55.7
M16	1.9	2.9	11.1	3.0	3.5	11.2	2.9	1.9
M17	107.2	146.6	422.4	264.2	138.3	430.0	267.3	55.4
M18	108.9	149.2	429.6	267.6	140.5	436.9	271.7	56.3
M19	11.6	19.3	98.8	28.2	19.0	101.5	28.3	12.3
M20	27.2	74.9	474.9	79.6	180.4	607.6	345.2	77.7
M21	27.2	74.9	474.9	79.6	180.4	607.6	345.2	77.7

Sites	**RCP 4.5MF**				**RCP 8.5MF**			
	DJF	**MAM**	**JJAS**	**ON**	**DJF**	**MAM**	**JJAS**	**ON**
M1	1.5	1.3	2.4	2.0	1.5	1.3	2.4	2.0
M2	5.6	4.8	9.2	7.5	5.5	4.8	9.2	7.5

M3	9.8	9.2	17.4	13.1	9.6	9.0	17.1	13.0
M4	66.5	97.1	135.7	81.3	66.8	91.8	136.7	82.2
M5	67.5	98.5	137.8	82.5	67.8	93.2	138.8	83.4
M6	75.8	113.3	190.0	99.7	75.4	106.4	185.2	97.4
M7	85.9	130.1	255.4	131.0	85.2	122.4	250.4	127.2
M8	5.0	9.4	34.7	17.1	4.8	8.8	34.6	16.3
M9	94.5	143.6	305.3	173.6	93.3	134.8	300.8	167.7
M10	95.2	144.5	307.3	174.7	94.0	135.7	302.8	168.8
M11	7.9	16.3	83.6	20.6	7.8	16.1	83.6	20.3
M12	104.2	159.5	397.0	210.5	103.2	150.6	392.1	204.0
M13	1.6	3.4	14.5	3.0	1.6	3.4	14.5	3.0
M14	6.8	11.3	67.0	19.3	6.8	11.4	66.8	19.5
M15	105.3	159.7	448.9	233.9	104.1	152.6	444.0	227.5
M17	1.8	2.8	10.9	3.0	1.8	2.8	10.9	3.0
M18	102.9	142.6	421.5	256.9	101.6	137.3	416.4	250.7
M19	104.5	145.0	428.3	261.1	103.3	139.5	423.1	254.8
M20	11.1	19.1	99.0	27.8	10.9	19.3	99.3	27.9
M21	132.2	185.9	594.9	332.3	130.6	179.7	589.3	325.3

Annex-11 Degree of hydrologic alterations of IHA parameters at Bimalnagar Hydrological Station for future (RCP 4.5)

Parameters	**Pre-Impact**	**C.D**	**Post Impact**	**C.D**	**P (%)**	***HA (%)***
Group #1 (Magnitude of monthly water conditions, m^3/s) Parameters						*122(H)*
January	50	0.09	109	0.51	116.7	16.4
February	43	0.16	124	0.63	187.3	44.4
March	43	0.20	143	0.55	229.6	44.4
April	50	0.26	166	0.56	231.2	86.6
May	71	0.58	202	0.47	182.6	44.4
June	198	0.38	304	0.47	53.9	156.8
July	414	0.70	598	0.19	44.5	44.4
August	648	0.25	675	0.13	4.1	16.4
September	390	0.24	541	0.09	38.6	156.8
October	167	0.26	389	0.48	132.9	156.8
November	94	0.21	251	0.64	167.7	20.4
December	63	0.08	115	0.57	82.4	164.8
Group #2 (Magnitude and duration of annual water extreme conditions, m^3/s) Parameters						*116(H)*
1-day minimum	39	0.17	97	0.57	44.5	3.7
3-day minimum	40	0.17	98	0.55	4.1	16.4
7-day minimum	41	0.17	99	0.55	38.6	44.4
30-day minimum	43	0.17	105	0.63	132.9	44.4
90-day minimum	46	0.15	118	0.64	167.7	44.4

1-day maximum	1090	0.26	1417	0.38	82.4	44.4
3-day maximum	966	0.21	1092	0.23	116.7	16.4
7-day maximum	837	0.31	926	0.21	187.3	44.4
30-day maximum	674	0.28	777	0.15	229.6	156.8
90-day maximum	525	0.27	663	0.13	231.2	156.8
Baseflow index	0.20	0.18	0.28	0.30	45.4	16.4
Group #3 (Timing of annual extreme, days) Parameters						*39(M)*
Date of minimum (Jmin)	73	0.09	17	0.12	-77.4	47.5
Date of maximum (Jmax)	207	0.13	204	0.10	-1.4	44.4
Group #4 (Frequency and duration of high and low pulses, numbers) Parameters						*59(M)*
Low pulse count	4	1.13	0	0.00	-100	41.4
Low pulse duration	6	2.64	6	3.25	9	78.9
High pulse count	3	1.50	1	2.00	-67	47.5
High pulse duration	5	9.25	144	0.85	2770	16.4
Group #5 (frequency and rate of change of water, m^3/s) Parameters						*37 (M)*
Rise rate	8	0.56	7	0.44	-11.4	16.4
Fall rate	-3	-0.32	6	-0.33	-89.52	54.1
Number of reversals (number)	137	0.22	122	0.23	-10.9	16.4
Overall degree (OD)						*80(H)*
Notes: CD is coefficient of Dispersion; H: High; HA: Hydrologic alteration; L: Low; M: Moderate; P: Percentage of deviation						

Annex-12 Weights for the components of river health

Components	RCP 4.5			RCP 8.5	
	BA	NF	MF	NF	MF
Water quality	0.36	0.24	0.22	0.39	0.22
Habitat Assessment	0.18	0.14	0.16	0.11	0.16
Biological	0.15	0.11	0.08	0.05	0.08
Hydrological	0.31	0.52	0.54	0.45	0.54

Annex-13 Integrated score of river health baseline versus future

Sites	Baseline	remark	RCP4.5NF	remark	RCP8.5NF	remark	RCP 4.5MF	remark	RCP8.5MF	remark
M1	0.53	Moderate	0.26	Poor	0.20	Very Poor	0.35	Poor	0.40	Poor
M2	0.39	Poor	0.23	Poor	0.18	Very Poor	0.28	Poor	0.28	Poor
M3	0.41	Moderate	0.18	Very Poor	0.15	Very Poor	0.23	Poor	0.24	Poor
M4	0.45	Moderate	0.46	Moderate	0.52	Moderate	0.46	Moderate	0.43	Moderate
M5	0.30	Poor	0.37	Poor	0.31	Poor	0.36	Poor	0.33	Poor
M6	0.31	Poor	0.41	Moderate	0.36	Poor	0.41	Moderate	0.40	Moderate
M7	0.34	Poor	0.43	Moderate	0.32	Poor	0.46	Moderate	0.43	Moderate
M8	0.28	Poor	0.15	Very Poor	0.15	Very Poor	0.17	Very Poor	0.20	Poor
M9	0.41	Moderate	0.44	Moderate	0.35	Poor	0.48	Moderate	0.48	Moderate
M10	0.44	Moderate	0.41	Moderate	0.34	Poor	0.43	Moderate	0.44	Moderate
M11	0.39	Poor	0.28	Poor	0.17	Very Poor	0.32	Poor	0.32	Poor
M12	0.41	Moderate	0.55	Moderate	0.45	Moderate	0.57	Moderate	0.60	Good
M13	0.58	Moderate	0.29	Poor	0.13	Very Poor	0.40	Moderate	0.39	Poor
M14	0.47	Moderate	0.35	Poor	0.20	Very Poor	0.42	Moderate	0.42	Moderate
M15	0.42	Moderate	0.51	Moderate	0.43	Moderate	0.52	Moderate	0.56	Moderate
M16	0.34	Poor	0.24	Poor	0.12	Very Poor	0.30	Poor	0.30	Poor
M17	0.52	Moderate	0.59	Moderate	0.49	Moderate	0.62	Good	0.66	Good
M18	0.41	Moderate	0.51	Moderate	0.42	Moderate	0.53	Moderate	0.56	Moderate
M19	0.48	Moderate	0.33	Poor	0.19	Very Poor	0.43	Moderate	0.41	Moderate
M20	0.46	Moderate	0.83	Excellent	0.55	Moderate	0.68	Good	0.72	Good
M21	0.59	Moderate	0.89	Excellent	0.62	Good	0.77	Good	0.82	Excellent
Mean	0.43		0.41		0.33		0.44		0.45	
SD	0.08		0.19		0.15		0.14		0.15	

Annex-13.1 Integrated score of river health baseline versus future (post-monsoon 2018)

Sites	Baseline	Remark	RCP4.5 NF	remarks	RCP8.5 NF	remarks	RCP4.5 MF	remarks	RCP8.5 MF	remarks
M1	0.77	Good	0.33	Poor	0.20	Poor	0.35	Poor	0.44	Moderate
M2	0.64	Good	0.22	Poor	0.13	Very Poor	0.22	Poor	0.25	Poor
M3	0.71	Good	0.19	Very Poor	0.12	Very Poor	0.21	Poor	0.23	Poor
M4	0.54	Moderate	0.39	Poor	0.55	Moderate	0.45	Moderate	0.37	Poor
M5	0.43	Moderate	0.27	Poor	0.24	Poor	0.37	Poor	0.30	Poor
M6	0.36	Poor	0.39	Poor	0.31	Poor	0.41	Moderate	0.38	Poor
M7	0.63	Good	0.40	Moderate	0.28	Poor	0.48	Moderate	0.42	Moderate
M8	0.37	Poor	0.16	Very Poor	0.14	Very Poor	0.21	Poor	0.22	Poor
M9	0.68	Good	0.51	Moderate	0.37	Poor	0.54	Moderate	0.54	Moderate
M10	0.35	Poor	0.38	Poor	0.28	Poor	0.33	Poor	0.36	Poor
M11	0.59	Moderate	0.24	Poor	0.16	Very Poor	0.38	Poor	0.31	Poor
M12	0.30	Poor	0.62	Good	0.43	Moderate	0.48	Moderate	0.54	Moderate
M13	0.60	Moderate	0.27	Poor	0.16	Very Poor	0.34	Poor	0.36	Poor
M14	0.74	Good	0.37	Poor	0.25	Poor	0.48	Moderate	0.50	Moderate
M15	0.21	Poor	0.57	Moderate	0.42	Moderate	0.48	Moderate	0.53	Moderate
M16	0.70	Good	0.27	Poor	0.16	Very Poor	0.38	Poor	0.39	Poor
M17	0.38	Poor	0.64	Good	0.46	Moderate	0.55	Moderate	0.61	Good
M18	0.72	Good	0.70	Good	0.49	Moderate	0.62	Good	0.69	Good
M19	0.37	Poor	0.23	Poor	0.14	Very Poor	0.29	Poor	0.30	Poor
M20	0.28	Poor	0.85	Excellent	0.49	Moderate	0.55	Moderate	0.62	Good
M21	0.44	Moderate	0.96	Excellent	0.59	Moderate	0.65	Good	0.73	Good

Annex-13.2 Integrated score of river health baseline versus future (pre-monsoon 2019)

Sites	Baseline	Remark	RCP4.5 NF	remarks	RCP8.5 NF	remarks	RCP4.5 MF	remarks	RCP8.5 MF	remarks
M1	0.27	Poor	0.12	Very Poor	0.09	Very Poor	0.16	Very Poor	0.21	Poor
M2	0.26	Poor	0.17	Very Poor	0.10	Very Poor	0.19	Very Poor	0.19	Very Poor
M3	0.24	Poor	0.14	Very Poor	0.07	Very Poor	0.13	Very Poor	0.15	Very Poor
M4	0.47	Moderate	0.45	Moderate	0.58	Moderate	0.39	Poor	0.36	Poor
M5	0.20	Very Poor	0.33	Poor	0.21	Poor	0.33	Poor	0.25	Poor
M6	0.40	Poor	0.36	Poor	0.26	Poor	0.40	Poor	0.35	Poor
M7	0.34	Poor	0.40	Poor	0.27	Poor	0.39	Poor	0.34	Poor
M8	0.31	Poor	0.18	Very Poor	0.14	Very Poor	0.22	Poor	0.21	Poor
M9	0.49	Moderate	0.49	Moderate	0.28	Poor	0.36	Poor	0.49	Moderate
M10	0.39	Poor	0.31	Poor	0.25	Poor	0.34	Poor	0.34	Poor
M11	0.30	Poor	0.30	Poor	0.14	Very Poor	0.38	Poor	0.28	Poor
M12	0.49	Moderate	0.43	Moderate	0.36	Poor	0.45	Moderate	0.47	Moderate
M13	0.32	Poor	0.33	Poor	0.17	Very Poor	0.48	Moderate	0.42	Moderate
M14	0.50	Moderate	0.48	Moderate	0.18	Very Poor	0.37	Poor	0.54	Moderate
M15	0.45	Moderate	0.43	Moderate	0.32	Poor	0.40	Poor	0.44	Moderate
M16	0.24	Poor	0.23	Poor	0.14	Very Poor	0.42	Moderate	0.29	Poor
M17	0.62	Good	0.53	Moderate	0.38	Poor	0.52	Moderate	0.58	Moderate
M18	0.53	Moderate	0.46	Moderate	0.33	Poor	0.46	Moderate	0.49	Moderate
M19	0.44	Moderate	0.31	Poor	0.12	Very Poor	0.41	Moderate	0.39	Poor
M20	0.53	Moderate	0.78	Good	0.45	Moderate	0.62	Good	0.64	Good
M21	0.69	Good	0.80	Good	0.50	Moderate	0.67	Good	0.67	Good

Annex-13.3 Integrated score of river health baseline versus future (post-monsoon 2019)

Sites	Baseline	Remark	RCP4.5 NF	Remarks	RCP8.5 NF	Remarks	RCP4.5 MF	Remarks	RCP8.5 MF	Remarks
M1	0.43	Moderate	0.24	Poor	0.42	Moderate	0.08	Very Poor	0.40	Poor
M2	0.32	Poor	0.25	Poor	0.30	Poor	0.10	Very Poor	0.39	Poor
M3	0.43	Moderate	0.21	Poor	0.29	Poor	0.09	Very Poor	0.35	Poor
M4	0.43	Moderate	0.29	Poor	0.36	Poor	0.52	Moderate	0.32	Poor
M5	0.36	Poor	0.25	Poor	0.33	Poor	0.21	Poor	0.28	Poor
M6	0.38	Poor	0.30	Poor	0.38	Poor	0.26	Poor	0.34	Poor
M7	0.41	Moderate	0.29	Poor	0.40	Poor	0.27	Poor	0.36	Poor
M8	0.27	Poor	0.10	Very Poor	0.22	Poor	0.08	Very Poor	0.12	Very Poor
M9	0.39	Poor	0.33	Poor	0.45	Moderate	0.26	Poor	0.39	Poor
M10	0.54	Moderate	0.34	Poor	0.41	Moderate	0.36	Poor	0.43	Moderate
M11	0.40	Moderate	0.22	Poor	0.31	Poor	0.15	Very Poor	0.35	Poor
M12	0.43	Moderate	0.44	Moderate	0.50	Moderate	0.38	Poor	0.53	Moderate
M13	0.41	Moderate	0.22	Poor	0.39	Poor	0.14	Very Poor	0.40	Moderate
M14	0.51	Moderate	0.25	Poor	0.38	Poor	0.20	Very Poor	0.39	Poor
M15	0.61	Good	0.46	Moderate	0.59	Moderate	0.38	Poor	0.57	Moderate
M16	0.27	Poor	0.21	Poor	0.29	Poor	0.07	Very Poor	0.36	Poor
M17	0.46	Moderate	0.49	Moderate	0.56	Moderate	0.41	Moderate	0.59	Moderate
M18	0.47	Moderate	0.42	Moderate	0.53	Moderate	0.34	Poor	0.48	Moderate
M19	0.28	Poor	0.22	Poor	0.32	Poor	0.12	Very Poor	0.33	Poor
M20	0.52	Moderate	0.88	Poor	0.69	Good	0.48	Moderate	0.71	Good
M21	0.43	Moderate	0.24	Poor	0.42	Moderate	0.08	Very Poor	0.40	Poor

Annex-13.4 Integrated score of river health baseline versus future (pre-monsoon 2021)

Sites	Baseline	Remark	RCP4.5 NF	remarks	RCP8.5 NF	remarks	RCP4.5 MF	remarks	RCP8.5 MF	remarks
M1	0.67	Good	0.22	Poor	0.13	Very Poor	0.26	Poor	0.16	Very Poor
M2	0.55	Moderate	0.22	Poor	0.10	Very Poor	0.24	Poor	0.32	Poor
M3	0.75	Good	0.22	Poor	0.11	Very Poor	0.21	Poor	0.35	Poor
M4	0.46	Moderate	0.52	Moderate	0.62	Good	0.50	Poor	0.32	Poor
M5	0.44	Moderate	0.46	Moderate	0.23	Poor	0.46	Very Poor	0.28	Poor
M6	0.36	Poor	0.41	Moderate	0.23	Poor	0.41	Very Poor	0.31	Poor
M7	0.41	Moderate	0.49	Moderate	0.25	Poor	0.50	Very Poor	0.36	Poor
M8	0.40	Moderate	0.19	Very Poor	0.10	Very Poor	0.20	Very Poor	0.10	Very Poor
M9	0.44	Moderate	0.46	Moderate	0.27	Poor	0.45	Very Poor	0.40	Poor
M10	0.53	Moderate	0.41	Moderate	0.26	Poor	0.45	Poor	0.41	Moderate
M11	0.40	Poor	0.30	Poor	0.11	Very Poor	0.36	Very Poor	0.15	Very Poor
M12	0.32	Poor	0.54	Moderate	0.35	Poor	0.56	Very Poor	0.57	Moderate
M13	0.70	Good	0.24	Poor	0.10	Very Poor	0.37	Very Poor	0.22	Poor
M14	0.79	Good	0.25	Poor	0.11	Very Poor	0.30	Very Poor	0.21	Poor
M15	0.39	Poor	0.55	Moderate	0.35	Poor	0.50	Moderate	0.58	Moderate
M16	0.45	Moderate	0.18	Very Poor	0.06	Very Poor	0.23	Very Poor	0.07	Very Poor
M17	0.44	Moderate	0.57	Moderate	0.36	Poor	0.58	Poor	0.61	Good
M18	0.20	Very Poor	0.48	Moderate	0.31	Poor	0.48	Very Poor	0.46	Moderate
M19	0.45	Moderate	0.22	Poor	0.11	Very Poor	0.34	Very Poor	0.15	Very Poor
M20	0.72	Good	0.83	Excellent	0.45	Moderate	0.70	Moderate	0.75	Good
M21	0.63	Good	0.87	Excellent	0.48	Moderate	0.67	Excellent	0.86	Excellent

Annex - 13.5 River Health Index: t-Test: two-sample assuming equal variances

Statistical Measures	Baseline	RCP4.5 NF	RCP8.5 NF	Baseline	RCP4.5 MF	Baseline	RCP8.5 MF
Mean	0.42	0.41	*	0.42	0.43	0.42	0.44
Variance	0.007	0.03		0.01	0.02	0.01	0.02
Observations	21	21		21	21	21	21
Pooled Variance	0.02			0.01		0.02	
Hypothesized Mean Difference	0			0		0	
df	40			40		40	
t Stat	0.25			-0.31		2.93	
P(T<=t) one-tail	0.4			0.37		0.00	
t Critical one-tail	1.68			1.68		1.68	
P(T<=t) two-tail	0.8			0.75		0.01	
t Critical two-tail	2.02			2.02		2.02	

*Note: * means data is not normally distributed*

Annex-14 Abundance of macroinvertebrates (post-monsoon 2018)

Order	Family	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20	M21
Ephemeroptera	Baetidae	28	200	100	24	19	7	213	100	353	54	40	200	190	222	250	180	99	59	166	21	11
	Leptophlebiidae	9	150	200	9		11					96		9					10	14	44	13
	Heptageniidae	1		15	3		200	50	150	182		29	28	5		30			78	81	20	24
	Ephemerellidae																	55				
	Potamanthidae				50																	
	Ephemeridae	20	8	18	73	30		32	86	89		6	18	31	82	19	88				17	54
	Caenidae			12		12		6	8		22											
Plecoptera	Perlidae	10	2		93		18		11			29	69	5	16	18	13	44	48	14	33	31
	Nemouridae																3		1			
Trichoptera	Hydropsychidae	7	2	14		35	100	28	112		4	103	85	10	29	41	24	76	88	6		14
	Polycentropodidae									33										4		
	Philopotamidae								45													
Megaloptera	Corydalidae																					8
	Sialidae															4						
	Psephenidae			14		12	14	9		37								12				
	Hydrophilidae			19																		
	Elmidae											12	23	4		4						
	Noteridae																					
Diptera	Blephariceridae						7			7						5						
	Athericidae																					
	Ceratopogonidae			4	6			5														
	Chironomidae	2	25	9	14	40	30	32	34	21	31		83		30	32		47	17	34		
	Simulidae			30											7				13	12		
	Syrphidae																		3			
	Tabanidae			10		9			7			52					9					
	Muscidae														3							
	Tipulidae																8		2			

Odonata	Gomphidae	8		8	17		34	6		25			9			12					22	7
Lepidoptera	Pyralidae								8						8	6						

Annex 14.1 Abundance of macroinvertebrates (pre-monsoon 2019)

Order	Family	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20	M21
Ephemeroptera	Baetidae	26	7	5	305	290	80	53	17	33	44	7	2		9	10	4		3			12
		10			60			25	56	8	4									3	3	
					19	23	14	10	21	17				8								
		38																				
	Leptophlebiidae			15	15				49													
	Heptageniidae	14	2	3				5	29				4	7	24	7	9	3		2	3	11
							2				7											
		4	7	6	4		20								2							
					4				22													
											7											
								4	9							5	3	2	1	4		
	Caenidae								23		3				**4**				3			22
Plecoptera	Perlidae	4			40	8	2	4	4						1							3
							6															
		16	1	5	10															1		
	Nemouridae	19		2	20																	
Trichoptera	Hydropsychidae				5	2	2			1	197	28	6	205	61	2	68		3	38	3	37
	Glososomatidae								4													
	Brachycentridae						1															
	Polycentropodidae								2	1	2											
	Molannidae																					
	Rhyacophilidae					8																

		2					6															
	Stenopsychidae						8				28						3			13		
	Leptoceridae								1													
	Philopotamidae	2			2				1		18	1			8			1				
Megaloptera	Corydalidae													9	2					2		
	Sialidae																			1		
Coleoptera	Dytiscidae				1																	
	Psephenidae		1		1						1									7		
														27			17			38		
	Hydrophilidae					1	1															
	Elmidae	3							1		3	3										1
	Noteridae														7					52		
Hemiptera	Gerridae																			1		
	Naucoridae																					3
	Belastomatidae											1										3
Diptera	Blephariceridae				4																	
	Athericidae				1				1	1												
	Ceratopogonidae					3	3				2											
	Chironomidae		1	2	1				6	1		3	7			3						1
	Empididae																					3
	Ephydridae			1											1							
	Phychodidae(black)											1										
	Simulidae	1		1	4				44				3	1	2							
	Tabanidae											1					4					
									1													
	Limoniidae	2							5			2										
	Muscidae	5																				
	Tipulidae	1	1		1						2	5		2	1		3	1	3	2		1

	Family	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20	M21
Odonata	Gomphidae					1		1	10	2	2	2		7	9	4	55	2	2	45	2	2
						1									2							
	Coenagrionidae																17					
Lepidoptera	Pyralidae								1		4	1								2		
	Physidae										3											

Annex-14.2 Abundance of macroinvertebrates (post-monsoon 2019)

	Family	**M1**	**M2**	**M3**	**M4**	**M5**	**M6**	**M7**	**M8**	**M9**	**M10**	**M11**	**M12**	**M13**	**M14**	**M15**	**M16**	**M17**	**M18**	**M19**	**M20**	**M21**
Ephemeroptera	Baetidae	16	10	121	18	270	180	260	42	112	174	229	87	397	97	190	664	1	35	64	88	30
				9				144	227	13	35	20			8	100				100	259	2
						11	86	51	31	31	32	103		160		50	73		33		34	8
							20															
	Leptophlebiidae	43	4	24	14	1				3	11	17			5	2	16		17	579		22
	Heptageniidae	6	29	9		11	67	27	4	1	8			138	24	2	325		12	56		2
							8				40											
		12			8	34	18	28			22				4							
	Ephemerellidae																					44
					6			200	41			7								5		15
											39											
		39	8				16	287	11				31		136	35				90		48
	Potamanthidae					1						10							154			
	Polymitarcyidae																2					

	Ephemeridae															6						
	Caenidae						2					3				2	1	6		2		1
Trichoptera	Hydropsychidae			2	44	11	69	41	19	2			1	134	1	7	184	1		56	4	
	Brachycentridae														5					1		
	Polycentropodidae	2		2			1						2	45	41		3		1	6		
	Molannidae				1	1																
	Phryganeidae														2							
	Stenopsychidae										4											
	Philopotamidae			1	2	5			1					7	48		20			14		
								1												6		
Megaloptera	Sialidae							1			2						17				1	
Coleoptera	Dytiscidae								1													1
	Psephenidae										1			242	1	4	83	2	1			
																				14		
	Elmidae				1		2		1	1		2	1				1					
	Noteridae									1									2			
Hemiptera	Belastomatidae									1			1									2
Diptera	Athericidae			2																		
	Tipulidae	1			8	2	1		8					3	1					2		6
	Chironomidae			20	4	6	7	1	78		50	9	18	31	26	19		20	3	12		
	Ceratopogonidae				1										1	2				5		

	Simulidae	1		2	2				3				1	242	9				11	26		
	Ephydridae			1														1				
	Tabanidae				1		1							1	1			5		2		
	Blephariceridae	4												1								
	Psychodidae (black)												1									
	Syrphidae				1																	
	Empididae											3										
	Dixidae											1										
	Muscidae										8										1	
	Culicidae								2						2		5					
Plecoptera	Perlidae				65	29	2	9	1		6	1			1		10					
					15		6															
		17	17	5	20		1															
	Nemouridae			2			2															
Odonata	Gomphidae						1				1			5	4	1				2		
Arhynchobdellida	Salifidae																6					
Lepidoptera	Pyralidae														2							

Annex-14.3 Abundance of macroinvertebrates (pre-monsoon 2021)

Order	**Family**	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20	M21
Ephemeroptera	Baetidae	56	39	100	154	25	25	31	33	12	8	5		18	10	17	7	5	5	44	35	9
	Caenidae																					
	Ephemerellidae																					
	Ephemeridae																					
	Heptageniidae	93	18	10	14	37	7	11	43	4	12	3	5	5	12	21	12			22		2
	Leptophelibidae		11				5	23						5	20						95	4
	Potamanthidae									40					5							
Plecoptera	Perlidae	22	9	5	14		6															
	Nemouridae			6																		
Trichoptera	Hydropsychidae	290				15	12		14	4		3	2	10	20	12	27	3	4	65	300	5
	Brachycentridae																					
	Canidae																				1	
	Ephemerellidae									1											5	
	Glososomatidae																					
	Leptoceridae																					
	Leptophlebiidae																				119	
	Molannidae																					
	Philopotamidae			3											6			2			4	
	Polycentropodidae													13	2						2	
	Rhyacophilidae				3																	
	Stenopsychidae										9											
Megaloptera	Corydalidae																			4		
	Sialidae																1					
Coleoptera	Dytiscidae																					
	Elmidae								4													

	Hydrophilidae					1																
	Noteridae																					
	Psephenidae					9											11			6		
Hemiptera	Gerridae																					
	Aphelocheridae														51					31		
	Naucoridae																					
	Belastomatidae																					
Diptera	Athericidae																					
	Blephariceridae																					
	Ceratopogonidae																2					
	Chironomidae	8	3	10		4	50	19	4	15			3	55	8			4			4	2
	Culicidae																					
	Dixide																1					
	Empididae	4		3				8													1	
	Ephydridae																					
	Limoniidae																					
	Muscidae																					
	Phychodidae(black)																					
	Simulidae	45		1			5								3	40		2			60	
	Syrphidae																					
	Tabanidae														1							
	Tipulidae			2		5						5					2				7	
Odonata	Gomphidae								22	4	3		4		4	7	25		2	10	2	8
	Coenagrionidae										1											
	Tipulidae	5																	6			
Lepidoptera	Pyralidae																					
	Physidae																					

Annex-15 Average values of hydraulic conditions (post-monsoon 2018)

Sites	Depth(m)	Vel avg	Substrates in %				wetted width(m)
			Megalithal%	Macrolithal %	Mesolithal %	Microlithal %	
M1	27.8	0.8	80	20			16
M2	20.5	0.9	30	70			9
M3	59.0	1	75	20	5		16
M4	59.0	1.4	25	60	15		9
M5	26.7	0.8	10	50	40		48.3
M6	31.3	0.8	60	40			20
M7	33.7	1	60	40			30
M8	49.5	1	70	5	5	20	8.3
M9	57.0	0.4	90	10			15
M10	28.3	0.7	90	10			
M11	38.3	0.2	60	40			30
M12	28.8	0.8	20	50	10	20	
M13	24.5	0.4	50	10	40		21.7
M14	48.3	0.2	20	30	50		33.3
M15	55.5	0.1	40	50	10		32.3
M16	24.5	0.3	80	20			6.2
M17	40.0	0.5	30	50	20		
M18	30.0	0.2	20	40	40		
M19	35.8	0.3	30	50	20		37.7
M20	51.7	0.1	40	60			30
M21	20.0	0.6	30	40	30		40

Note: Vel avg is average velocity in (m^3/s)

Annex-15.1 Average values of hydraulic conditions (post-monsoon 2019)

Sites	depth	Vel avg	Substrates in %			wetted width(m)
			Megalithal%	Macrolithal %	Mesolithal %	
M1	19.7	0.4	15	35	50	40
M2	22.5	0.4	45	45	10	60
M3	22.8	0.4	25		75	10
M4	25.9	0.9	25	55	15	17
M5	30.3	0.2	65	10	25	30
M6	30.6	0.7	10	40	50	40
M7	33.0	0.2	100			
M8	33.1	0.7	30	40	30	45
M9	35.4	0.3	85	15		49.3
M10	36.4	0.5	70	30		22
M11	37.3	0.4	10		90	46
M12	39.1	0.2	90	10		50
M13	41.8	0.4	60	25	15	27
M14	45.7	0.8	10	90		15

M15	46.0	0.3	70	30		12
M16	46.0	0.6	70	30		21
M17	46.0	0.3	50	25	25	15
M18	47.2	0.3			100	27
M19	48.3	0.8	15	45	40	28
M20	48.9	0.3	85	10		33
M21	50.1	0.5	40	45	15	35

Annex-15.2 Average values of hydraulic conditions (pre-monsoon 2021)

			Substrates in %			wetted width(m)
Sites	**Depth(m)**	**Vel avg**	**Megalithal%**	**Macrolithal %**	**Mesolithal %**	
M1	0.9	25	70	20	10	5
M2	1	10	90	10		19
M3	0.8	70	90	10		1
M4	1.2	60	70	10	20	1
M5	0.4			15	85	2
M6	0.8	15	50	30	30	2
M7	1	10	10	10	80	50
M8	0.8	70	30	30	40	6
M9	0.5	85	100			2
M10	0.5	65	85	5	10	3
M11	0.5	70	90	10		15
M12	0.8	45	70	30		21
M13	0.4	50	90	10		4
M14	1	15	20	10	70	21
M15	0.6	90	80	15	5	23
M16	0.3	25	20	10	70	17
M17	0.4	10	80	20		45
M18	0.1	100				30
M19	0.5	30	40	20	40	
M20	0.2	85	90	10		
M21	0.5	40	70	30		15

Annex-16 Average flow health score at sampling sites and at the watershed

Sites	BA	RCP4.5 NF	RCP 8.5 MF	RCP4.5 MF	RCP8.5 MF
M1	0.1	0.0	0.0	0.0	0.0
M2	0.1	0.0	0.0	0.0	0.0
M3	0.1	0.0	0.0	0.0	0.0
M4	0.1	0.3	0.0	0.3	0.3
M5	0.1	0.3	0.3	0.3	0.3
M6	0.2	0.3	0.3	0.3	0.3
M7	0.3	0.3	0.3	0.3	0.3
M8	0.1	0.0	0.0	0.0	0.0
M9	0.3	0.4	0.4	0.4	0.3
M10	0.3	0.4	0.4	0.4	0.4
M11	0.1	0.0	0.0	0.0	0.0
M12	0.5	0.5	0.5	0.5	0.5
M13	0.1	0.0	0.0	0.0	0.0
M14	0.1	0.0	0.0	0.0	0.0
M15	0.6	0.5	0.5	0.5	0.5
M16	0.1	0.0	0.0	0.0	0.0
M17	0.6	0.5	0.5	0.5	0.5
M18	0.6	0.5	0.5	0.5	0.5
M19	0.1	0.0	0.0	0.0	0.0
M20	0.7	0.7	0.7	0.7	0.7
M21	0.7	0.7	0.7	0.7	0.7
Outlet (Grid 63)	0.72	0.71	0.71	0.73	0.72

Annex-17 Water quality index averaged of all the seasons under both RCPs scenarios in future

Sites	RCP4.5NF	Remark	RCP8.5NF	Remark	RCP4.5MF	Remark	RCP8.5MF	Remark
M1	44	Excellent	34	Excellent	43	Excellent	43	Excellent
M2	44	Excellent	34	Excellent	43	Excellent	43	Excellent
M3	37	Excellent	30	Excellent	37	Excellent	37	Excellent
M4	30	Excellent	200	Poor	28	Excellent	28	Excellent
M5	28	Excellent	23	Excellent	27	Excellent	27	Excellent
M6	26	Excellent	24	Excellent	27	Excellent	27	Excellent
M7	30	Excellent	27	Excellent	31	Excellent	31	Excellent
M8	45	Excellent	42	Excellent	45	Excellent	46	Excellent
M9	30	Excellent	27	Excellent	30	Excellent	31	Excellent
M10	30	Excellent	28	Excellent	31	Excellent	32	Excellent
M11	32	Excellent	28	Excellent	32	Excellent	32	Excellent
M12	42	Excellent	39	Excellent	43	Excellent	44	Excellent
M13	62	Good	58	Good	63	Good	63	Good
M14	34	Excellent	30	Excellent	34	Excellent	34	Excellent
M15	35	Excellent	32	Excellent	35	Excellent	36	Excellent
M16	41	Excellent	36	Excellent	41	Excellent	41	Excellent
M17	32	Excellent	29	Excellent	32	Excellent	33	Excellent
M18	32	Excellent	29	Excellent	33	Excellent	33	Excellent
M19	39	Excellent	35	Excellent	39	Excellent	39	Excellent
M20	61	Good	32	Excellent	36	Excellent	37	Excellent
M21	70	Good	38	Excellent	42	Excellent	42	Excellent

Annex-17.1 Water quality index for pre-monsoon 2021under both RCPs scenarios in future with respect to baseline

Sites	BA	Remark	RCP 4.5NF	Remark	RCP 8.5NF	Remark	RCP 4.5MF	Remark	RCP 8.5MF	Remark
M1	51	Good	50	Excellent	42	Excellent	39	Excellent	49	Excellent
M2	50	Excellent	52	Good	44	Excellent	40	Excellent	50	Good
M3	52	Good	49	Excellent	44	Excellent	36	Excellent	49	Excellent
M4	71	Good	54	Good	399	Unfit for drinking	26	Excellent	51	Good
M5	44	Excellent	33	Excellent	30	Excellent	27	Excellent	31	Excellent
M6	39	Excellent	26	Excellent	27	Excellent	23	Excellent	28	Excellent
M7	51	Good	38	Excellent	38	Excellent	33	Excellent	40	Excellent
M8	141	Poor	124	Poor	125	Poor	39	Excellent	127	Poor
M9	58	Good	44	Excellent	45	Excellent	26	Excellent	47	Excellent
M10	56	Good	42	Excellent	43	Excellent	25	Excellent	44	Excellent
M11	37	Excellent	36	Excellent	36	Excellent	29	Excellent	37	Excellent
M12	141	Poor	113	Poor	114	Poor	26	Excellent	117	Poor
M13	199	Poor	217	Very poor	213	Very poor	33	Excellent	218	Very poor
M14	72	Good	72	Good	71	Good	29	Excellent	73	Good
M15	200	Poor	167	Poor	168	Poor	26	Excellent	173	Poor
M16	277	Very poor	322	Unfit for drinking	314	Unfit for drinking	31	Excellent	328	Unfit for drinking
M17	207	Very poor	176	Poor	177	Poor	30	Excellent	182	Poor
M18	243	Very poor	206	Very poor	207	Very poor	30	Excellent	213	Very poor
M19	81	Good	80	Good	79	Good	31	Excellent	80	Good
M20	58	Good	86	Good	50	Good	34	Excellent	52	Good
M21	93	Good	139	Poor	81	Good	32	Excellent	84	Good

Annex-18 Hydro-climatic extremes in the Himalayan Watersheds: a case of the Marshyangdi Watershed, Nepal

Theoretical and Applied Climatology

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ORIGINAL PAPER

Hydro-climatic extremes in the Himalayan watersheds: a case of the Marshyangdi Watershed, Nepal

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Abstract

Climate change/variability and subsequent exacerbation of extremes are affecting human and ecological health across the globe. This study aims at unpacking hydro-climatic extremes in a snow-fed Marshyangdi watershed, which has a potential for water infrastructure development, located in Central Nepal. Bias-corrected projected future climate for near (2014–2033) and midfuture (2034–2053) under moderate and pessimistic scenarios were developed based on multiple regional climate models. Historical (1983–2013) and future trends of selected climatic extreme indices were calculated using RClimDex and hydrological extremes using Indicators of Hydrologic Alteration tool. Results show that historical trends in precipitation extremes such as number of heavy and very heavy precipitation days and maximum 1-day precipitation are decreasing while the temperature related ext[illegible] have both increasing and decreasing trends (e.g., warm spell duration index, warm days and summer days are increasing whereas cold spell duration index, cool days and warm nights are decreasing). These results indicate drier and hotter conditions over the historical period. The projected future temperature indices (hot nights, warm days) reveal increasing trend for both the scenarios in contrast with decreasing trends in some of the extreme precipitation indices such as consecutive dry and wet days and maximum 5-day precipitation. Furthermore, the watershed has low mean hydrological alterations (27.9%) in the natural flow regime. These results indicate continuation of wetter and hotter future in the Marshyangdi watershed with likely impacts on future water availability and associated conflicts for water allocation, and therefore affect the river health conditions.

Abbreviations

CD Coefficient of dispersion

CPA Change-point analysis

DHM Department of Hydrology and Meteorology

H High

HA Hydrologic alteration

IHA Indicators of Hydrologic Alteration

IPCC International Panel for Climate Change

L Low

M Moderate

masl mean above sea level

MF Mid-future

NF Near future

OD Overall degree

P Percentage of deviation

PPT Precipitation

Q Discharge

RCM Regional climate model

RCP Representative concentration pathway

RVA Range of variability approach

Tmax Maximum temperature

Tmin Minimum temperature

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1 Introduction

Climate change and variability is recognized as a major threat for the environment and sustainable development (Lal et al. 2012). It is evident that a change in the climate, depending upon location, may cause disastrous consequences on the socioeconomic survival of millions of people (Bhattarai et al. 2007). Therefore, studies on climate change, hydro-climatic extremes, and potential impacts on various sectors have gained momentum in recent years (Chen et al. 2007). In the last few decades, hydro-climatic variations became more prominent and were studied widely at global, regional, and local scales. These extreme climatic events like heat waves, floods, and drought induced by the hydro-climatic variability are expected to exacerbate in the future potentially due to climate change thus posing a major challenge to various sectors such as agriculture, biodiversity, and related ecosystem services that support livelihoods (Shrestha et al. 2017). The socioeconomic impacts of those changes are significant in all countries; however, lowand middle-income countries are especially vulnerable (IPCC 2013). Such countries experience higher fatalities even when exposed to hazards of similar magnitude and further with the 1 °C additional warming, risks associated with such types of extreme events increases progressively (IPCC 2013).

A warmer world is projected to bring more precipitation across the world as well as in Nepal; most models project a wetter and warmer future (2040–2059) mostly in the range of 2–3 °C, depending on the location and scenarios considered (Agrawala et al. 2003). Baidya et al. (2008) observed the general increasing trend in the temperature and precipitation extremes all over Nepal indicating more weather-related extreme events (like flood and landslides) in the future. Similarly, Manandhar et al. (2012) revealed a warming trend in the Kali Gandaki River Basin at higher altitudes with variable trends in precipitation indices. Bastakoti et al. (2016) also showed an increasing trend of climatic extreme in the recent past. Shrestha and Nepal (2016) observed changes in temperature and rainfall patterns at Makwanpur district of Nepal. Furthermore, Shrestha et al. (2017) found an increasing trend of extreme climatic events in Koshi river basin though longterm trend was not observed in rainfall pattern. In Western Nepal too, warmer and wetter future is projected in Chamelia watershed of Mahakali river basin (Pandey et al. 2019). The warming trends observed over the past several decades exacerbate the hydrological cycle and hydrological systems in many ways. Some of them include change in precipitation patterns, widespread melting of snow and ice; increase in atmospheric water vapor; increase in evaporation; and changes in soil moisture and runoff causing natural variability on inter-annual to decadal time-scales (Bates et al. 2008). Therefore, increased climate variability, could have influence on extreme climatic events like floods and droughts, both in frequency and intensity, affecting Nepal in various ways (Agrawala et al. 2003; Chaulagain 2006; Society of Hydrologists and Meteorologist 2012). Thus, understanding the historical as well as projected future trends in hydroclimatic variables, especially amount and significance of the trends in the extremes, are useful for informed climateresilient development planning and decision-making.

There are various statistical methods and tools available for evaluating climatic trend as described in literatures (Helsel and Hirsch 2002; Khon et al. 2007; Some'e et al. 2012; Duhan and Pandey 2013). The knowledge on amount of the long-term trends, change points (if any), their position in the time series, and statistical significance of the trends are very important as they allow the interpretation of its possible causes (Moraes et al. 1998). There are many parametric and nonparametric methods suitable for detection and attribution of trends and breaks in hydro-climatic series. Nonparametric tests are widely used as they will work with independent data and can accommodate outliers. One of the widely used nonparametric tests for detecting a trend in hydro-climatic time series is the Mann–Kendall (Mann 1945; Kendall 1975; Shrestha et al. 1999; Nepal 2016; Khatiwada et al. 2016). RClimDex (Zhang and Yang 2004), a R-based tool, is also available in public domain for calculating trends in climatic variables (i.e., temperature and precipitation) and their statistical significance. RClimDex has been used by many studies over the years. They include but not limited to Manton et al. (2001), Kiktev et al. (2003), Alexander et al. (2006), Tank et al. (2006), Baidya et al. (2008), Islam (2009), Donat et al. (2013), and Shrestha et al. (2017). The tool can calculate 27 indices related to temperature and precipitation as defined by Expert Team on Climate Change Detection and Indices (ETCCDI) (WMO 2009).

In addition to determining the historical climatic trend, projecting future climatic extreme plays a vital role for the climate impact studies. Future climate of an area is generally projected using General Circulation Models (GCMs) or Regional Circulation Models (RCMs). However, RCM has been widely used for the climate impact studies due to its higher resolution and better capturing of regional conditions. Many recent studies have used RCMs in climate projection and impact studies (Kulkarni et al. 2013; Fang et al. 2015; Devkota and Gyawali 2015; Khadka et al. 2016; Magar et al. 2016; Rajbhandari et al. 2017; Bhattarai et al. 2018; Pandey et al. 2019). RCM projections can further be downscaled using approaches such as linear scaling (Teutschbein and Seibert 2012), quantile mapping (Gudmundsson et al. 2012), local intensity scaling (Fang et al. 2015), power transformation (Fang et al. 2015), variance scaling (Teutschbein and Seibert 2012; Fang et al. 2015), and delta change (Ruiter 2012) to make RCM projections usable for a watershed level.

Similarly, a large number of studies (Wang et al. 2012; IPCC 2013; Panda et al. 2013; Kundzewicz et al. 2015; Asadieh et al. 2016; Dery et al. 2016) have examined potential trends in observed streamflow during the twentieth century, at scales ranging from catchment to global. Some studies have detected significant trends in selected indicators of flow and demonstrated statistically significant links with trends in temperature or precipitation (Bates et al. 2008). Trends in various indicators of streamflow, one of the important hydrological components that can be altered by both climatic and nonclimatic factors, can be analyzed by various statistical approaches. Indicators of Hydrological Alteration (IHA) (Richter et al. 1996; Ritcher et al. 1997) is a tool that has a capability to analyze 33 indices related to hydrological extremes (Kiesling 2003; Bharati et al. 2016). The hydro-climatic time series may also have abrupt changes in addition to gradual changes (or trend). In such cases, one needs to calculate trends separately before and after such abrupt changes. Statistical tests such as Pettitt's Change Point (Pettitt 1979) and Mann-Kendall (Mann 1945; Kendall 1975) are widely used (Liu et al. 2012; Xia et al. 2014; Mallakpour and Villarini 2016) to detect a change point and statistical significance in hydro-climatic time series.

There are many studies focused on various aspects of climate change in Nepal, ranging from climate change impact assessments (e.g., Pandey et al. 2019, 2020) to flood risk assessments in climate-change context (e.g., Devkota and

Bhattarai 2015; Devkota and Maraseni 2018). A summary of selected studies related to climate change in Nepal are provided in Appendix Table 6. However, there are limited studies focusing on climate projection using RCMs and the most recent representative concentration pathways (RCP) scenarios in Central Nepal in general, and Marshyangdi watershed. Furthermore, studies focusing on both historical and future climatic extremes as well as hydrological extremes are almost nonexistent. Marshyangdi is a snow-fed/Himalayan catchment having high potential for water infrastructure development, and it hosts a good number of hydropower projects. The watershed has a potential to generate at least 3251.8 MW of electricity (Jha 2010). Currently, three hydropower projects, namely, Marshyangdi (69 MW), Middle Marshyangdi (70 MW), and Upper MarshyangdiA (50MW) are in operation and six more have got license. Therefore, understanding hydro-climatic extremes in that watershed is important for informed-adaptation planning. Thus, we aim to unpack hydro-climatic extremes in a Marshyangdi, located in Central Nepal which feds to Narayani river basin (Fig. 1). The objectives of this study are as follows: (i) to characterize historical and projected trends in climatic extremes and (ii) to characterize hydrological extremes in the watershed.

2. Materials and methods

Overall methodological framework is shown in Fig. 2. It consists of preparation of historical time series of climatic data (temperature and precipitation) at selected stations, projection of future climate, selection of suitable set of indices for climatic extremes, evaluation of trends in those indices, evaluation of hydrological indices related to extremes, and finally direction and magnitude of hydroclimatic trends with its significance obtained. All these aspects are elaborated in the following sub-sections.

2.1 Study area

Marshyangdi watershed is a sub-basin of one of the major river systems, the Gandaki River Basin, in Central Nepal. It is located between 27° 50′ 42″ and 28° 54′ 11″ N latitudes and 83° 47′ 24″ and 84° 48′ 04″ E longitudes (Fig. 1), covering an area of 4148 km^2. The elevation of this watershed varies between 274 and 8042 m above the mean sea level (masl). The major portion of the watershed lies above 45% slope and are covered by snow and glacier, i.e., most of the area lies between 4000 and 6000 masl.

Climate in the watershed varies from Tropical Savannah in the lower belt to Polar frost type in the higher altitudes (Karki et al. 2016). The mean slope of this basin is 29.42°. Average annual maximum and minimum temperatures are 26°°C (June) and − 6°°C (January), respectively (Sharma 2017). Population in the four districts covered by the study watershed is 0.77 million (CBS 2019). Major land use/cover pattern in the watershed is the Grassland, followed by Barren land and Agricultural land, respectively(Sharma 2017).This regionis a part of the major Annapurna Trekking route from Besisahar (in Lamjung district) where the local economy also depends upon it.

The Marshyangdi River is perennial in nature and has a typical dendritic drainage system which begins at the confluence of two mountain rivers, the Khangsar and Jharsang, northwest ofthe Annapurna massifat analtitude of3600masl. Then it flows eastward through Manang district and southward through the Lamjung district covering other districts Gorkha and Tanahu. Finally, it joins the Trishuli river system at Mugling as one of the major tributaries of the Saptagandaki River system. Major tributaries of the Marshyangdi River includes Khudi, Dordi, Chepe, and Daraudi.

2.2 Historical trend analysis

Historical time series of daily observed temperature, both maximum and minimum, and precipitation at 12 climatic stations and observed river discharge data at 2 stations were collected for the period of 1970–2018 from the Department of Hydrology and Meteorology, Nepal. However, data at only 11 stations (Appendix Table 7), including one hydrological station, were selected for further use after an exploratory data analysis. Then suitable data length was selected (Appendix Table 7) considering the missing values calculated for each month per year for variables like maximum temperature (Tmax), minimum temperature (Tmin), precipitation, as well as for discharge.

Data quality control (QC) was carried out using RClimDex statistical tool, with the purpose of identifying errors in data processing, such as errors in manual keying (Alexander et al. 2006). Months with missing values of more than 10 days were considered month with missing data and coded accordingly while preparing data for RClimDex. We defined outliers in daily maximum and minimum temperatures as the values beyond the range of three standard deviations (SD) of the mean (i.e., mean ± 3*SD)) (Zhang and Yang 2004; Vincent et al. 2005). Similarly, 25 and 0 °C were defined as upper and lower thresholds of daily maximum temperature and 25 mm as the threshold of daily precipitation. A set of indices used in this analysis are based on the 27 indices related to daily

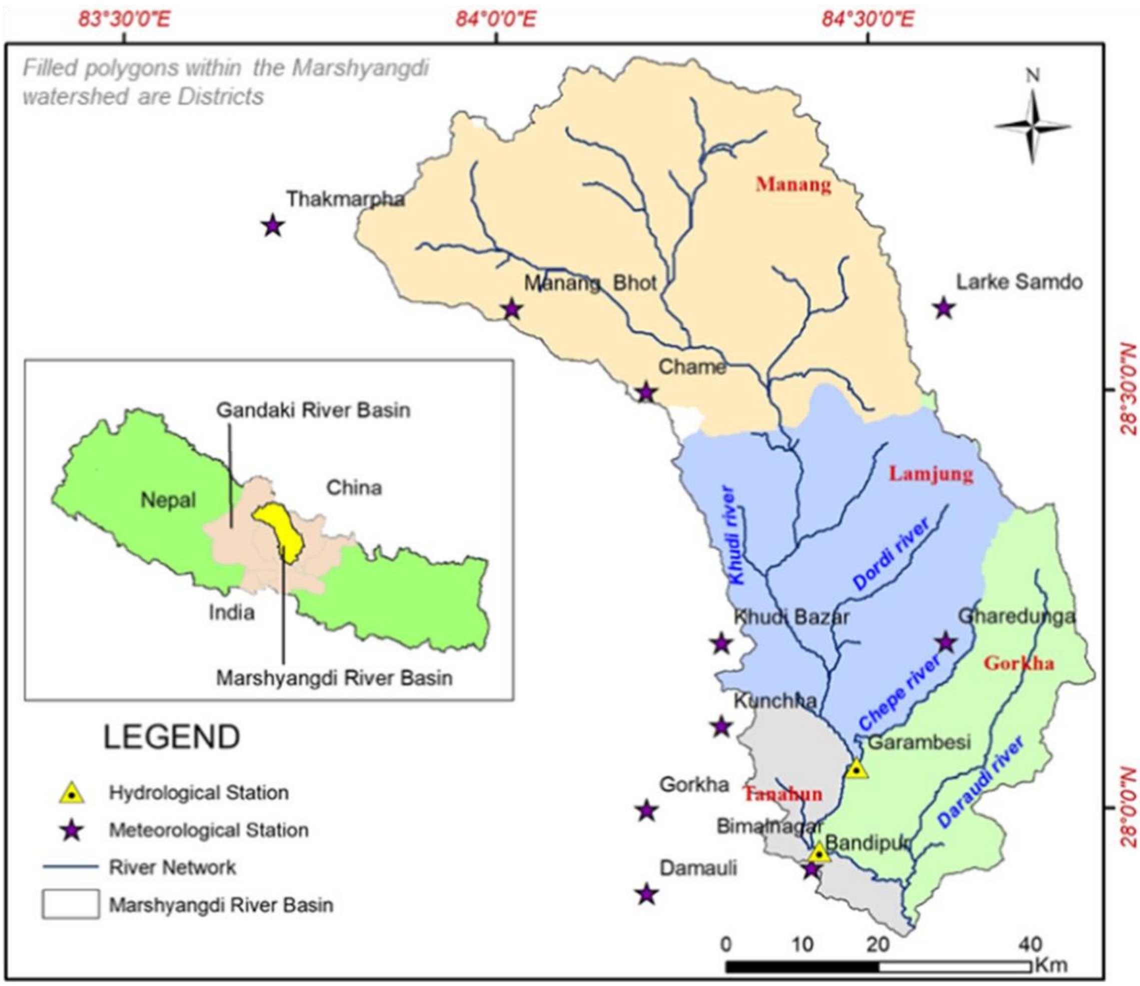
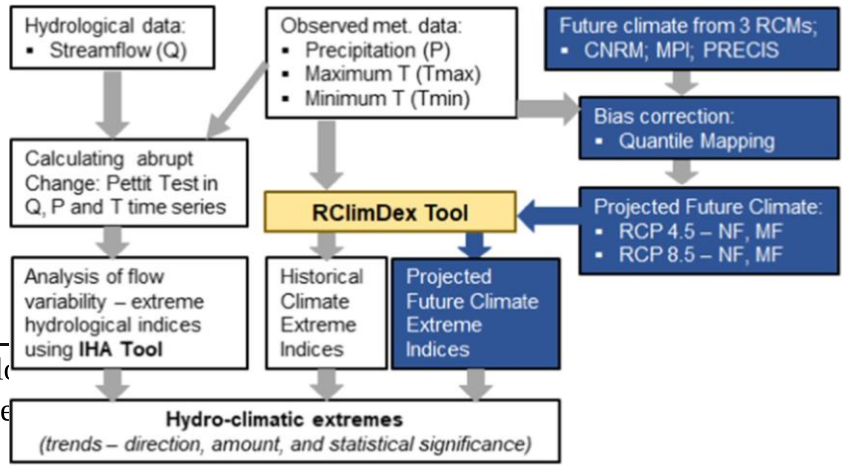


Fig. 1 Location and topographical details of the Marshyangdi watershed in Nepal

Fig. 2 Methodological framework. RCP, representative concentration pathways; RCMs, regional climate models; NF, near future; MF, mid-future; T, temperature; IHA, indicators of hydrological alteration; Met, meteorological



temperature and precipitation devel… Expert Team on Climate Change De… Indices (ETCCDI) (WMO 2009). … (1.0) was used to calculate trends in the climatic indices on an annual basis at various stations using daily precipitation and temperature data of varying length, as presented in Appendix Table 7. Out of 27 extreme indices, 23 indices (13 related to temperature;10 related to precipitation) selected for analyzing climatic extremes in this study are presented in Table 1. The trends in terms of magnitude, direction, and statistical significance were estimated using the methods described by Zhang and Yang (2004).

2.3 Future climate extremes analysis

Future climate projection is based on outputs of the Coupled Model Inter-comparison Project-Phase 5 (CMIP5), a collaborative climate-modelling process coordinated by the World Climate Research Programme (WCRP) using different climate forcing's. Future climate projection was carried out at four meteorological stations, namely, Thakmarpha (index:604), Khudi Bazzar (index:802), Gorkha (index:809), and variables. For example, value for day 1 (i.e., 1 January) was calculated as an average of 31 values of 1st January (i.e., from 1983 to 2013) and that for day 365 (i.e., 31 December) was calculated as an average of 31 values of 31st December (i.e., from 1983 to 2013). Then three different Regional Climate Models (RCMs), namely, ACCESS-1, CNRM-CM5, and MPI-ESM-LR of 0.5 × 0.5° horizontal resolution were downscaled from the South Asia CORDEX data portal (http://cccr.tropmet.res.in/home/index. jsp) and then divided into two periods namely, near-future (2014–2033) and mid-future (2034–2053) to project future scenarios. Considering the focus of this study on river health in connection to water infrastructure development, this study considered future period up to the mid-century only. These RCMs were selected based on literature review (Appendix Table 6). Generally, RCM outputs are only available for RCP4.5 and RCP8.5 and occasionally for RCP2.6. Hence, in this study, RCP4.5 is selected as a medium-stabilizing scenario, stabilization without overshoot pathway

Chame (index:816) as these stations have long-term time

leading to 4.5 W/m^2 (~ 650 ppm CO_2) at stabilization after 2100 and RCP8.

Table 1 Definitions of extreme climatic indices used in this study (source: Zhang and Yang 2004)

5 as a very high emission scenario, which refers to rising

S. No.	ID	Indicator name	Definitions	Unit
1	SU25	Summer days	Annual count when TX (daily maximum) > 25 °C	Days
2	TR20	Tropical nights	Annual count when TN (daily minimum) > 20 °C	Days
3	TXx	Max Tmax	Monthly maximum value of daily maximum temp	°C
4	TNx	Max Tmin	Monthly maximum value of daily minimum temp	°C
5	TXn	Min Tmax	Monthly minimum value of daily maximum temp	°C
6	TNn	Min Tmin	Monthly minimum value of daily minimum temp	°C
7	TN10p	Cool nights	Percentage of days when TN < 10th percentile days	Days
8	TX10p	Cool days	Percentage of days when TX < 10th percentile	Days
9	TN90p	Warm nights	Percentage of days when TN > 90th percentile	Days
10	TX90p	Warm days	Percentage of days when TX > 90th percentile	Days
11	WSDI	Warm spell duration indicator	Annual count of days with at least 6 consecutive days when TX > 90th percentile	Days
12	CSDI	Cold spell duration indicator	Annual count of days with at least 6 consecutive days when TN > 90th percentile	Days
13	DTR	Diurnal temperature range	Monthly mean difference between TX and TN	°C

14	RX1day	Max 1-day precipitation amount	Monthly maximum 1-day precipitation	mm
15	RX5day	Max 5-day precipitation amount	Monthly maximum consecutive 5-day precipitation	mm
16	SDII	Simple daily intensity index	Annual total precipitation divided by the number of wet days in the year	mm/day
17	R10	Number of heavy precipitation days	Annual count of days when PRCP ≥ 10 mm	Days
18	R20	Number of very heavy precipitation days	Annual count of days when PRCP ≥ 20 mm	Days
19	CDD	Consecutive dry days	Maximum number of consecutive days with RR < 1 mm	Days
20	CWD	Consecutive wet days	Maximum number of consecutive days with RR ≥ 1 mm	Days
21	R95p	Very wet days	Annual total PRCP when RR > 95th percentile	mm
22	R99p	Extremely wet days	Annual total PRCP when RR > 99th percentile	mm
23	PRCPTOT	Annual total wet-day precipitation	Annual total PRCP in wet days (RR ≥ 1 mm)	mm

radiative forcing pathways leading to 8.5 W/m^2 (~ 1370 ppm CO_2) by 2100. In order to remove the systematic bias in the downscaled data, quantile mapping bias correction technique was applied to all the raw daily temperature and precipitation time series prior to the calculation of the extreme climatic indices by using RClimDex as mentioned in Sect. 2.2. Future climatic extreme indices were analyzed based on ensemble time series data.

2.4 Hydrological extreme analysis

IHA as described in Mathews and Ritcher (2007) were used for evaluating hydrological extremes in the Marshyangdi watershed. IHA uses a nonparametric range of variability approach (RVA) (Richter et al. 1997) to characterize alterations in inter- and intra-annual variation in river flow. RVA is based upon comprehensive statistical characterization of the temporal variability in hydrologic regime quantifying the degree of alteration of 33 ecologically relevant hydrological parameters (Appendix Table 10) that describe crucial relationships between flow and ecological functions.

RVA analysis places the category boundaries of 17 percentiles from the median yielding an automatic delineation of three categories of equal size, as follows: the lowest category contains all values less than or equal to the 33rd percentile (low alteration); the middle categorycontains all values falling in the range of the 34th to 67th percentiles (moderate alteration); and the highest category contains all values greater than the 67th percentile (high alteration) (Richter et al. 1998). A positive hydrological alteration value means that the frequency of values in the category has increased from the pre- to the post-impact period (with a maximum value of infinity), while a negative value means that the frequency of values has decreased (with a minimum value of − 1). Each IHA is calculated in terms of median value, deviation degree, and degree of hydrological alteration (Appendix 1) between two periods to assess impacts of intervention on alterations. The pre- and post-impact periods were determined as per Pettitt's (1979) test on the annual average data to identify any abrupt change points in the streamflow time series in the Marshyangdi watershed.

2.5 Identification of change point

The approach after Pettitt 1979) was applied to detect a single abrupt change point in climatic as well as hydrological data (Pohlert 2018) to provide input in the IHA tool. The Pettit's test is a nonparametric test, which is useful for evaluating the occurrence of abrupt changes in climatic records (Sneyers 1990; Tarhule and Wool 1998; Smadi and Zghoul 2006; Gao et al. 2011). It tests the H0: The variables follow one or more distributions that have the same location parameter (no change), against the alternative: a change point exists. The Pettitt's test is one of the most commonly used tests for change point detection becauseofitssensitivitytobreaksinthemiddleofanytimeseries (Wijngarrd et al. 2003). This test is based on the Mann-Whitney two-sample test (rank-based test) and allows the detection of a single shift at an unknown point in time because of the lack of distributional assumptions (Javari 2016).

3. Results and discussion

3.1 Historical trends in climatic extremes

3.1.1 Temperature-based indices

Decadal trends of the 13 temperature-based extreme climatic indices at four meteorological stations are shown in Table 2. Statistically significant trend values at 5% ($p < 0.05$) level of significance are marked with an asterisk in Table 2. The results clearly indicate varying amount, direction, and significance (statistically) of the trends across the stations. Furthermore, such variations are clearly visible also among the indices under the same group (i.e., fixed-threshold index, absolute extreme index, percentile-based index, and duration-based index).

Among the threshold-based indices, "ice days (ID)" index does not have any trend (trend = 0) at three stations and insignificant negative trend at one station, i.e., at Chame (index:816); therefore, it was discarded for further analysis. However, "summerdays(SU25)" index has shown significant positive trends at Khudi (index:802) and Gorkha (index:809) stations, insignificant positive trend at Thakmarpha (index:604), and insignificant negative trend at Chame (index:816) (Table 2). Among the absolute extreme indices, for example, "tropical nights (TR20)" index has significant positive trend at Gorkha (index:809) stations and insignificant positive trend at Khudi (index:802) whereas no trends were observed (trend = 0) at the other two stations. Similarly, index TXn has positive trends across all the stations with varying amount and level of significance and other three indices (TNx, TNn, TXx) have mixed trends in terms of magnitude, direction, and level of significance (Table 2). In case of three percentile-based indices, number of warm days (TX90p) has positive trends at all the stations, number of cool nights (TN10p) has positive trend only at two stations, while the number of warm nights (TN90p) has positive trend at only one station Khudi (index:802) and number of cool days (TX10p) has no positive trends (i.e., significant negative trends) at all the stations (Table 2). It again reflects heterogeneity in percentile-based climate extreme indices derived from temperature time series. Finally, among the duration-based indices, DTR has statistically significant positive trends at three stations, WSDI also has positive trends at those three stations but are statistically insignificant, and CSDI has

Table 2 Historical decadal trends in the climate extreme indices in the Marshyangdi watershed

Temperature-based extreme indices

Station Index	Station Name	Fixed Threshold Indices	Absolute Extreme Indices					Percentile based Indices				Duration-based Indices		
		SU 25	TR20	TXx	TNx	TXn	TNn	TN90p	TN10p	TX90p	TX10p	WSDI	CSDI	DTR
604	Thakmarpha	0.02	0.00	0.00	-0.01	0.08	-0.02	-0.14	0.20	0.50	-0.38	0.30	0.15	0.09
816	Chame	-0.03	0.00	-0.07	-0.42	0.71	0.12	-0.48	0.57	0.42	-0.94	0.75	0.80	0.30
802	Khudi	0.24	1.13	0.01	0.09	0.06	0.09	0.15	-0.87	0.38	-0.26	0.17	-2.40	-0.02
809	Gorkha	1.81	1.33	0.10	0.04	0.09	-0.01							0.07

Precipitation-based extreme indices

Station Index	Station Name	Fixed Threshold Indices		Absolute Extreme Indices			Percentile-based Indices		Duration-based Indices		
		R10	R20	RX1day	RX5day	PRCPTOT	R95p	R99p	CDD	CWD	SDII
604	Thakmarpha	-0.02	0.03	0.67	0.82	0.51	1.00	-0.07	1.14	-0.05	0.02
802	Khudi	-0.26	-0.11	-2.47	-3.78	-18.71	-15.55	-7.18	0.95	-0.32	-0.11
806	Larke	-1.32	-0.49	-0.04	-1.67	-21.58	-8.06	-3.32	-1.87	0.18	-0.17
807	Samdo Kunchha	0.04	0.06	0.32	1.44	1.42	3.35	-0.31	1.00	-0.04	0.17
808	Bandipur	-0.52	-0.33	-0.07	-0.46	-15.83	-1.25	-0.76	0.73	0.08	-0.09
809	Gorkha	-0.24	-0.14	-0.23	0.30	-5.36	2.65	0.01	0.40	-0.08	-0.01
816	Chame	0.76	-0.26	-0.72	0.80	-0.20	-9.33	-4.20	2.45	0.91	0.08
817	Damauli	0.04	0.00	-0.59	-0.08	-1.60	-2.73	-2.03	0.33	-0.10	0.07
820	Manang	-0.37	-0.11	-0.56	-1.67	-8.38	-3.18	-0.60	0.57	-0.04	-0.01
823	Bhot Gharedunga	0.31	0.28	0.73	0.7	10.07	10.13	2.76	0.59	-0.30	0.27

*Statistically significant indices

positive trends only at two stations (Table 2). Such rising trends in the warm temperature indices and decreasing trends in the cool temperature indices are reported in other recent studies as well (e.g., Karki et al. 2020; Poudel et al. 2020).

Though the temperature extreme indices have certain magnitude of trends over the years, the actual index value varies from year to year as indicated in Appendix Fig. 14 for TX90p as an example. For the period of 1984–2013, TX90p at Khudi Bazzar (index:802) station has an average value of 9.3 °C, trend of + 0.36°C/year, and the index value varies from 0.81 to 25.8 °C. This indicates the significance of understanding these variabilities in addition to average annual value and long-term trend while applying the results for informed decision-making.

3.1.2 Precipitation-based indices

Trends in 10 precipitation-based climate extreme indices are shown in Table 2. They are also grouped under the following four categories, namely, fixed threshold indies (2), absolute extreme indices (3), percentile-based indices (2), and duration-based indices (3). Trends in the indices are evaluated at 5% level of significance (i.e., $p < 0.05$) at 10 stations distributed across the Marshyangdi watershed. Precipitationbased indices also show variation in trend amounts, directions, and statistical significance across the 10 stations with no distinct spatial trends.

Both the indices under threshold-based category, namely, R10 (number ofheavy precipitation days) and R20(number of very heavy precipitation days), show insignificant decreasing trends at six out of 10 stations. Both indices, in most of the cases, show the same direction and significance in the trends, though the magnitude of trends are different (Table 2). Similar results are reported in other studies as well (e.g., Lamichhane et al. 2020). Among the duration-based indices, "consecutive dry days (CDD)" shows insignificant positive trends at seven out of 10 stations whereas at two stations Kunchha (index: 807) and Chame (index: 816), trends are significantly positive. "Simple daily intensity index (SDII)" show insignificant positive trends at five out of 10 stations, and "consecutive wet days (CWD)" show insignificant positive trends only at three out of 10 stations (Table 2). All the trends in remaining stations are negativebut statistically insignificant.Incaseofthree absolute extreme indices, RX1day and PRCPTOT have negative indices with varying magnitude at seven out of 10 stations. Some of those indices are also statistically significant, for example, PRCPTOT at three stations (i.e., Larke Samdo, Bandipur, and ManangBhot) and RX1day at Khudi (Table 2). The RX5day index on the other hand has negative trends only at five out of 10 stations, with only one of them (i.e., Khudi) being statistically significant. There magnitude of indices varies widely across the stations for all three indices. Finally, for two percentile-based indices (i.e., R95p and R99p), R99p trends are negative (insignificant) at all eight stations and that of R95p are negative, two of them being statistically significant, at five out of 10 stations (Table 2).

The increasing trend of CDD index is also observed over the southern and northern slopes of Central Himalayas and across the Narayani river basin (Sigdel and Ma 2016; Lamichhane et al. 2020). Similarly, Karki et al. (2017) observed the similar trend of CDD across the country warning that such increase in the dry period can impact negatively in agricultural activities and hydropower generation, thus affecting economic aspects of the livelihood. Increasing trends in the climatic indices have also been reported at many stations of the Koshi basin of Nepal (Shrestha et al. 2017). Such climatic extremes may have implications in public health as well as it may cause respiratory-related health problems in Nepal (Karki et al.2017).

Like temperature-based extremes, precipitation-based extreme indices also have inter-annual variability as shown in Appendix Fig. 14 for Rx5day as an example. For the period of 1984–2013, Rx5day at Khudi Bazzar station (index: 802) has an average value of 299.6 mm, trend of − 3.78 mm/year, and the index value varies from 244 to 414 mm with a coefficient of variation of 43.6 mm. Understanding such variabilities are helpful to use the results cautiously.

3.2 Projected future trends in climatic extremes

Projected future trends in climatic extremes are based on an ensemble of three RCMs (CNRM, ACCESS, and MPI) under RCP4.5 and RCP8.5 scenarios for both NF and MF periods and presented in Table 3 (please refer to Appendix Table 6 for the detailed characteristics of the RCMs). The RCM outputs were bias corrected for the historical period (1983–2013) and projected for the future periods. The performance of the RCM outputs for the historical periods was of acceptable quality after bias corrections.

3.2.1 Projected climatic extreme trends in the Marshyangdi watershed

Temperature-based indices Across the stations, the trends in extreme climatic indices were evaluated for an ensemble time series generated based on the three RCMS (i.e., CNRM, ACCESS, and MPI). Result shows a gradual increase in the extreme temperature indices at some stations from baseline to MF, while some indices are observed to be decreasing gradually at all the stations and some indices shows mixed trends (Table 3). For example, summer days (SU25) index shows a gradual increase (insignificant) at the Chame (index: 816) station from baseline (− 0.03 days/year) to MF (0.11 days/year) under RCP4.5 and RCP8.5 scenarios, but it does not show any trend during NF under RCP8.5. Similarly, TXx at

Chame shows increasing (insignificant) trend from baseline (− 0.07 °C/year) to NF and MF for both RCPs with a similar trend of 0.05 °C/year, but during MF under RCP4.5 shows a slight decreasing trend of 0.03 °C/year. TNx shows no change from baseline (− 0.01 °C/year) to NF under RCP4.5; however, it increases (significant) to NF and MF for both RCP4.5 and RCP8.5 with a trend amount of 0.07 °C/year at Thakmarpha

(index:604). TNx at Chame (index:816) shows increasing (significant) trend from baseline (− 0.42 °C/year) to MF (0.09 °C/year) under RCP4.5 and RCP8.5; however, the trend was insignificant during NF under both RCPs.

At the Khudi Bazzar (index:802) station, TXn shows gradual increasing (insignificant) trend from baseline (0.06 °C/ year) to increasing (significant) trend in MF under RCP4.5 and RCP8.5 (0.11 °C/year). However, some percentile-based extreme temperature indices show an increasing trend at more than one stations for the future scenarios. For example, TN90p increases from baseline at stations Thakmarpha (insignificant), Khudi (insignificant), as well as Chame (significant) (0.1 days/year, 0.15 days/year, − 0.48 days/year) to MF with significant trends at the three stations for both RCPs (0.56 days/year, 0.61 days/year, 0.62 days/year). At the Gorkha (index:809) station, though it does not show any change in trend in the baseline, it increases significantly from 0.2 days/year in

NF4.5 to 0.5 days/year from NF to MF under both RCPs except during MF under RCP8.5 where it decreases slightly to 0.07 days/year. Other climatic extremes like “Warm Spell Duration Indicator (WSDI)”shows increasing (insignificant) trend from baseline (0.17 days/year) to MF under both RCP scenarios (0.52 days/year) at the Khudi bazzar station, but the trend is significant in NF for both RCPs (Table 3).

Precipitation-based indices Precipitation-based climate extreme indices do not show gradual increasing trend at any stations from baseline to future periods (NF and MF) under both RCP scenarios (4.5 and 8.5) (Table 3). For example, Rx1day at the Khudi Bazzar (index:802) is projected to increase (insignificant) from baseline (− 2.47 mm/year) to NF and MF (0.1 mm/days) under both RCPs, but the magnitude of trend value was less in comparisonwithNFforbothRCPs.Indexlike “simpledailyintensity index (SDII)” and number of very heavy precipitation days (R20) do not show any gradual increases from baseline to MF under both RCPs (mixed trend) at all the stations (Table 3). Similarly, annual total wet-day precipitation (PRCPTOT) at the Chame station shows increasing (insignificant) trend from baseline (− 0.20 mm/year) to MF (3.18 mm/year) under both RCPs whereas during NF under RCP8.5, it shows negative

(insignificant) trend (− 1.81 mm/year).

Some extreme precipitation indices show increasing trend only from baseline to NF and then decreases during MF. For example, RX5day increases (insignificant) from baseline (0.82 mm/year) to NF (1.38 mm/year) and then decreases

(insignificant) during MF under RCP4.5 (− 1.22 mm/year) and RCP8.5(−0.27 mm/year)atthe Thakmarpha (index:604) station

Table 3 Projected trends in future climatic extreme indices based on an ensemble of three RCM outputs

S. No.	Baseline					Near future, RCP4.5				Mid-future, RCP4.5				Near future, RCP8.5				Mid-future, RCP8.5			
	Indices	604	816	802	809	604	816	802	809	604	816	802	809	604	816	802	809	604	816	802	809
1	SU25	0.02	− 0.03	1.09*	1.81*	0.00	0.01	0.85*	0.71*	− 0.03	0.06	0.39	0.17	0.00	0.00	0.51*	0.43	0.01	0.11	0.40	0.12*
2	Id0	0.00	− 0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3	TR20	0.00	0.00	1.13*	1.33*	0.00	0.00	1.07*	0.66*	0.00	0.00	1.07*	1.84*	0.00	0.00	0.73	0.37	0.00	0.00	1.13*	0.00
4	Fd0	0.31	0.41	− 0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
5	GSL	1.36*	1.99	− 0.01	0.03	0.50	0.53	0.00	0.00	− 0.16	− 0.14	0.00	0.00	− 0.11	0.28	0.00	0.43	− 0.01	0.06	0.00	0.00
6	TXx	0.00	− 0.07	0.01	0.10*	0.02	0.05	0.06*	− 0.04	− 0.02	0.03	0.03	− 0.08*	0.04*	0.05	0.03	0.00	− 0.02	0.05	0.03	0.05
7	TXn	0.08	0.71*	0.06	0.09*	0.14*	0.07	0.11	0.08	0.05	− 0.02	0.11*	− 0.02	0.11	0.02	0.02	0.37	0.07	0.06	0.11*	− 0.02
8	TNx	− 0.01	− 0.42*	0.09	0.04*	− 0.01	0.02	0.00	0.01	0.06*	0.08*	0.08*	0.05*	0.04*	0.06	0.06*	0.00	0.07*	0.09*	0.08*	0.08*
9	TNn	− 0.02	0.12*	0.09	− 0.01	0.00	0.00	0.09*	0.07	0.00	0.00	0.02	0.08*	0.00	0.00	0.08	0.00	0.00	0.00	0.02	0.00
10	TX10p	− 0.38*	− 0.95*	− 0.26*		− 0.48*	− 0.23*	− 0.38*	− 0.36*	− 0.24	− 0.23*	− 0.45*	− 0.38*	− 0.63*	− 0.43*	− 0.46*	− 0.01*	− 0.41*	− 0.46*	− 0.44*	− 0.21*
11	TX90p	0.50	0.42	0.38*		0.44*	0.34*	0.34*	0.23*	0.16	0.13	0.47*	0.24	0.41*	0.26*	0.28*	0.04*	0.34*	0.45*	0.47*	0.25
12	TN10p	0.20	0.57*	− 0.87*		− 0.23*	− 0.26*	− 0.47*	− 0.32*	− 0.33*	− 0.33*	− 0.55	− 0.63*	− 0.43*	− 0.38*	− 0.45*	0.03*	− 0.51*	− 0.49*	− 0.54*	− 0.33*
13	TN90p	− 0.14	− 0.48*	0.15		0.28*	0.21*	0.27*	0.24*	0.49*	0.50*	0.62*	0.63*	0.31*	0.25*	0.30*	0.07*	0.56*	0.62*	0.61*	0.50*
14	WSDI	0.30	0.75	0.17		0.58	0.68	0.52*	− 0.01	0.39	0.11	0.52	0.13	0.57	0.37	0.44*	− 0.35	− 0.01	0.13	0.52	0.28
15	CSDI	0.15	0.80*	− 2.40		− 0.14	− 0.09*	− 0.74*	− 0.18*	− 0.17	− 0.25	− 0.85	− 0.13	− 0.22*	− 0.23*	− 0.19	0.30	− 0.49	− 0.26	− 0.69	− 0.25
16	DTR	0.09*	0.30*	− 0.02	0.07*	0.04*	0.01	0.00	0.01	− 0.01	− 0.03*	− 0.01	− 0.03*	0.03*	0.02	0.00	− 0.36	− 0.01	− 0.02	− 0.01	− 0.02
17	Rx1day	0.67	− 0.72	− 2.47*	− 0.23	0.87	0.88	0.54	− 0.23	− 1.12	− 0.17	0.10	− 0.99	− 0.58	− 0.14	0.31	0.25	− 0.14	− 0.46	0.10	− 0.17
18	Rx5day	0.82	0.80	− 3.78*	0.30	1.38	2.44*	− 0.58	− 1.60	− 1.12	− 0.14	− 0.13	− 0.20	− 0.80	0.18	0.24	0.43	− 0.27	− 0.13	− 0.13	− 0.14
19	SDII	0.02	0.08	− 0.11	− 0.01	0.04	0.01	− 0.04	− 0.05	− 0.03*	0.00	0.06	0.03	0.00	0.01	0.04	− 0.34	− 0.01	0.02	0.06	0.00
20	R10mm	− 0.02	0.76	− 0.26	− 0.24	0.29*	0.04	0.18	− 0.48*	− 0.20*	− 0.11	0.55	0.47	0.10	0.03	− 0.09	0.00*	− 0.15	0.31	0.56	− 0.11
21	R20mm	0.03	− 0.26	− 0.11	− 0.14	0.07	0.14	− 0.24	− 0.07	− 0.04	− 0.04	0.25	0.10	− 0.08	− 0.07	0.11	1.00	− 0.07	0.08	0.24	− 0.04
22	R25mm	0.03	− 0.18	− 0.07	− 0.12	0.09*	0.16	− 0.36	− 0.01	− 0.05	− 0.09	0.35	− 0.04	− 0.04	0.04	0.29	1.77	− 0.06	0.04	0.34	− 0.09
23	CDD	1.14*	2.45*	0.95	0.40	0.28	0.23	− 0.08	0.26	0.29	− 0.25	0.94*	0.66	0.94*	0.45	0.37	0.07	0.31	0.24	0.94*	− 0.25
24	CWD	− 0.05	0.91	− 0.32	− 0.08	− 0.09	0.29	− 0.03	0.23	0.07	− 0.22	− 0.32	0.03	0.10	− 0.27	− 1.35	0.57	− 0.02	− 0.30	− 0.32	− 0.22
25	R95p	1.00	− 9.33	− 15.55	2.65	5.83*	7.12	− 3.29	− 3.92	− 4.44*	− 0.43	7.22	0.54	0.16	− 1.65	9.53	0.00	− 3.45	1.99	7.64	− 0.43
26	R99p	− 0.07	− 4.20	− 7.18	0.01	3.01	5.48	5.48	− 4.02	− 2.47	− 0.88	3.59	− 0.99	− 1.50	− 1.52	− 3.81	0.09	− 1.90	− 0.55	3.59	− 0.88
27	PRCPTOT	0.51	− 0.20	− 18.71	− 5.36	5.42	3.54	− 6.46	− 9.57	− 2.34	0.89	14.67	7.17	− 0.99	− 1.81	3.30	0.48	− 1.71	3.18	14.77	0.89

*Significant at 95% confidence interval

Table 4 Projected changes in future climatic extreme indices (based on ensemble time series) for RCP8.5 scenarios across four stations in the Marshyangdi watershed

Indices	Thakmarpha (index:604)			Chame (index:816)			Khudi (index:802)			Gorkha (index:809)		
	Hist	Change (%)		Hist	Change (%)		Hist	Change (%)		Hist.	Change (%)	
		NF	MF		NF	MF		NF	MF		NF	MF
SU25	0.9	− 100.0	− 61.7	0.7	− 85.4	360.4	255.7	1.8	4.6	227.7	4.2	− 99.7
TX10p	9.8	− 29.9	− 30.7	7.7	− 9.6	− 12.7	10.4	− 34.5	− 35.0			
TXx	25.2	− 5.7	− 3.2	24.1	− 0.6	4.4	34.9	− 1.8	0.1	5.5	− 4.5	− 28.2
TNx	15.4	− 49.5	5.2	12.4	16.8	28.3	24.0	0.7	7.3	24.2	− 1.3	− 36.7
TXn	3.1	150.1	211.7	6.3	11.3	33.3	14.6	22.2	27.3	13.7	17.7	− 43.6
TN10p	8.9	− 39.7	− 35.9	7.3	− 29.1	− 22.7	10.7	− 36.9	− 35.9			
TX90p	9.2	− 25.5	− 25.4	7.3	− 8.2	− 5.7	9.7	− 30.8	− 29.1			
TN90p	9.6	− 29.4	− 30.6	7.3	− 9.5	− 7.6	9.7	− 30.5	− 30.9			
CSDI	3.2	− 70.2	9.6	6.7	− 84.3	− 66.3	15.2	− 88.5	− 72.3			
WSDI	70.5	50.6	52.0	8.2	− 51.6	− 52.2	4.7	− 19.9	− 23.1			
CDD	5.7	− 43.0	− 45.2	65.3	− 60.5	− 59.6	58.5	− 56.5	− 52.4	63.4	− 54.7	− 47.4
CWD	384.1	87.5	61.0	22.9	39.1	36.9	31.8	189.9	171.7	11.9	154.8	165.3
PRCPTOT	28.2	15.4	10.7	1101.4	5.7	4.4	3359.4	7.4	7.6	1735.1	2.7	− 30.8
R99p	35.7	58.6	33.6	93.2	− 2.1	4.1	155.1	18.6	20.0	129.4	− 17.4	− 25.1
RX1day	57.1	− 1.8	− 10.7	41.4	21.9	22.4	128.9	− 31.4	− 27.8	101.6	− 38.3	− 49.1
RX5day	2.6	− 38.5	− 16.3	105.1	− 13.1	− 10.6	294.1	− 16.8	− 14.0	195.6	− 27.3	− 52.2
R20	9.7	− 31.2	− 46.5	9.5	− 34.4	− 40.2	61.4	9.0	11.7	28.9	− 21.7	− 77.8
R10	9.7	− 37.3	− 32.7	42.0	− 39.3	− 39.6	90.8	30.1	27.7	53.3	22.4	− 49.3
SDII	3.7	− 30.5	− 31.7	9.9	− 38.7	− 38.6	22.6	− 25.5	− 25.7	16.2	− 38.0	− 61.9

Notes: Historical (Hist.) values are the actual values with units as indicated in Table 2; change (%) are the change in future w.r.t. baseline

NF, near future; MF, mid-future

(Table 3). Similarly, the number of heavy precipitation days (R10) at the same station shows an increasing (insignificant) trend from baseline (− 0.20 mm/year) to a significant increasing trend in NF (0.29 mm/year) for RCP4.5, but it decreases (insignificant) in MF (− 0.15 mm/year) under RCP8.5.

Furthermore, some stations show decreasing trends in extreme precipitation indices from baseline to NF and then to MF under both RCP scenarios. For example, consecutive dry days

(CDD) as well as CWD decrease (insignificant) at the Chame station from baseline (2.45 days/year, 0.91 days/year) to NF and MF (0.24 days/year, −0.30 days/year) under RCP4.5 and RCP8.5. Simple daily intensity index (SDII) also shows decreasing trend from the baseline (0.08 days/year) to MF (0.02 days/year), but it does not show any trend during MF under RCP4.5.

3.2.2 Projected changes in future climatic extreme indices

w.r.t. baseline

Projected changes in temperature-based extremes Changesin the model-based extreme climatic indices at the four meteorological stations Thakmarpha (index:604), Khudi (index:802), Gorkha (index:809), and Chame (index:816) of the Marshyangdi basin for NF (2014–2033) and MF (2034–2053) against the historical period (1983–2013) for RCP4.5 and RCP8.5 scenarios are shown in Appendix Table 8 and Table 4, respectively.Temperature-basedextremeindicesforbothscenariosareprojectedtoincreasemoreinMFcomparedwithNF,with higher magnitude of changes being projected in RCP8.5 than in RCP4.5. For example, TNx increases at all the stations gradually from NF to MF but at the Chame station, its magnitude was the highest at NF (15.9%) as well as at MF (23.6%) for RCP4.5. In contrast, TXx decreases at all the stations except during MF at the Chame and Khudi, respectively.

Likewise, for RCP4.5 (Appendix Table 8), summer days (SU25) gradually increases at two stations only, Khudi and Gorkha. In case of RCP8.5 (Table 4), it increases for both NF and MF at Khudi, only during NF at Gorkha and only during MF at Chame, with the highest average values (360.4%). Furthermore, index TXx at Chame is the highest for RCP4.5 (1.9%) and RCP8.5 (4.4%) in MF but decreases at the rest of the three stations for both RCPs except at Khudi.

In overall, trends in hot nights (TN90p, significant), warm days (TX90p; insignificant at 1 station), Max Tmin (TNx, significant), hot days (TXx; insignificant), and WSDI are projected to increase from baseline to future under both RCP scenarios at all the stations. On the contrary, cool

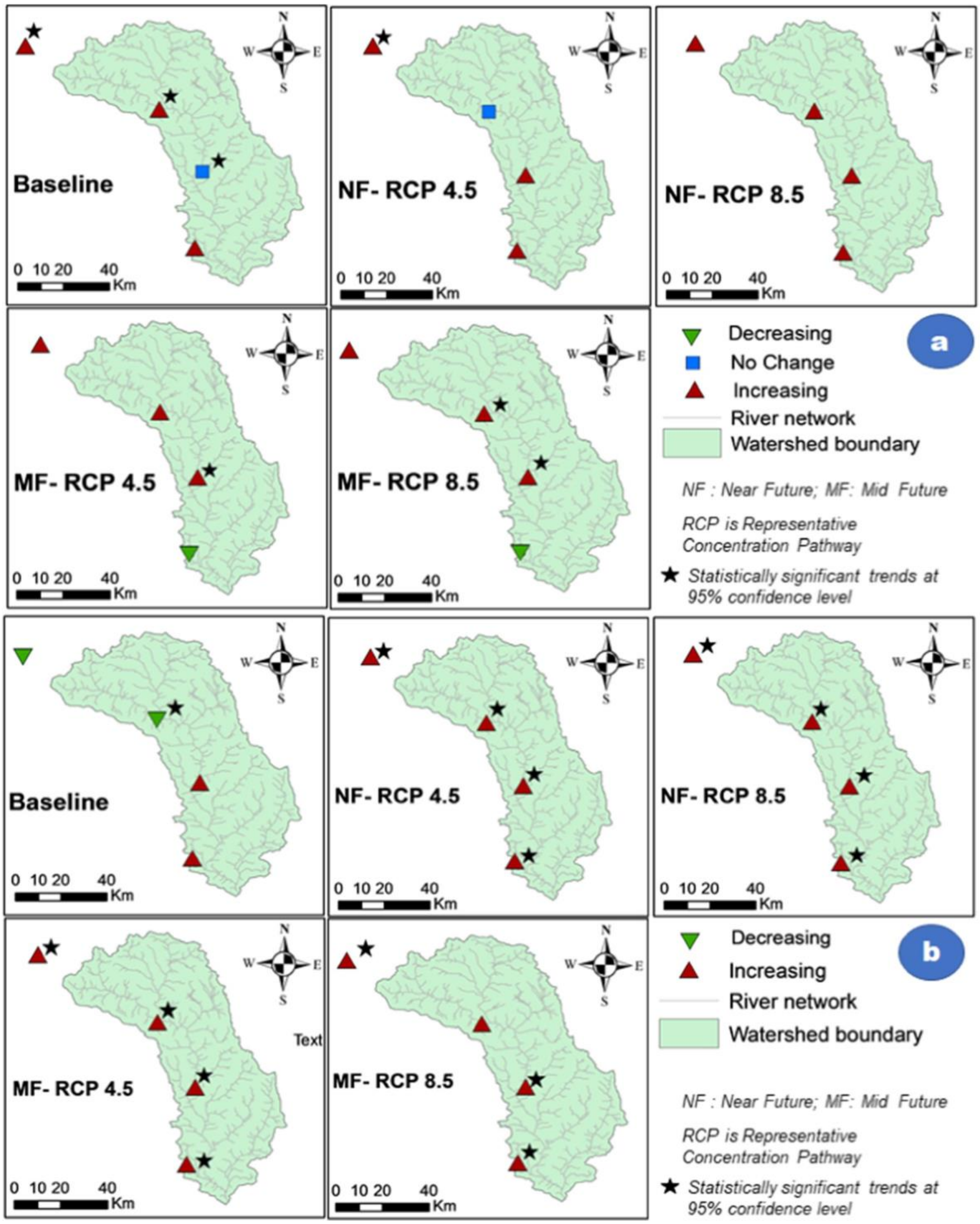


Fig. 3 Spatial distribution in trends across the stations a TXn and b TN90p

nights (TN10p; significant), cool days (TX10p; significant), and CSDI (insignificant) are projected to decrease from baseline to future under both RCP scenarios. The diurnal temperature range (DTR) is also projected to decrease (insignificant) in future periods for both RCP scenarios.

Projected changes in precipitation-based extremes Precipitation-based extreme indices are projected to decrease in the future at most of the stations for both RCPs, but with varying magnitudes (Appendix Table 8; Table 4). For example, SDII is projected to decrease at all the stations for both the RCPs. Also, CDD are projected to decrease at all the stations for future scenarios for both RCPs and CWD is projected to increase. PRCPTOT is projected to increase gradually at most of the stations from NF to MF for RCP4.5 with the highest percentage increase during MF (16%) at Thakmarpha. However, for RCP8.5, PRCPTOT increases only during NF at the three stations (except Gorkha during MF) with the highest percentage increase during NF at Thakmarpha (15.4%). Importantly, R99p at two stations Thakmarpha and Khudi is projected to increase from NF to MF for both the RCP scenarios whereas at Chame only for MF. Likewise, RX1day is projected to increase widely (from − 1.8 to 8.4%) at Thakmarpha but decrease from 27.4% in NF to 24.8% in MF at Chame. Other intense precipitation indices like RX5day are projected to decrease at all the stations (except in NF at Thakmarpha) for both the RCP scenarios. The R10, on the other hand, is projected to increase with higher percentages in NF in comparison with MF at Khudi and Gorkha stations and decrease at other two stations with varying percentages. Furthermore, R20 for RCP4.5and RCP8.5 is projected to increase only at the Khudi station albeit with different magnitudes.

The changes in the annual occurrence of summer days (SU), annual occurrence of tropical nights (TR), number of heavy precipitation days (R10), and number of very heavy precipitation days (R20) can have profound impacts on various sectors including ecosystems, as elaborated in literatures such as Alexander et al. (2006). And increase in projected warm temperature indices (warm days and nights (WSDI)) and the corresponding decreases in cool temperature indices (cool days, cool nights (CSDI)) have been observed all over Nepal under both RCP scenarios (4.5, 8.5) for the future (MoFE 2019).

3.2.3 Spatial distribution of climatic extremes

The spatial distribution in projected changes of the extreme climatic indices for RCP4.5 and RCP8.5 from the baselineand future periods (i.e., NF and MF) at four meteorological stations are discussed hereunder. As expected, different indices show varying degree of variation across the stations in terms of magnitude and direction of trends. Some indices may have some distinct trends from upstream to downstream while some may not. This section discusses spatial variation in selected set of indices.

Trends in monthly minimum of daily maximum temperature (TXn) are increasing significantly at all the stations in baseline (expect no significant trend at a station located in the middle of the watershed) and MF (both the scenarios), increasing insignificant trends in MF under both RCP scenarios (significant at middle of the watershed), and decreasing trends when towards north under both RCPs and scenarios (Fig. 3a). The rate of increase is higher from south towards north in the watershed.

Consecutive dry days (CDD) show distinct increasing trends from baseline to near and mid-future (significant trends towards north for baseline and NF4.5). However, the Gorkha station does not show any trends during baseline and NF8.5 while at some stations, insignificant decreasing trends are depicted (Appendix Fig. 6). In case of CWD, the trends for baseline as well as all future periods and scenarios are also increasing insignificantly at all the stations, except the case for MF under RCP4.5 (mixed trends) and insignificantly decreasing trends at all the stations in MF8.5 scenarios as well as at Thakmarpha and Khudi for NF both scenarios

(Appendix Fig. 7).

Trends in warm days (TX90p) are increasing insignificantly at three stations (except Khudi located in the southern part of the watershed) during the baseline. However, it shows significant increasing trends at all the stations in NF for both RCPs except at Khudi where the trend was significantly decreasing and at Gorkha showing no distinct trend. Similar increasing trends were also observed across all the stations for mid-future for both RCP scenarios (significant at MF8.5; Appendix Fig. 8). Similar historical (or baseline) trends were also observed by other studies in different parts of Nepal (e.g., Baidya et al. 2008; Shrestha et al. 2016a; Rajbhandari et al. 2017).

Trendsinwarm nights (TN90p) are significantly increasing in northern mountainous part of the watershed from the baseline to NF and MF under both scenarios. However, it shows significant decreasing trends in baseline at the Chame station while insignificant decreasing trend at Thakmarpha (Fig. 3b). Trendsincoldnights (TN10p) are decreasing atall the stations for all future periods and scenarios; however, mixed for baseline, with increasing trends at the stations located in the northern mountainous part of the watershed (Appendix Fig. 9). These results are consistent with the result of Panday et al. (2015) and Rajbhandari et al. (2017) for the Eastern Himalaya.

Trends in extreme wet days (R99p) show insignificant mixed trends for baseline and NF under RCP4.5 scenarios while it shows insignificant decreasing trends at most of the stations for NF8.5 (except Gorkha) and MF in both scenarios (expect at Khudi) (Appendix Fig. 10). In case of very wet days (R95p), the trends are also increasing insignificantly at all the stations for future except at that at baseline, it shows mixed trends (Appendix Fig. 11).

3.3 Trends in hydrological extremes

3.3.1 Change point analysis

Change point analysis (CPA), a powerful statistical technique to determine abrupt changes in a time series (Chang and Byun 2012), was used to identify pre- and post-impact periods for assessing hydrological extremes. In this study, the change points were identified for annual maximum (Tmax), minimum (Tmin), and average (Tav) temperatures at four stations;

Table 5 Degree of hydrological alterations of IHA parameters at Bimalnagar hydrological station in Marshyangdi watershed

Parameters	Pre-impact	CD	Post-impact	CD	P (%)	HA (%)
Group 1 (Magnitude of monthly water conditions (m^3/s)) parameters						24.4.0 (L)
January	50.2	0.09	50.02	0.10	− 0.4	59.4 (M)
February	43.3	0.16	44.10	0.14	1.8	28.9 (L)
March	43.3	0.20	42.90	0.16	− 0.9	28.9 (L)
April	50.15	0.26	54.53	0.30	8.7	21.9 (L)
May	71.4	0.58	82.95	0.42	16.2	28.9 (L)
June	197.5	0.38	210.00	0.75	6.3	21.9 (L)
July	414	0.70	573.00	0.15	38.4	7.1 (L)
August	648	0.25	659.50	0.18	1.8	21.9 (L)
September	390	0.24	444.80	0.43	14.1	7.1 (L)
October	167	0.26	195.40	0.28	17.0	28.9 (L)
November	93.7	0.21	95.60	0.25	2.0	28.9 (L)
December	63	0.08	65.45	0.12	3.9	8.6 (L)
Group 2 (Magnitude and duration of annual water extreme conditions (m^3/s)) parameters						16.8 (L)
1-day minimum	39	0.17	37.25	0.12	− 4.5	7.1 (L)
3-day minimum	39.97	0.17	38.50	0.14	− 3.7	7.1 (L)
7-day minimum	40.57	0.17	40.70	0.21	0.3	28.9 (L)
30-day minimum	42.57	0.17	42.63	0.16	0.1	7.1 (L)
90-day minimum	45.7	0.15	45.23	0.14	− 1.0	7.1 (L)
1-day maximum	1090	0.26	1219.00	0.31	11.8	21.9 (L)
3-day maximum	966.3	0.21	1086.00	0.19	12.4	62.5 (H)
7-day maximum	836.9	0.31	930.90	0.24	11.2	7.1 (L)
30-day maximum	674.4	0.28	761.40	0.21	12.9	21.9 (L)
90-day maximum	525	0.27	609.30	0.19	16.1	7.1 (L)
Baseflow index	0.20	0.18	0.17	0.26		7.1 (L)
Group 3 (Timing of annual extreme (days)) parameters						29.3 (L)
Date of minimum (Jmin)	73	0.09	69	0.14	− 5.5	36.8 (M)
Date of maximum (Jmax)	207	0.13	208	0.09	0.5	21.9 (L)
Group 4 (Frequency and duration of high and low pulses (numbers)) parameters						16.0 (L)
Low pulse count	4	1.13	5	2.0	25.0	36.8 (M)
Low pulse duration	5.5	2.64	5	3.2	− 9.1	21.9 (L)
High pulse count	3	1.50	3	0.3	0.0	0.7 (L)
High pulse duration	5	9.25	3.5	10.3	− 30.0	4.5 (L)
Group 5 (frequency and rate of change of water (m^3/s)) parameters						54.4 (M)
Rise rate	8.3	0.56	9.5	0.51	14.5	27.8 (L)
Fall rate	− 3.1	− 0.32	− 4.75	− 1.20	53.2	55.7 (M)
Number of reversals (number)	137	0.22	132.5	0.79	− 3.3	79.7 (H)
Overall degree (OD)						27.9 (L)

CD, coefficient of dispersion; H, high; HA, hydrological alteration; L, low; M, moderate; P, percentage of deviation annual precipitation at nine stations; and annual flow time series at one hydrological station in the Marshyangdi watershed. Results are tabulated in Appendix Table 9. The change points for various variables occurred at different years, some with statistical significance and some without. For example, change point for Tmax and Tmin at the Thakmarpha station is identified in 2002 (significant) and 2000 (insignificant).

Similarly, at the Khudi station, change points for Tmax, Tmin, and precipitation are detected in 1992 (insignificant), 1986 (significant), and 1990/2004 (insignificant), respectively. In case of river discharge, CP in time series is detected in 1999 (insignificant). The CP at other stations are reported in Appendix Table 9. Following the CP detected in discharge time series as 1999, as well as significant CP for the precipitation at Manang Bhot, we have taken this year to separate pre- and post-impact periods in the IHA tool. Literatures (e.g., Khadka and Pathak 2016) also report flood causalities in the Barpak village of Gorkha district, located within the watershed, during the same year the CP was detected. However, no specific mechanism for the CP could be identified.

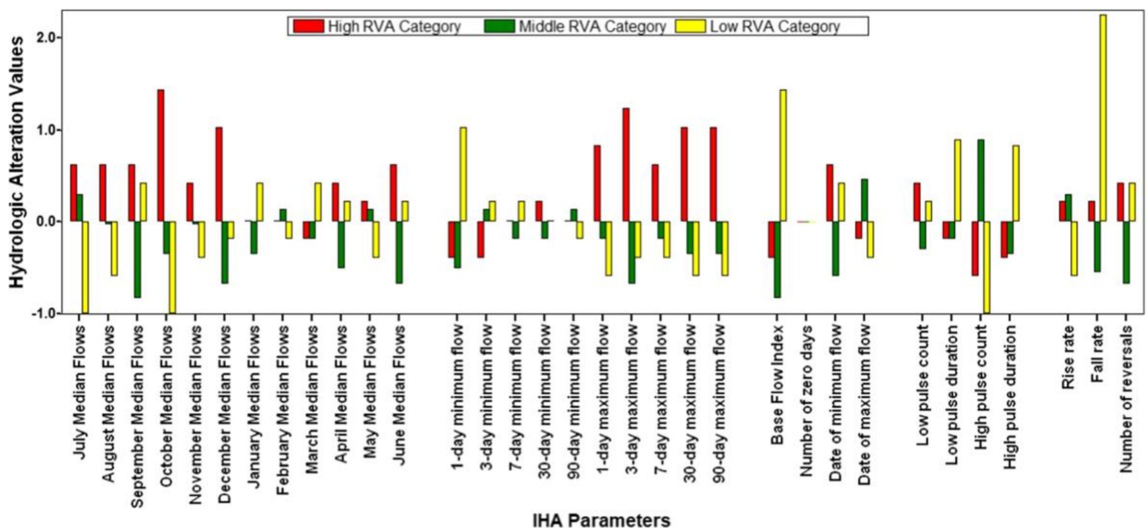


Fig. 4 Hydrological alterations (values shown in bars) for all 33 IHAs

3.3.2 Changes in flow characteristics after change point

The median value, degree of deviation, and degree of alteration for the IHA parameters characterizing five groups of extreme flow regimes at Bimalnagar hydrological station in the Marshyangdi watershed are listed in Table 5 and elaborated hereunder. Percentage of deviation (P), degree of hydrological alteration (HA), and overall hydrological alteration were calculated using Eqs. (1), (2), and (3) detailed in Appendix

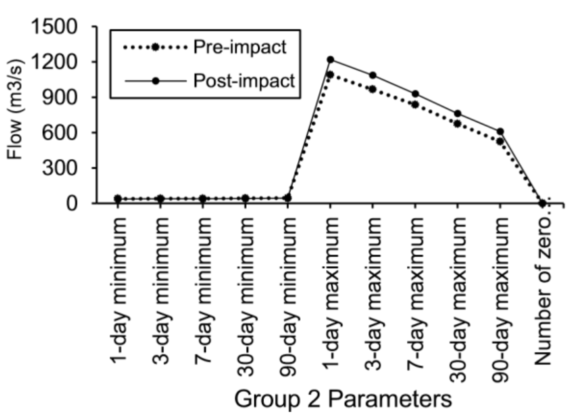
1. Values of hydrological alterations for each indicator are shown in Fig. 4. An overall mean hydrological alteration of all the 32 parameters is estimated as low, with a value of 27.9%, whereas alterations of 32 parameters within five groups vary widely as elaborated in following sub-sections.

Alterations in magnitude of monthly streamflow

As depicted from Table 5 and plotted in Appendix Fig. 12, the monthly median parameters increased from pre- to post-impact period, and the increases in monthly median values under high RVA category, except in January and March, have been observed indicating an insignificant increase of the frequency of observed values than the upper RVA limit. The degree of deviation (P) is negative only for the January and March out of 12 months (Table 5), suggesting that streamflow has been increased from pre- to post-impacted period. Calculation of degree of HA for monthly stream flow shows that monthly stream flows fall within the category of low alteration (D < 33%), except in the month of January where the alteration is moderate (33% < D < 67%). In a nutshell, median values among the Group-1 IHAs show low hydrological alteration (24.4%).

Alterations in annual extreme flow conditions

Analysis of median values of degree of deviation and degree of hydrological alteration for the annual extreme flow conditions (11 IHAs under Group-2 and 2 IHAs under Group-3) reveal that degree of deviation is highest (16.1%) for a 90-day maximum, followed by 30day maximum (12.9%) (Fig. 5) whereas it decreases in 1-day, 3day, and 90-day minimum extreme flow parameter from pre- to post-impact period. This suggests a possible increase in flood magnitude, which may have been both beneficial as well as harmful effects depending on channel morphology, types of substrate, depth, and other



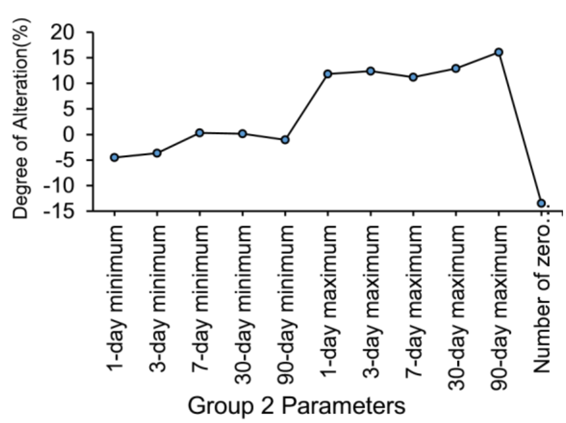


Fig. 5 Annual extreme flows—flow value (left) and degree of deviation (right)

geomorphological characteristics (Stefanidis et al. 2016). Furthermore, increase in 1-day, 3-day, and 7-day maximum flow causes change in the floodplains due to dominant particle size of bed materials inducing ecological implications like low oxygen and prolongation of duration of stressfulhightemperatures(Graf2006).HA indicateslowdegree of alteration (< 33%) among the indices; however, for the 3-day maximum, it shows moderate alteration (Table 5). Overall, the degree of hydrological alteration for Group-2 is 16.8%, indicating the low hydrological alteration (D < 33%).

In case of timing of annual minimum extremes (i.e., indicators under Group-3), the degree of deviations (%) is negative, i.e., timing of 1-day minimum is moving backward from the 69th day to 73rd (delayed by 5 days); however, 1-day maximum is also moving forward from the 207th day to 208th day from pre- to post-impact period. Thus, lagging of Julian date of minimum streamflow indicates that annual minimum values will appearearly in the year threating the riverine environment (Xue et al. 2017). The hydrological alterations for timing of 1-day minimum (Jmax) and 1-day maximum (Jul-min) are identified as moderate and low category, respectively (Table 5). The overall degree of hydrological alteration of IHAs under Group-3 is low with a value of 29.3% (33% < D < 67%). Thus, observed shift in occurrence of low flows implies earlier drying up of the downstream channel, which may have adverse consequences on the flood plain habitats, ecology, and navigability of a river (Sharma et al. 2019).

Alterations in frequency and duration of high and low flow pulses Among the Group-4 parameters, the frequency of low (25th percentile) pulse count increases from the pre- to postimpact period; however, the and high (75th percentile) pulse counts does not show any change, while the duration of high and low pulse counts decreases from the pre- to post-impact period (Table 5). The degree of deviation (5, Appendix Fig. 13) for the low pulse counts is 25% which falls under high RVA category (Fig. 4). Degree of hydrological alteration for low pulse count is characterized as “moderate (M)” but for other three parameters under Group-4 are characterized as “low (L).” Thus, four parameters under Group-4, altogether, show low degree of hydrological alteration (16%). The increase in the low pulse counts may cause frequent dry and wet situations, thus, potentially worsening the ecological development of the Marshyangdi river floodplain. However, the low alteration in the high pulse count as well as duration may not favor the riverine ecosystem due to the limited nutrients availability for plants along the riverbank affecting the promotion of river biodiversity (Xue et al. 2017). Thus, low pulse count may induce geomorphic implications like the prolongation of a channel and bank stability, which increased frequency of depositional regimes in the channels. Concomitantly associated ecological implications include stress for plants due to the changes in frequency and magnitude of soil moisture, which causes anaerobic condition and may lack availability of floodplain for aquatic organisms (Graf 2006).

Alterations in rate and frequency of flow conditions The Group-5 parameters, altogether, exhibit moderate hydrological alteration of 54.4%. However, the hydrological alteration varies across the parameters; showing highest alteration in reversals (79.9%) followed by fall rate (55.7%) (Table 5). The increase in rise rate and fall rate in the post-impact period, suggests that the rate of change from high flow to low flow conditions and vice versa would be accelerated. It implies early arrival of peak streamflow in the downstream channel (Sharma et al. 2019), which corresponds well to the results of backward shifting of timing of 1-day maximum as discussed earlier. Number of reversals (number of times that flow switches from one type of period to another) of streamflow conditions which indicate change from rising water condition to falling water condition and vice versa decreases from preto post-impact period (Table 5), indicating low intraannual fluctuations in water conditions of the downstream channel. Higher degree of deviation (53.2%) for the fall rate compared with deviations in number of reversals (− 3.3%) indicates high hydrological alteration for the number of reversals and moderate alteration for fall rate, respectively. This increase in rise and fall rate indicates the rise in abruptness in streamflow. The accelerated rise and fall rate, which indicates the rise in abruptness of streamflow, could trap aquatic organisms in floodplains and strand terrestrial organisms on floodplain island The Nature Conservancy (2009). This may affect the stability of plant and animal habitat (Xue et al. 2017). Based on RVA results, most of the parameters in groups 1 and 2 as well as indicators related to low pulse count (group 4) and group 5 parameters increased under high RVA category, which reflects increase in frequency of observed values than the upper RVA limit (Fig. 4).

3.3.3 Trends in extreme hydrological indices

We analyzed trends in 15 hydrological extreme indices and tabulated results (i.e., trends, average value of indices, and interannual variability) in Appendix Table 11. Fifteen selected hydrological extreme indices having varying direction and magnitude of trends. Some indices such as 3-, 7-, and 30-day maximum flows show increasing (statistically insignificant) annual trends of + 7.5 m^3/s/year, 4.4 m^3/s/year, and 5.5 m^3/s/year, respectively; whereas 1-day and 90-day maximum flows have increasing (statistically significant) trends of 0.4 m^3/s/year and 4.8 m^3/s/year, respectively. However, 3-, 7-, 30- and 90-day minimum flows have insignificantly decreasing trend (Appendix Table 11).

Like climate extreme indices, hydrological extremes also have inter-annual variability in the index value, as shown in Appendix 2, Table 11 for 1-day maximum flow as an example. The index has an average value of 1287.21 m^3/s with a trend (statistically significant) of + 0.36 m^3/s/year during1987–2015; however, the index value varies from 679 to 2270 m^3/s for the aforementioned period, with a coefficient of variation of 0.30. It is therefore important to note those variabilities too while using the results for informed decision-making on managing hydrological extremes.

4. Conclusions

This study assessed hydro-climatic extremes in the Marshyangdi watershed for historical as well as future periods at four climatic stations and one hydrological station. An ensemble of three regional climate models (RCMs) were used to project future climate and assess projected trends in the climatic extremes under RCP4.5 and RCP8.5 scenarios for two future periods, namely, near future and mid-future. Key conclusions specific to the study of watershed, based on analysis of the results, are listed hereunder. Though it reflects some aspects of the Himalayan watersheds, we need to study more on watersheds to generalize the conclusions for the entire Himalayan region.

& Climatic extremes over the historical period (1983–2013) indicate hotter and drier conditions in the watershed, albeit with varying amount and significance (statistical) across the stations. Temperature-related indices such as WSDI and TX90p have increasing trends whereas TN90p and TX10p have decreasing trends. Heavy precipitation indices suchasR10,R20,RX1day, and R99pshow increasing trends for almost half of the 10 stations where CDD are increasing at most of the stations.

& Future is projected to be wetter and warmer in the Marshyangdi watershed. Significant increase in trends for maximum temperature-related extremes (e.g., TN90p, TX90p, and TNx) and significant decrease for minimum-temperature-related extremes (e.g., TN10p, TX10p) from baseline to future periods under both the scenarios and future periods are considered. However, precipitation extremes such as R99, RX5day, CWD, and CDD are projected to decrease, with potential implications on water availability and its distribution across seasons.

& Overall hydrological alterations as an indication of hydrological extremes is estimated as low (HA = 27.9%) in the Marshyangdi watershed. Increase in the median flow values especiallyduringtheperiodofMarch–Augustandconsequent increase in the 30- and 90-day maximum values indicates the possibility of flood in the basin. On the other hand, increase in rise rate and decreases in the fall rate represent abruptness in the streamflow and inter-annual variability. Further, projected increase in climate change along with anthropogenic influences may affect the natural flow regime of the Marshyangdi watershed which may exacerbate in the future and the implications pointed out could have severe ecological consequences with the high degree of hydrological alteration

The watershed spans from the mountains in the north to the plains in the south, and the climatic extremes are analyzed at multiple stations spanning from north to south. The results therefore could be indicative of extremes at particular physiographic regions at other basins in Nepal as well. Like other snow-fed and glacierized catchments, which are highly influenced by climate change and associated melting of snow/glacier (Mingjie et al. 2013), projected increase in average annual precipitation at all the stations and higher increase in temperature in the Marshyangdi watershed and associated melting of snow/glacier may lead to an increase in water availability. As there are many hydropower projects as well as agricultural areas in the watershed, increase in water availability can lead to positive implications, if that could be harnessed properly. However, increase in average annual rainfall is associated with increase in number of heavy and very heavy precipitation days too, which means, available rainfall will be highly skewed over certain periods in a year. If excess precipitations are not stored in watersheds, hydrological extremes may increase in magnitude as well as frequency, which is clearly evident in the analysis of hydrological alteration indicators in this study. The increase in hydrological extremes means potential increase in loss and damage in the watershed. These results imply that investment in various water storage mechanisms, such as soil water storage in watershed, rainwater harvesting at household and community levels, storage in aquifers, and storage in river corridor itself is required to make productive use of excess rainfall and runoff and at the same time reduce potential losses and damages associated with hydrological extremes. Therefore, analyzing historical as well as future climatic extremes together with hydrological extremes are valuable to get a bigger picture for designing interventions for water resources development and management in a holistic way.

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Appendix 1. Formula for calculatinghydrological alteration

The percentage of deviation degree of each hydrological alteration of streamflow regime is calculated as (Timpe and Kaplan 2017; Xue et al.2017):

$$P_i(\%) = \frac{(M_{post} - M_{pre})}{M_{pre}} * 100 \qquad (1)$$

where M_{post} is the median for the post-impact period and M_{pre} is the median for the pre-impact period. After calculation of percentage of deviation degree, these values were then averaged by parameter groups and across all parameters. A positive P_i value indicates an increased median value in the postimpacted period compared with the pre-impacted period while

a negative P_i suggests a decreased median value in the postimpacted period compared with the pre-impacted period.

Degree of hydrological alteration of a flow regime can be further calculatedfor eachindicator according tothe following equation (Ritcher et al.1998)

$$D_i = \left| \frac{OF - EF}{\quad} \right| 100 \qquad (2)$$

EF

where OF is the observed number of post-impacted years for which the value of the indicator falls within the RVA target range, from 25th percentile to 75th percentile, as suggested by Richteretal.(1998);EFistheexpectednumberofpost -impacted years for which the value of indicator falls within the targeted range and can be estimated by r × NT (r is percentage of preimpactedyearsforwhichthevalueofanindicatorf allswithinthe RVA target range and NT is total number of post-impacted years). As different hydrological indices may show different variabilities in flow regime, hence, an overall degree (OD) of hydrological alteration of all indices may be computed as:

$$\frac{\sum_{i=1}^{32} D_i}{32} \quad 2$$

Dᵢ ¼ð3Þ

Appendix 2. Relevant tables referred in the manuscript

Table 6 Climatic models and scenarios used in climate change-related studies in Nepal

S. No.	River basin/ watershed	Climate model(s)	Scenarios	Time period	Focus	References
1	•Bagmati	•HadCM3	•SRES: A2; B2	B: 1970–1999 NF: 2010–2039 MF: 2040–2069 FF: 2070–2099	•Hydrological impact of future climate	Babel et al. (2013)
2	•Bagmati	•HadCM3	•SRES: A2; B2	Future decades: 2020; 2050;2080	•Climate change impact on irrigation water requirement	Shrestha et al. (2013)
3	•Chamelia	•ACCESS_CCAM •CNRM_CCAM •MPI.ESM_CCAM •MPI.E.MPI_REMO •ICHEC_RCA4	•RCP: 4.5; 8.5	B: 1980–2005 NF: 2021–2045 MF: 2046–2070 FF: 2071–2095	•Climate change impact on hydrology	Pandeyet al. (2019)
4	•Dudhkoshi	•PRECIS	•SRES: A1B	B: 2000–2010 NF:2040–2050 FF:2086–2096	•Climate change impact on hydrological regime	Nepal (2016)
5	•Hindukush Himalaya	•PRECIS	•SRES: A1B	NF: 2011–2040 MF: 2041–2070 FF: 2071–2098	•Climate change	Kulkarni et al. (2013)
6	•Hindukush Himalaya	•CMIP3 •CMIP5	•SRES: B1, A1B, and A2 for CMIP3 •RCP8.5 for CMIP5	B: 1970-1999 MF: 2020–2049 FF: 2070–2099	•Change and trends of temperature and precipitation indices	Pandayet al. (2015)
7	•Indrawati	•ECHAM4/OPYC3 •HadCM3 model	•SRES: A2; B2	B: 1961–1999 Future decades: 2020; 2050; 2080	•Climate change impact on flow regime	Bhatta (2016)
8	•Indrawati	•HadGEM3-RA •MIROC-ESM	•RCP: 4.5; 8.5	B: 1995–2004		Shrestha et al. (2016d)

Table 6 (continued)

S. No.	River basin/ watershed	Climate model(s)	Scenarios	Time period	Focus	References
		•MRI-CGCM3		Future decades: 2020; 2030; 2040; 2050; 2060; 2070; 2080; 2090	•Climate change impact on hydrology and water availability	
9	•Kaligandaki	•GCM •CMCC-CMS	•RCP: 4.5; 8.5	B:1981–2010 F: 2041–2070 FF: 2071–2100	•Climate change impact on hydrological regime and water balance	Bajracharya et al. (2018)
10	•Karnali	•GCM from CanESM2	•RCP: 2.6; 4.5; 8.5	NF: 2011–2040 MF: 2041–2070 FF: 2071–2100	•Climate change	Shrestha et al. (2016b)
11	•Koshi	•CNRM-CM3 •CSIRO-Mk3.0 •ECHam5 MIROC 3.2	•SRES: A2; B1	B: 1971–2000 F: 2016–2045	•Climate change imp act on hydrological regime	Bharati et al. (2012)
12	•Koshi	•GCMs (10)	•SRES: B1; A1B; A2	3 future periods: 2020s; 2055s; 2090s	•Precipitation projection	Agarwal et al. (2014)
13	•Koshi	•CSIRO-Mk3.5 •ECHam5 •MIROC3 •CNRM-CM3	•SRES: A2; B1	B: 971–2000 NF: 2016–2045 FF: 2036–2065	•Climate change impact on water availability	Bharati et al. (2014)
14	•Koshi	•PRECIS-HADCM3Q •PRECIS-ECHAM05	•SRES: A1B	B: 1976–2000 F: 2040–2060	•Climate change •Hydrological regime	Devkota and Gyawali (2015)
15	•Koshi	•CNRM-CM3 •CSIRO-Mk3.5 •ECHam5 MIROC3.2	•SRES: A2; B1	B: 1971–2000 NF: 2030 FF: 2050	•Climate change impact on hydrological regime	Bharati et al. (2016)
16	•Koshi	•GCMS (10)	•SRES: B1; A1B; A2	NF: 2011–2030 MF: 2046–2065 FF: 2080–2099	•Climate projection	Agarwal et al. (2016)
17	•Koshi: Tamor, Arun, Dudhkoshi,	•PRECIS-ECHAM05 •PRECIS-HadCM3	•SRES: A1B	B: 2000–2008 F: 2041–2060	•Climate change •Snowmelt hydrology	Khadka et al. (2016)

	Tamakoshi, Sunkoshi					
18	•Koshi	•CMIP5 GCMs (8)	•RCP: 4.5; 8.5	B: 1961–1990 F: 2021–2050	•Projection of future climate	Rajbhandari et al. (2016)
19	•Koshi	•PRECIS	•SRES: A1B	NF: 2011–2040 MF: 2041–2070 FF: 2071–2098	•Project future extreme climate	Rajbhandari et al. (2017)
20	•Kulekhani	•CCSR/NIE •CGCM3 •CSIROECHM4 •HadCM3	•SRES: A2; B2	B: 2010–2039 NF: 2040–2069 FF: 2070–2099	•Climate change impact on future river discharge	Shrestha et al. (2014)
21	•Marshyangdi	•GCM SDSM (4.2)	•SRES: A1B	Future decades: 2030–2050, 2080	•Future water availability •Change in rainfall pattern	Parajuli et al. (2015)
22	•Marshyangdi	•CanESM2	•RCP: 2.6; 4.5; 8.5	NF: 2011–2040 MF: 2041–2070 FF: 2071–2100	•Climate change projection	Khadka and Pathak (2016)
23	•Narayani	•HadCM3 •PRECIS RCM	•SRES: AIB	B: 1970–2000 F: 2030–2060	•Climate change impact on hydrology •Future flood magnitude	Bhattarai et al. (2018)
24	•Sunkoshi	•PRECIS •ECHAM5 •RegCM4 •ECHAM4	•SRES: A1B; A2	NF: 2041–2050 FF: 2051–2060	•Climate change impact on hydrology	Magar et al. (2016)
25	•Tamakoshi	•HADCM3 •CGCM3	•SRES: A2 and B2; A2 and A1B	B: 2000–2009 F: 2000–2059	•Future change in climate	Khadka et al. (2014)
26	•Tamakoshi	•MIROC-ESM, MRI •CGCM3 •MPI-ESM M	•RCP: 4.5; 8.5	NF: 2015–2039 MF: 2040–2069 FF: 2070–2099	•Climate change impact in hydropower	Shrestha et al. (2016c)
27	•West Seti	•ECHAM5 •HadCM3 in PRECIS •Era40, CCSM •ECHAM5 GFDL •HadCM3 in WRF	•SRES: A1B	B: 1971–2000 F: 2031–2060	•Climate change impact on water balance and crop yields	Gurung et al. (2013)

28	•West Seti	•WRF/GRADS	•RCP: 4.5	B: 1996–2013 F: 2050	•Impact of climate change on water availability and future flow	Maharjan et al. 2016
29	•West Seti	• •MPI-ESM-LR	•RCP: 4.5; 8.5	B: 1976–2005	•Streamflow projection	

Table 6 (continued)

S. No.	River basin/ watershed	Climate model(s)	Scenarios	Time period	Focus	References
		• •PRECIS-1 • •NorESMI1-M • •ICHEC-EC-EARTH •CCM4 •CNRM-CM5 •MPI-M-MPI •ESM-LR		F: 2071–2100		Shrestha et al. (2017)

B, baseline; F, future; FF, far future; MF, mid-future; NF, near future; RCP, representative concentration pathway; SRES, special report on emission scenarios

Table 7 Details of the hydrometeorological stations used in this study

Index	Station	Data	Data length	Latitude (°N)	Longitude (°E)	Altitude (m)	District
604	Thakmarpha	P, T	1983–2013	28.8	83.7	2566	Mustang
802	Khudi Bazar	P, T	1983–2013	28.3	84.4	823	Lamjung
806	Larke Samdo	P	1979–2017	28.7	84.6	3650	Gorkha
807	Kunchha	P	1977–2017	28.1	84.4	855	Lamjung
808	Bandipur	P	1977–2017	27.9	84.4	965	Tanahu
809	Gorkha	P, T	1977–2017	28.0	84.2	1097	Gorkha
816	Chame	P, T	1990–2011	28.6	84.2	2680	Manang
817	Damauli	P	1977–2014	28.0	84.3	334	Tanahu
820	Manang Bhot	P	1981–2012	28.7	84.0	3420	Manang
823	Gharedunga	P	1977–2013	28.2	84.6	1120	Lamjung
439.3	Bimalnagar	Q	1987–2015	27.57	84.25	354	Tanahu

Source: DHM, Nepal

P, precipitation; T, temperature; Q, discharge

Table 8 Projected changes in future climatic extreme indices (based on ensemble time series) for RCP4.5 scenarios across four stations in the Marshyangdi watershed

Indices	Thakmarpha (index:604)		Chame (index:816)		Khudi (index:802)		Gorkha (index:809)	
	Hist.	Change (%)	Hist.	Change (%)	Hist	Change (%)	Hist	Change (%)

		NF	MF		NF	MF		NF	MF		NF	MF
SU25	0.9	−100.0	−61.7	0.7	−78.1	−41.5	255.7	1.6	5.0	227.7	3.5	8.8
TX10p	9.8	−30.3	−31.4	7.7	−11.1	−11.2	10.4	−34.2	−32.8			
TXx	25.2	−5.5	−3.4	24.1	−1.2	1.9	34.9	−1.3	0.1	34.4	−4.1	−3.4
TNx	15.4	−0.8	2.8	12.4	15.9	23.6	24.0	2.1	7.3	24.2	−0.9	2.5
TXn	3.1	146.7	178.7	6.3	12.9	21.9	14.6	23.4	27.4	13.7	16.9	25.2
TN10p	8.9	−42.3	−38.8	7.3	−29.4	−26.4	10.7	−35.4	−34.0			
TX90p	9.2	−26.2	−24.5	7.3	−6.7	−7.0	9.7	−28.9	−26.5			
TN90p	9.6	−30.7	−30.0	7.3	−8.8	−8.0	9.7	−31.0	−28.4			
CSDI	3.2	−29.5	−49.9	6.7	−78.3	−70.1	15.2	−75.9	−68.0			
WSDI	3.7	39.6	78.0	8.2	−41.8	−59.5	4.7	−18.8	−22.0			
CDD	70.5	−40.4	−36.6	65.3	−61.9	−48.9	58.5	−56.8	−52.4	63.4	−57.8	−44.5
CWD	5.7	66.3	71.6	22.9	43.2	38.0	31.8	226.0	171.7	11.9	164.0	117.9
PRCPTOT	384.1	8.1	16.0	1101.4	6.6	9.1	3359.4	7.3	7.6	1735.1	−0.3	2.1
R99p	28.2	50.0	64.8	93.2	4.7	4.0	155.1	16.0	20.0	129.4	−28.0	−20.6
RX1day	35.7	−1.8	8.4	41.4	27.4	24.8	128.9	−33.5	−27.8	101.6	−47.5	−40.5
RX5day	57.1	2.5	−2.1	105.1	−4.6	−11.1	294.1	−18.2	−14.0	195.6	−34.9	−26.7
R20	2.6	−36.9	−19.7	9.5	−38.6	−32.8	61.4	10.7	11.3	28.9	−25.9	−17.9
R10	9.7	−39.9	−30.1	42.0	−42.1	−35.6	90.8	32.4	27.4	53.3	19.5	17.3
SDII	9.7	−32.5	−30.0	9.9	−38.1	−37.6	22.6	−26.5	−25.3	16.2	−40.5	−38.4

Notes: Historical (Hist.) values are the actual values with units as indicated in Table 2; change (%) are the change in future w.r.t. baseline

NF, near future; MF, mid-future

S. No.	Station name (index)	Variable	Change point (year)	p value
1	Thakmarpha (604)	Minimum temperature (Tmin)	2000	0.26
		Maximum temperature (Tmax)	2002	0.01*
		Average temperature (Tav)	2000	0.01
		Precipitation (PPT)	NA	
2	Khudi (802)	Tmin	1986	0.001*
		Tmax	1992	0.01
		Tav	2000	0.01*
		PPT	1990/2004	0.38
3	Gorkha (809)	Tmin	2002	0.03*
		Tmax	1991	1E−04
		Tav	2000	0.01*
		PPT	1986/1996	0.41
4	Chame (816)	Tmin	2002	0.002*
		Tmax	2000	0.001*
		Tav	1997	0.840
		PPT	1998	1.100
5	Larke Samdo (806)	PPT	1998	0.002*
6	Kunchha (807)	PPT	1997	0.910

Table 9 Change-point analysis for hydro-meteorological variables in the Marshyangdi watershed

7	Damauli (817)	PPT	1990	0.120
8	Gharedunga (823)	PPT	1985	0.690
9	Manang Bhot (820)	PPT	1999	0.010*
10	Bimalnagar (439.3)	Q	1999	0.37

*Significant at 95% confidence interval

Table 10 Summary of hydrologic parameters used in the indicators of hydrologic alteration

IHA statistics group (number of parameters)	Regime characteristics	Hydrological characteristics
Group 1: Magnitude of monthly water conditions (12 parameters)	•Magnitude •timing	•Mean or median value for each calendar month
Group 2: Magnitude and duration of annual water extreme conditions (12 parameters)	•Magnitude	•Annual maxima and minima, 1-day mean
	•Duration	•Annual maxima and minima of 3-day mean
		•Annual maxima and minima of 7-day mean (weekly)
		•Annual Maxima and minima of 30-day mean(monthly)
		•Annual maxima and minima of 90-day mean
		•Number of zero-flow days
		•Base flow index
Group 3: Timing of annual extreme (2 parameters)	•Timing	•Julian date of each annual 1-day maxima
		•Julian date of each annual 1-day maxima
Group 4: Frequency and duration of high and low pulses (4 parameters)	•Magnitude	•No of high pulses in each year
	•Frequency	•No of low pulses in each year
	•Duration	•Mean or median duration of high pulses within each year
		•Mean or median duration of low pulses within each year
Group 5: Rate and frequency of water (3 parameters)	•Frequency	•Rise rates: mean or median of all positive differences between consecutive daily means
	•Rate of change	•Fall rates: mean or median of all negative differences between consecutive daily means
		•Number of hydrologic reversals

Table 11 Trends in selected hydrologic extreme indices

S. No.	Index name	Index value (mean)	Index value range	CV	Amount of trend
*1	1-day min	39.3	30.4–51.7	0.14	− 0.35
2	3-day min	40.1	30.6–51.7	0.13	− 0.21
3	7-day min	41.1	31.2–52.3	0.13	− 0.19
4	30-day min	43.3	34.8–54.6	0.12	− 0.11
5	90-day min	46.7	37.6–60.8	0.12	− 0.09
6	1-day max	1287.2	679–2270	0.30*	+ 0.36*
7	3-day max	1049.3	450–1773	0.25	7.51
8	7-day max	881.1	324.4–1140	0.20	4.43
9	30-day max	701.2	210.9–909.3	0.21	5.51
10	90-day max	558.6	117.1–729.8	0.22	4.77*
11	Low pulse count	6.6	0–19	0.81	0.23*
12	High pulse count	3.6	1–8	0.54	0.00*
13	Rise rate	8.8	0.8–23	0.49	0.01
14	Fall rate	− 4.7	− 10.8 to (− 1.6)	0.57	− 0.12
15	Reversals	139.9	44–224	0.33	2.80*

Statistically significant trends at 95% confidence level

Appendix 3. Relevant figures referred in the manuscript

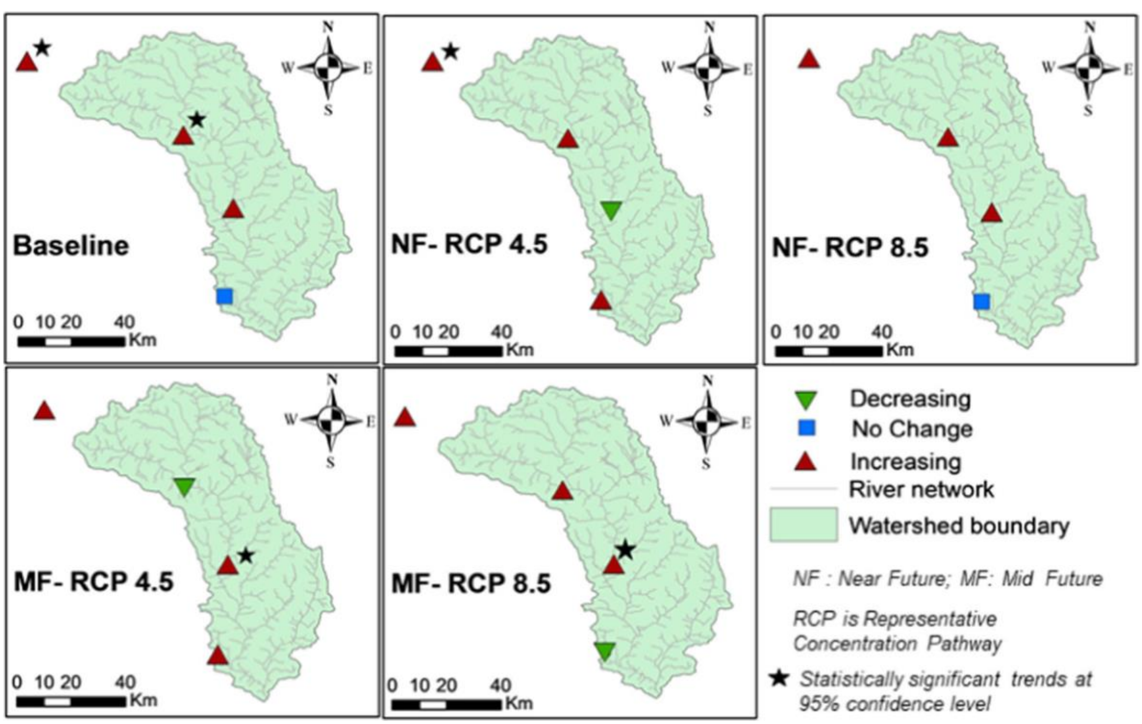

Fig. 6 Trends in consecutive dry days (CDD) across the stations

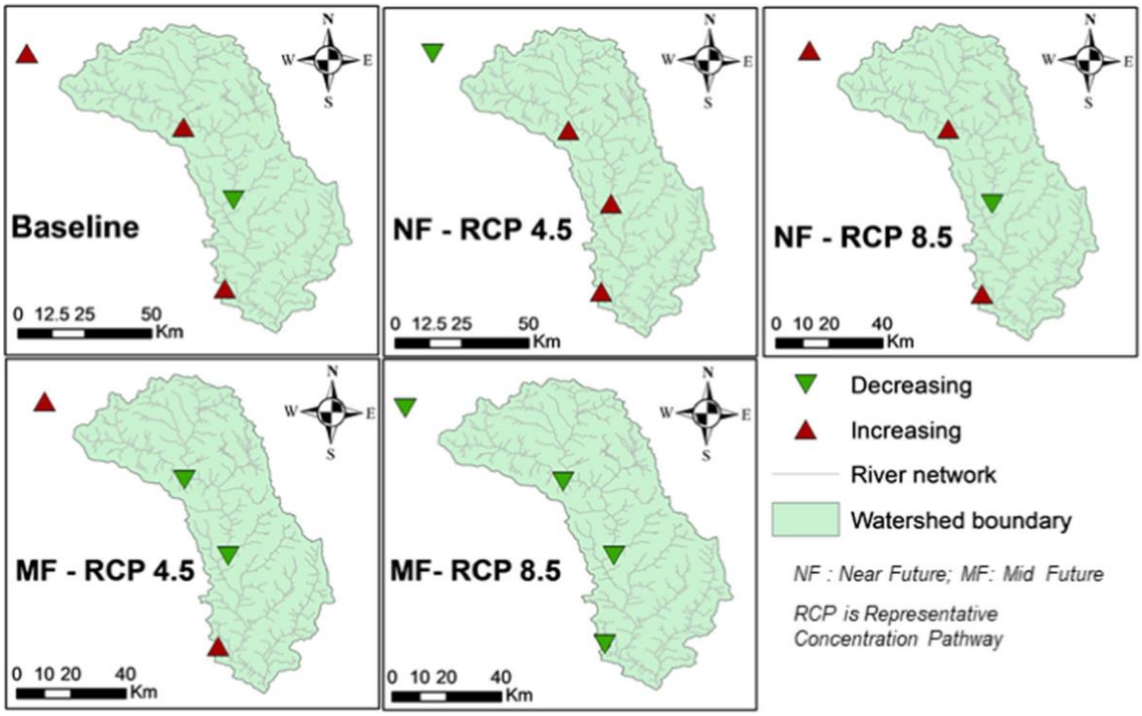

Fig. 7 Trends in consecutive wet days (CWD) across the stations

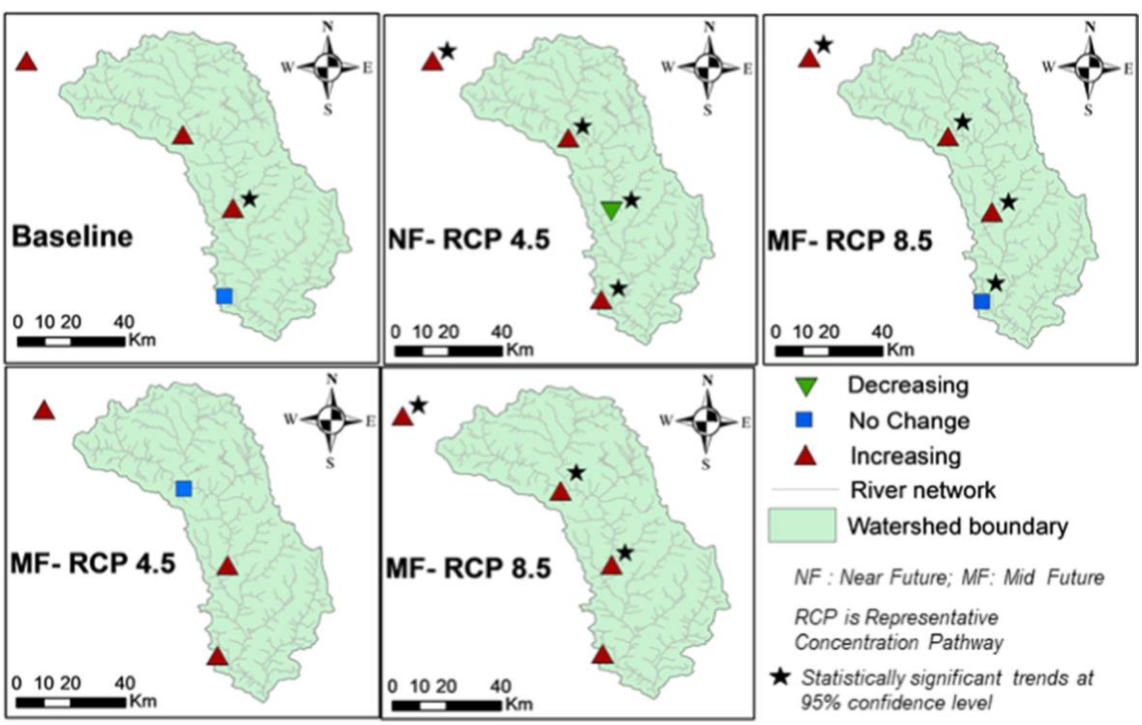

Fig. 8 Spatial distribution in warm days (TX90p) trends

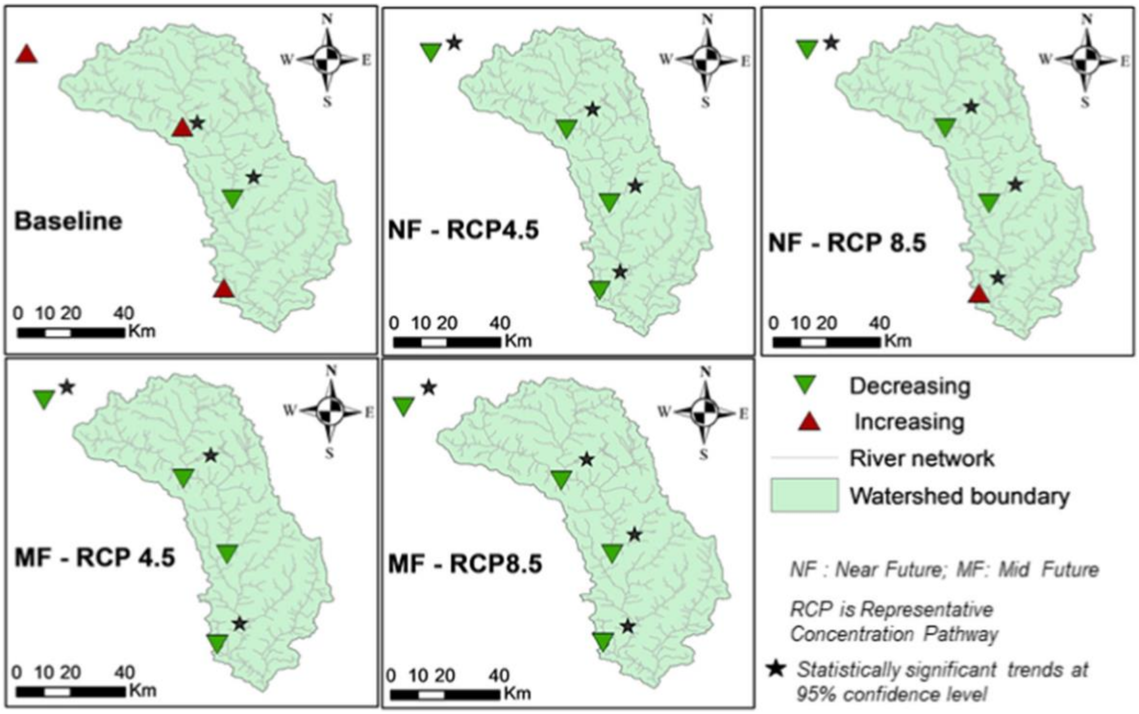

Fig. 9 Spatial distribution in cold nights (TN10p) trends

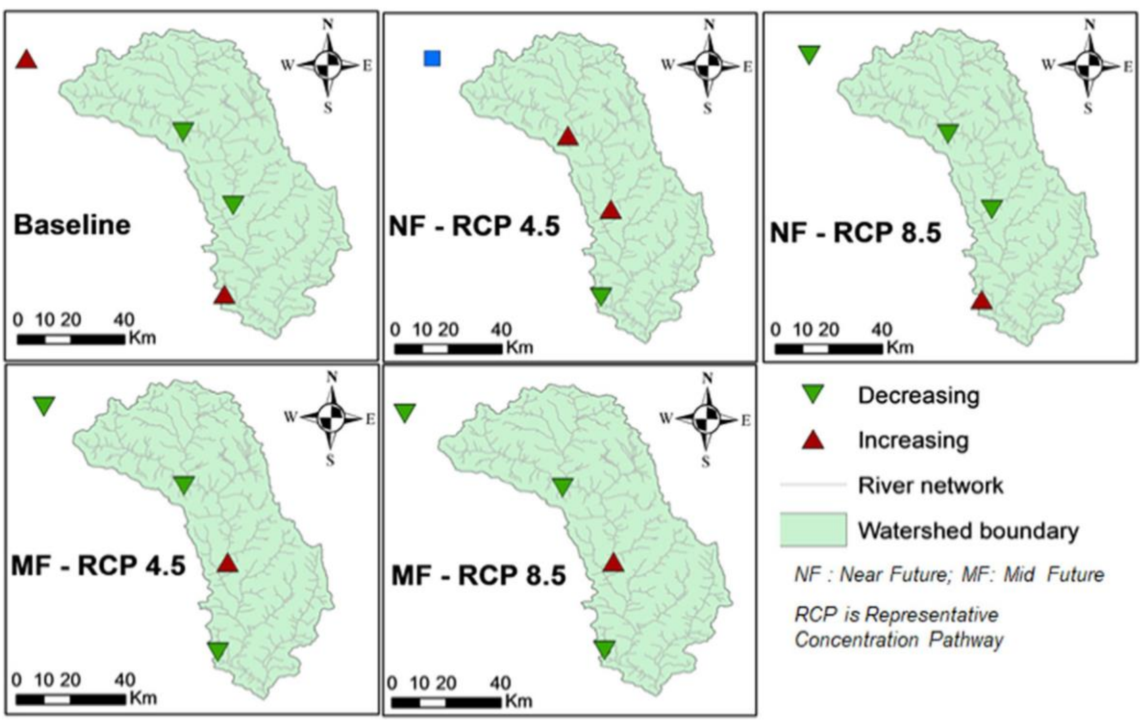

Fig. 10 Extremely wet days (R99p) for different future scenarios

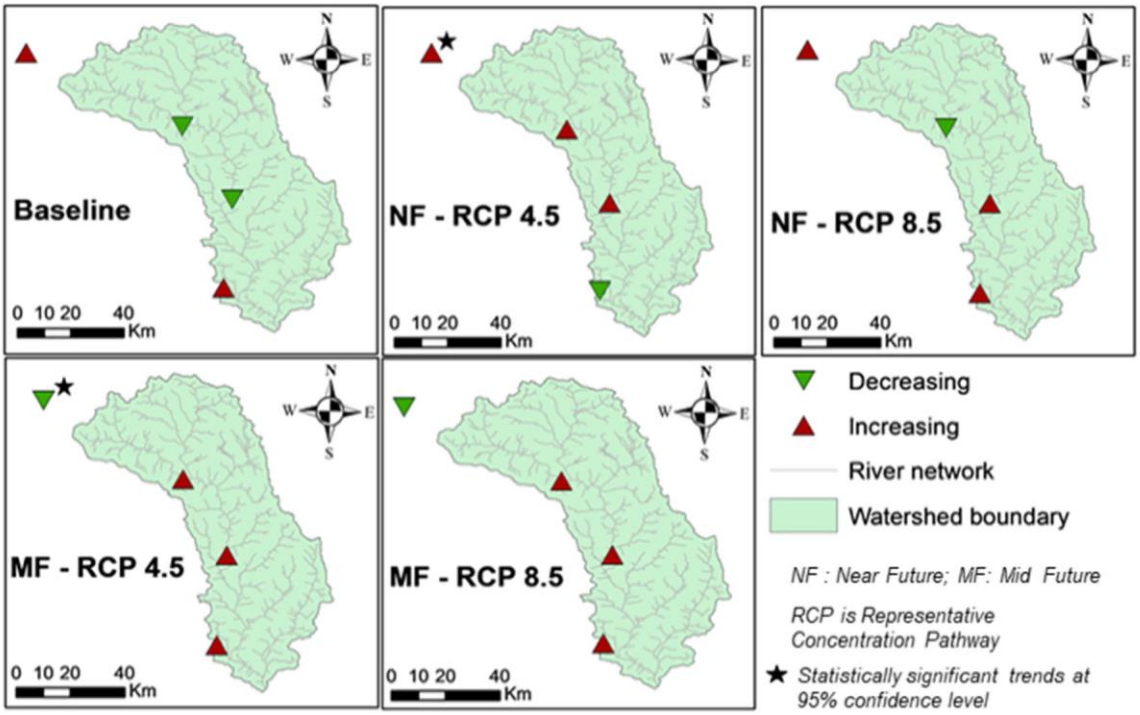

Fig. 11 Very wet days (R95p) for different future scenarios

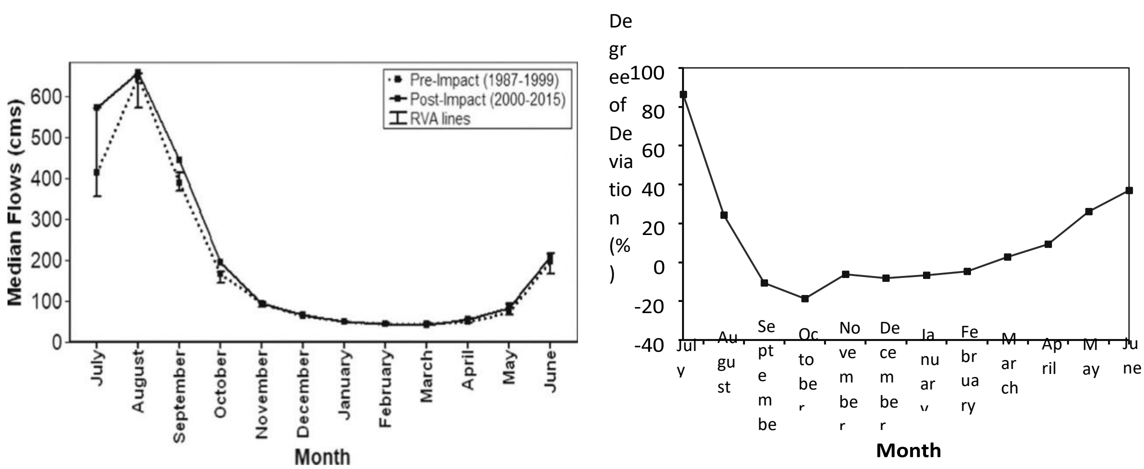

Fig. 12 Monthly median flows (group 1 parameters)—flow value (left) and degree of deviation (right)

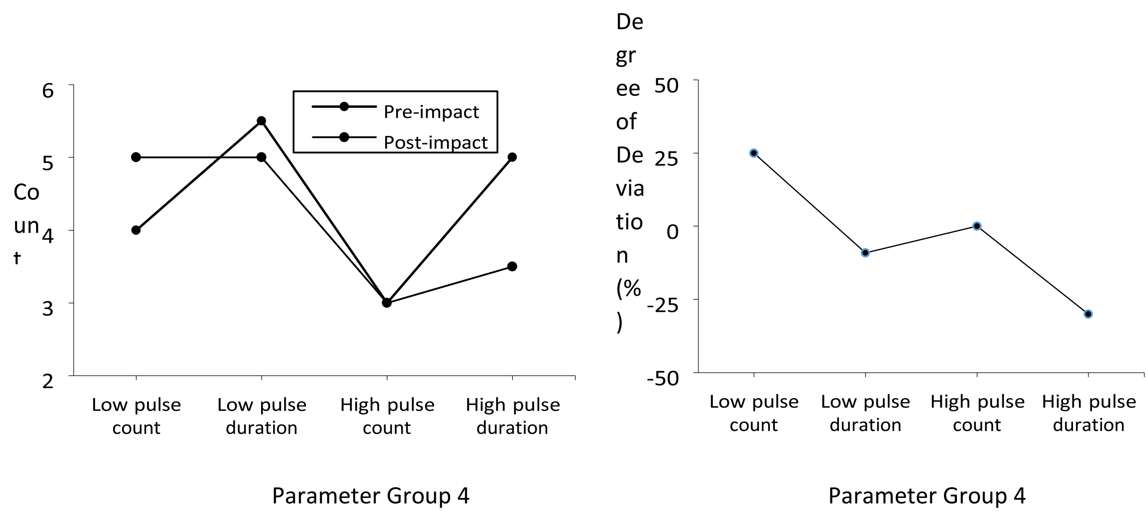

Fig. 13 Pulse count and duration (left and degree of deviation on those values (right))

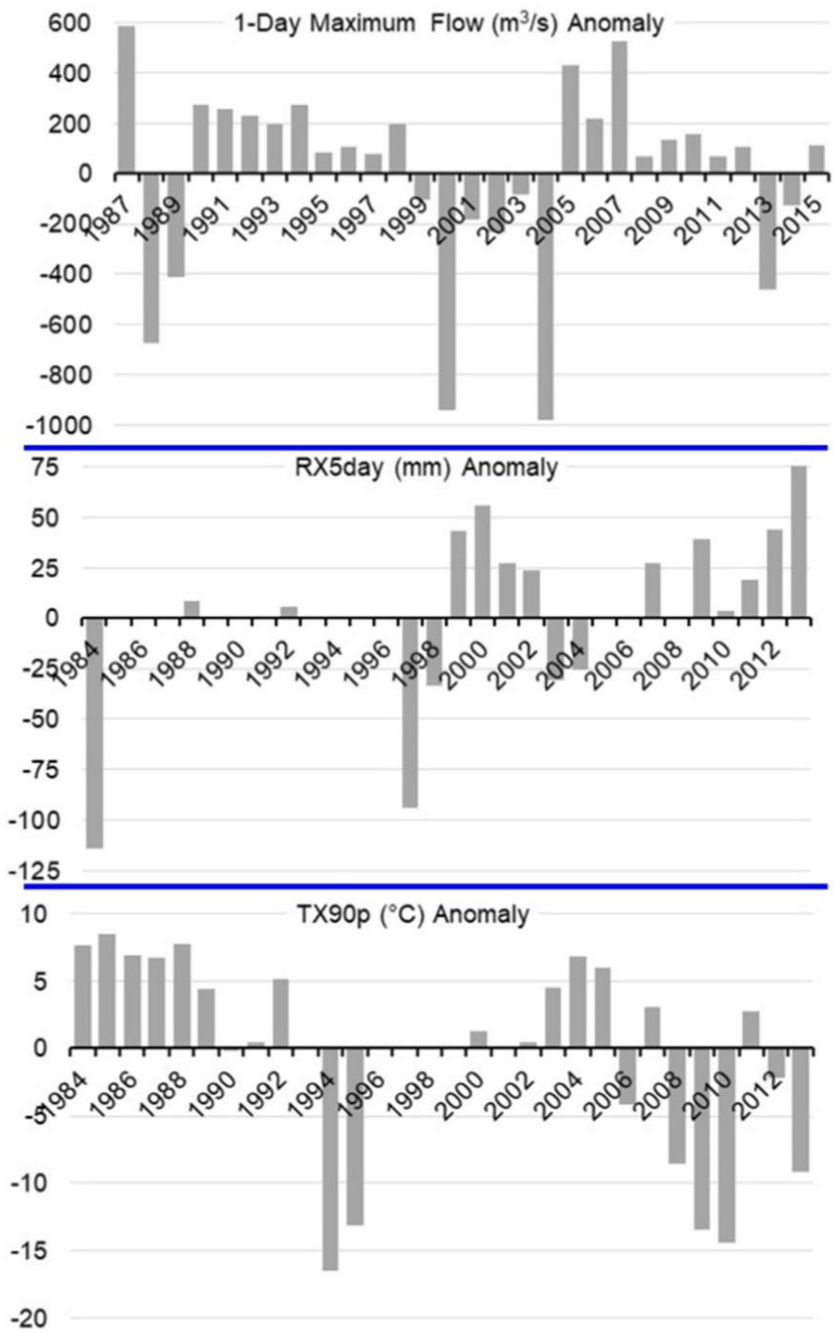

Fig. 14 Anomaly of selected hydro-climatic extreme indices

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Annex-19 Water Quality of Marshyangdi River, Nepal: An Assessment Using Water Quality Index (WQI)

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WATER QUALITY OF MARSHYANGDI RIVER, NEPAL: AN ASSESSMENT USING WATER QUALITY INDEX (WQI)

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ABSTRACT

Water quality index (WQI) is a valuable arithmetic tool that depicts the overall status of water quality in a single number to prioritize for management interventions. This study aims to assess water quality based on the WQI to provide insights into the status of the aquatic ecosystems in the Marshyangdi River basin, a tributary of the Narayani River, originating from the Himalaya. Water samples were collected from twenty-one sampling locations in the Marshyangdi River covering four districts from upstream (Kangsar) to the downstream region (Mugling) during pre-monsoon season (May) 2019. Eight selected physico-chemical parameters (TDS, pH, EC, DO, Cl^-, NH_3,

PO_4^{3-}, NO_3^-) were analyzed and aggregated in the form of WQI. Results showed that WQI ranges from 32.5 to 46.9, indicating the excellent water quality suitable for the sustenance of the aquatic ecosystem at all the sampling locations. These study results are expected to provide the baseline information on the present status of water quality along the longitudinal section of the Marshyangdi River, which could be helpful for the concerned authorities to manage water quality for the sustenance of the aquatic ecosystem.

Keywords: Aquatic life, freshwater, Marshyangdi, Water Quality Index

INTRODUCTION

Freshwater ecosystems are home for diverse macroorganisms, which play a significant role in maintaining ecological functions and services (Rinzin *et al.*, 2009). It is, therefore, important to protect freshwater sustainably. However, freshwater ecosystems have been seriously threatened worldwide due to its unsustainable use and inadequate management because of pollution, climate change impacts, over-exploitation, and other stresses (IPCC, 2007; Gleeson *et al.*, 2012; Gyawali *et al.*, 2015). Such unsustained use of freshwater has threatened its availability in many parts of the world, affecting adversely the public and river health, agricultural production, and livestock populations in the entire Himalayan region (Kannel *et al.*, 2007b; ICIMOD, 2015).

Monitoring of water quality has become a necessity to safeguard public health and protect valuable freshwater resources (Kannel *et al.*, 2007b). Water quality can be assessed based on Water Quality Index (WQI) computed by aggregating together physical, chemical and biological parameters. The WQI, therefore, helps to transform large number of parameters into a single dimensionless number which depicts the overall water quality status at a certain location over time (Espejo *et al.*, 2012). The WQI has become one of the popular and effective tools for assessing the health status of river water quality (Chapman,1992; Bordalo *et al.*, 2001; Lumb *et al.*, 2011; Espejo *et al.*, 2012) by providing the information in an understandable and useable form for the public (Darapu *et al.*, 2011; Ruhayu *et al.*, 2015). It is because, the final information is in the form of values and transformation table so that layman can understand simply looking at it.

WQI was first proposed by Horton (1965) and since then many different frameworks for WQI assessment have been developed. Some of them, as reported in Said *et al.* (2004), are the US National Sanitation Foundation Water Quality Index (NSFWQI; Brown *et al.*, 1970), Canadian

Water Quality Index (CCME, 2001), British Columbia

Water Quality Index, (BCWQI; Zandbergen & Hall, 1998), Oregon Water Quality Index, (OWQI; Cude, 2001). However, there is no "rule of thumb" on selecting input or important variables, one can select parameters based on water quality measurements relevant to the study site (CCME, 2006). But, in all approaches of WQI calculation, four common steps are used (Abassi & Abassi, 2012): (i) selection of variables, (ii) transformation, following a common scale, of these variables that have initially of different dimensions, (iii) creation of subindices by assignment of a weighting factor to each transformed variable, and (iv) computation of a final index score using the aggregation of sub-indices. Then the computed WQI values are categorized into qualitative classes such as "excellent" "good", "poor", "very poor" and unsuitable for the intended purpose based on the WQI score.

In the Nepalese context, the studies related to water quality based on WQI are quite limited (Kayastha, 2015). Furthermore, most of the studies have been conducted in the Bagmati River, and only a few others have focused their studies on the watersheds of Western Nepal (Gurung *et al.*, 2019; Thapa *et al.*, 2020). Most of the water quality studies have compared its suitability with the drinking water quality standard of the respective country and with the World Health Organization Guidelines (WHO, 2006; WHO, 2017). For example, Regmi *et al.* (2017) investigated the water quality aspect of the major rivers in the Kathmandu Valley for the aquatic ecosystems and recreation using the Canadian Council of Ministers of the Environment water quality index (CCME WQI). Kannel *et al.* (2007b) used WQI to evaluate spatial and temporal changes of the water quality in the Bagmati river basin (Nepal) during 1999–2003 and classified the water quality into three groups, namely, good, medium, and bad. Similarly, Thapa *et al.* (2020), based on WQI scores, revealed that the water from the springs of the Jhimruk watershed is excellent in the post-monsoon, while in the pre-monsoon season, it ranges from excellent to good condition thus, indicating no threat to consumer's health. Protection of the aquatic environment is eminent to the world water resources. Maintaining a healthy aquatic environment in Nepal is important for the aquatic economic resources and promoting tourism (Smakthin & Shilkapar, 2005). To date, none of the study was conducted to assess the water quality based on WQI in the Himalayan watersheds which hosts many hydropower projects with the potentiality of affecting river health. Hence to fill that knowledge gap this study was conducted in Himalayan snow-fed Marshyangdi River at different locations, including its tributaries, to assess the status of water quality for the sustenance of aquatic organisms.

MATERIALS AND METHODS

Study area

The Marshyangdi river is a perennial snow-fed river with a length of approximately 150 km and located within 27°50'42" to 28°54'11" N Latitudes and 83°47'24" to 84°48'04" E Longitudes covering a watershed area of 4,748 sq. km as shown in Fig. 1. The Marshyangdi River begins at the confluence of two mountain rivers, the Khangsar and the Jharsang, in northwest of the Annapurna massif at an altitude of 3600 above mean sea level (masl) then it flows eastward through Manang district and southward through the Lamjung district covering other districts, Gorkha and Tanahu, and finally, it joins the Trishuli River at Mugling. The major sources of the Marshyangdi are the glaciers of the Annapurna Himalaya range, Manaslu Himalaya range and Larkya Himalayan sub-range, besides seasonal springs and monsoon rains. The elevation of this watershed varies between 274 to 8,042 meters masl, representing the bioclimatic zones from subtropical (1,000-2,000 m) to alpine zone (4000-5000) (Shrestha, 2008). The climate varies from Tropical Savannah in the lower belt to Polar frost type in the higher altitudes (Karki *et al.*, 2016). The watershed is predominated by the grassland (17.4%), followed by barren land (11.7%), agricultural land (11.28%) and the remaining occupied by other land cover types such as, shrubland, forest, water bodies, snow and glaciers, and built-up area (ICIMOD, 2010).

Presently three hydropower projects Marshyangdi [(69MW), Middle Marshyangdi (70MW), and Upper Marshyangdi (50MW)] are in operation in the

Marshyangdi basin, and 47 additional hydropower projects of various sizes (2MW-600 MW) are in different stages of construction (DOED, 2020) in the main river and in its tributaries. Water abstraction for hydropower may alter hydrology downstream and affects river health.

Furthermore, river is disturbed at various locations due to intensive sand mining activities. These activities in the watershed may affect river health, thus necessitating the need to assess water quality at different locations.

Sampling locations

This study was conducted during pre-monsoon (May) 2019. Twenty-one sampling locations from downstream (before mixing with Trisuli river) to upstream (non-impact area) were selected for the physicochemical analysis of the water. The site selection was based on the presence of major tributaries, anthropogenic influences such as tourism, hydropower and accessibility of the sampling locations. Among the total 21 locations; 15 were in the mainstream and six in the tributaries. The detailed characteristics of the sampling locations are provided in Fig. 1 and Table 1.

Water Sample collection and analysis

A composite sampling technique was employed to collect the water samples from the surface of the river for the analysis of physico-chemical parameters. The surface water samples with three replicates were collected and then composited and stored in a clean 500-milliliter polyethylene bottle. Water samples were then kept in a cool box at 4° C to minimize microbial activity and brought to the laboratory for chemical analysis, following standard procedures (APHA, 2005). The physico-chemical parameters such as hydrogen ion concentration (pH), total dissolved solids (TDS), electrical conductivity (EC), dissolved oxygen (DO), were measured in situ using HANNAHI98129 probe. Chloride was determined by silver nitrate titration method while nitrate (NO_3^-), ammonia (NH_3) and phosphate (PO_4^{3-}) were determined in the laboratory following APHA (2005).

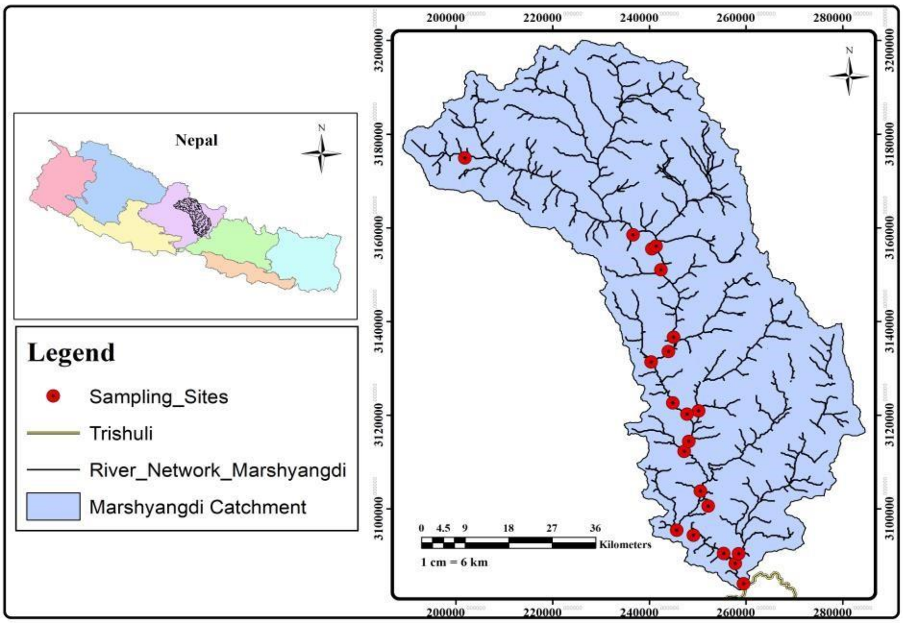


Figure 1. Study area and sampling locations along the Marshyangdi River

Table 1. Description of sampling locations in the Marshyangdi River and its tributaries.

Site name	Site Code	Altitude (m)	Latitude	Longitude	Site description
Mugling	M01	216	84° 33'22.21	27° 51' 26.67"	Downstream of the river, before mixing with Trisuli River
Abukhaireni	M02	227	84⁰ 32'25.58"	27° 53' 20.80"	Below the confluence point after mixing of Daraudi River with Marshyangdi
Daraudi River	M03	271	84° 33'06.11"	27° 54' 54.68"	Tributary
Marshyangdi D/S	M04	286	84° 30'53.17"	27° 54' 55.25"	Downstream from Marshyangdi HP
Marshyangdi U/S	M05	335	84° 27'59.37"	27° 56' 59.13"	Upstream of Marshyangdi HP
Chudi River	M06	378	84° 24'53.67"	27° 57' 33.00"	Tributary river, dominated by human activities (washing, bathing)
Turture	M07	368	84° 27'47.59"	28° 02' 06.57"	Downstream to the confluence of Tributary River Chepe to Marshyangdi
Chepe River	M08	490	84° 28'48.69"	28° 03' 23.90"	Tributary
Paudi River	M09	477	84° 25'40.28"	28° 06'42.16"	Tributary
Bhoteodar	M10	492	84° 26'14.88"	28° 07' 49.52"	Upstream of Paudi
Dordi River	M11	640	84° 27'24.89"	28° 11' 22.33"	Tributary
Middle Marshyangdi D/S HP	M12	582	84° 25'58.00"	28° 10'59.70 "	Downstream to Middle Marshyangdi HP
Middle Marshyangdi U/S HP	M13	610	84° 24'05.40"	28° 12' 13.11"	Upstream to Middle Marshyangdi HP
Khudi River	M14	798	84° 21"15.90"	28° 16' 58.55'	Tributary
Upper Marshyangdi D/S HP	M15	851	84° 23'18.67"	28° 18' 12.39"	Downstream to Upper Marshyangdi HP
Upper Marshyangdi U/S HP	M16	861	84°23'58.86"	28° 19' 52.52"	Upstream to Upper Marshyangdi HP
Tal Bazzar	M17	1675	84°22'24.57"	28° 27' 56.54"	Settlement; tourism area
Dharapani	M18	1813	84°21'31.08"	28° 30' 25.20"	Cross-sectional point, the site after mixing with Dudh Khola
Chame	M19	2604	84°15'30.61"	28° 33' 11.53"	Below Chame Bazzar and Hotspring

Dhukurpokhari	M20	3156	84° 09’36.53”	28° 36' 29.33"	Minimum human activities: Undisturbed site
Khangsar	M21	3714	83° 56’55.12”	28° 40' 28. 23"	Minimum human activities: Undisturbed site

Note: M: Marshyangdi; HP: Hydropower; U/S: Upstream; D/S: Downstream

Calculating Water Quality Index (WQI)

In this study the mean of physicochemical parameters, namely TDS, pH, EC, DO, Cl^-. NH_3, PO_4^3, NO_3^- were used to determine the suitability of water for sustenance of the aquatic ecosystem. These eight parameters were chosen based on a literature review (Pesce & Wunderlin, 2000; Said *et al.*, 2004; Kannel *et al.*, 2007a, b; Regmi *et al.*, 2017). Then weight to each parameter (w_i) was assigned according to its relative importance (Sanchez *et al.*, 2007) in the overall quality of water for the protection of the aquatic ecosystem based on percent compliance with the objective value. Weights of 5, 4, 3, 2, 1 were assigned to the quality parameters when range of 0-20, 21-40, 41-60, 61-80 and 81-100 % of samples are within the permissible limit respectively (Raychaudhuri *et al.*, 2014). Second, the relative weight (Wi) was calculated for each parameter based on equation (1).

$$Wi = \frac{wi}{\sum_{i=1}^{n} wi} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where, Wi is the relative weighting; wi is the weighting of each parameter and $\sum wi$ is the sum of all parameters and n is the number of parameters.

In the next step, quality rating for each parameter was assigned by dividing the concentration in each water sample by respective standard according to the guidelines,

and the result was multiplied by 100 as per equation (2)

$$qi = C_i/S_i*100 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where, q_i= is the quality rating; C_i= is the concentration of each chemical parameter in each water sample in milligrams per litre; S_i = is the standard for each chemical parameter in milligrams per litre.

Finally, the water quality index was calculated by adding the sub-index of water quality (SIi) for each parameter using equation (3), which was then summed up to find out the final WQI using equation (4).

$$SI_i = W_i . q_i \quad (3)$$

$$WQI = \sum_{i=1}^{n} SIi \quad (4)$$

Where, SI_i is the sub-index of water quality, Wi is the relative weighting, qi is the quality rating scale, and WQI is the water quality index.

At last, the water quality of the river is categorized into five classes Excellent, Good, Poor, Very Poor, Unfit for Drinking based on the WQI value range (Table 2).

Table 2. Classification of computed Water Quality Index (WQI) values (Raychaudhari et al., 2014)

WQI Range	Type of water
< 50	Excellent water
50.1 – 100	Good water
100.1 – 200	Poor water
200.1– 300	Very poor water
>300.1	Unfit for drinking

RESULTS AND DISCUSSION Physico-chemical characteristics of river water

The mean of the selected eight physico-chemical parameters across the sampling sites are presented in this section (Table 3; Fig. 2a, b & c). The results of study do not reveal spatial variation across the studied sites within the studied physico-chemical parameters.

pH is an important physico-chemical parameter of river water which influences the biotic composition of the system. It plays a vital role in an aquatic ecosystem since all the biochemical functions and retention of physicochemical attributes of the water is greatly dependent on pH (Tadesse *et al.*, 2018). However, it can be toxic when it is more than the desirable limit and affect aquatic life due to its influence on ammonia, hydrogen sulfide and heavy metals (Klontz, 1993; Tadesse *et al.*, 2018). In the present study pH ranges from 8.3 (M11, Dordi River) to 9.0 (M06, Paudi

River) (Table 3), showing not much variation and within the permissible limit. The observed values of pH indicate the alkaline nature of water, agreeing with one of the studies done at the Marshyangdi River (Ghezzi *et al.*, 2019). The authors have mentioned that the water samples were slightly alkaline in the river due to sufficient carbonates across different geological and tectonic stratigraphic units in Tethyan Himalayan Sequence (THS) and Greater Himalayan Sequence (GHS).

Dissolved oxygen (DO) is a common indicator of the health of an aquatic ecosystem. The saturation concentration of DO (oxygen in water) is a function of the water temperature and salinity (Loucks & Beek, 2017). High amount of DO indicates that the water quality is good (high quality) due to the self-purification capacity of the water. The dissolved oxygen (DO) values at the studied locations range from 5.1 mg/L (M17; Tal Bazzar) to 7.4 mg/L (Turture; M07) (Table 3), indicating the presence of optimum value for the sustenance of aquatic life.

Table 3. Physicochemical parameters of Marshyangdi River during pre-monsoon 2019 (n=3)

Site Code	pH	DO (mg/L)	TDS (mg/L)	EC μS/cm	Cl^- (mg/L)	NH_3 (mg/L)	NO_3^- (mg/L)	PO_4^{3-} (mg/L)
M01	8.8	6.1	144.0	286.5	32.66	0.04	1.07	0.03
M02	8.7	7.1	121.5	251.5	84.85	0.07	0.74	0.06
M03	8.9	6.4	113.5	226.0	12.07	0.04	0.03	0.02
M04	8.9	6.6	158.5	316.5	19.53	0.10	0.92	0.01
M05	8.8	6.9	152.5	308.0	18.82	0.18	1.00	0.01
M06	9.0	5.2	94.0	186.5	8.52	0.06	0.85	0.01
M07	8.7	7.4	97.0	297.5	15.62	0.05	1.11	0.01
M08	8.5	6.4	51.5	106.0	7.10	0.05	0.59	0.01
M09	9.0	5.7	61.0	123.0	11.72	0.07	0.26	0.02
M10	8.5	7.2	145.0	279.5	19.88	0.03	1.03	0.01
M11	8.3	7.1	39.9	148.0	11.36	0.03	1.11	0.01
M12	8.5	7.3	148.5	295.0	19.17	0.11	0.59	0.01
M13	8.8	6.8	122.5	248.5	35.86	0.03	1.22	0.02
M14	8.5	6.5	49.5	100.0	9.94	0.03	1.40	0.10
M15	8.4	6.7	175.0	351.5	25.21	0.03	1.11	0.05
M16	8.8	5.9	175.5	360.0	22.72	0.03	0.67	0.02
M17	8.9	5.1	165.0	328.5	18.11	0.03	1.25	0.04
M18	8.9	5.6	153.0	312.0	12.03	0.03	1.37	0.04
M19	8.9	6.7	105.0	299.5	11.36	0.03	1.41	0.04
M20	8.9	5.9	127.5	249.0	13.49	0.03	1.15	0.04
M21	8.7	6.5	168.0	357.5	12.78	0.03	0.78	0.04

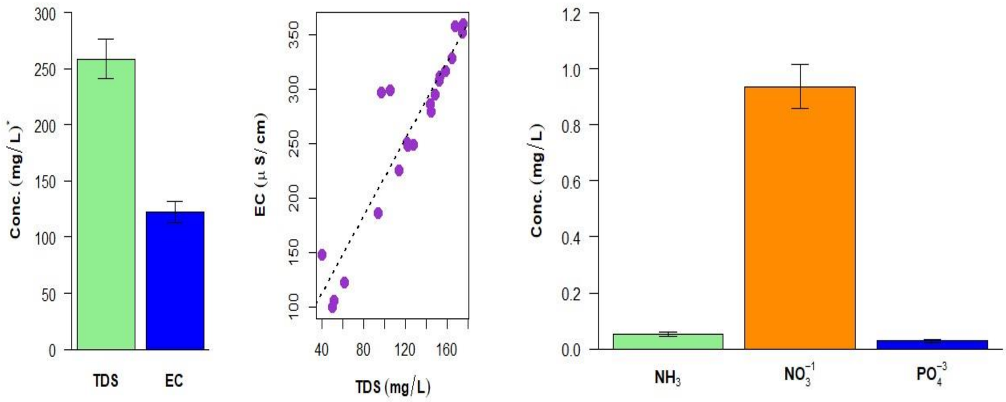
Total dissolved solids (TDS) are one of the most important parameters to consider for the sustenance of aquatic life and it is linearly correlated with Electrical conductivity (EC) Fig. 2a. TDS values ranges from 39.9 mg/L at M11 (Dordi River) to 168 mg/L at M21

(Khangsar; Marshyangdi River), which is quite below the prescribed standard (Table 4), indicating no effect on the aquatic ecosystem. However, if its content exceeds the limit, it may affect the osmoregulation of freshwater in organisms, reduces the solubility of gases (like oxygen) as well as limit the utility of water for various purposes (drinking, irrigation and industrial) (Tadesse *et al.*, 2018). A high concentration of TDS also reduces water clarity, decreasing photosynthesis, increasing the water temperature after combining with toxic compounds and heavy metals ultimately affecting the aesthetic value and physicochemical properties of water (Tadesse *et al.*, 2018; Gurung *et al.*, 2019).

The electrical conductivity (EC) is a measure of the ions or salinity, which gives an estimate of the presence of certain ions reflecting the presence of high dissolved solids (Orebiyi *et al.*, 2010; Kayastha, 2015). EC ranges from 100 µS/cm (M14; Khudi) to 357.5 µS/cm (M21; Kangsar) (Table 3), which are within the permissible levels (Table 4), but it may induce corrosive nature in water if exceeded its limit (Tadesse *et al.*, 2018).v Chloride occurs naturally in all types of freshwaters, usually in low concentration. The value of chloride in the river ranges from 7.1 mg/L (M08; Chepe River) to 84.8 mg/L (M02; below the confluence with Daraudi River), which is quite low in comparison to the permissible level for aquatic organisms (500 mg/L) (Table 4).

Dissolved inorganic phosphorus, inorganic nitrogen is generally regarded as critical nutrients to the aquatic ecosystem functioning (Dodds, 2002; Allan & Castillo, 2007; Hamid *et al.*, 2020). These nutrients (nitrates, phosphate) may be attributed due to the processes of organic mineralization derived principally from the surface runoff (Tadesse *et al.*, 2018). In the present study nutrients like phosphate (PO_4^{3-}) and nitrate (NO_3^-) are within the prescribed limit (Table 4), indicating no threat of eutrophication which might occur due to the nutrient enrichment in water systems (Loucks & Beek 2017).

WQI across the sampling locations The WQI of the Marshyangdi River is calculated and presented in Table 5.WQI values range from 32.5 to 46.9 indicating the water quality falls in the excellent category a t all the locations (Table 2), thus ensuring the protection o f aquatic life in the Marshyangdi River. Table 4 presents the prescribed values for water quality used in the computation of WQI, which reveals that most of the parameters were within acceptable limits. The previous study in Jhimruk River watershed also indicated the excellent water quality during the pre-monsoon season based on the water quality index (Thapa *et al.*, 2020). In addition, Rana and Chettri (2015) also reported that the stream possesses good water quality based on WQI in Bhalu Khola, a tributary of the Budhigandaki River. Similarly, Gurung *et al.* (2019) revealed that the water quality ranges from being poor to good conditions in the spring sources located in the rural watershed of Western Nepal based on the water quality index suggesting using the water for domestic purposes after suitable treatment.



. 2a

Fig. 2b

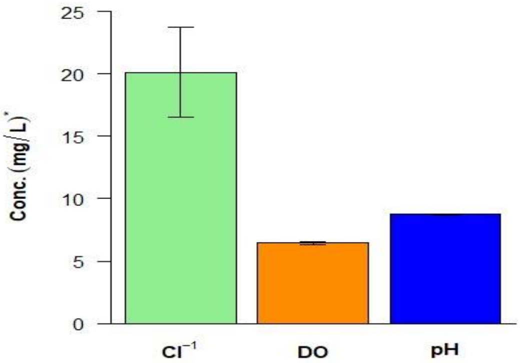


Fig. 2c

Figure 2. Selected physico-chemical parameters of Marshyangdi River; a) TDS and EC; b) NH_3, NO_3^{-1} and PO_4^{-3}; and c) Cl^-, DO and pH (*represent unit for pH, as pH units).

Table 4. Water quality standards, weight (wi) and calculated relative weight (Wi) for each parameter.

Category	Parameters	Prescribed values	Percent compliance	Weight (wi)	Relative weight (Wi)	References
Physical	EC	1000	100	1	0.13	BBWMSIP (1994) in Regmi *et al.* (2017); BIS (2012)
	TDS	1000	100	1	0.13	BBWMSIP (1994) in Regmi *et al.* (2017)
	pH	6.5-9	100	1	0.13	CBS (2019); CCME (2001)
Chemical	NH_3	1.2	100	1	0.13	CPCB (979) in Singh and Kaushik (2018)
	Cl^-	500	100	1	0.13	BBWMSIP (1994) in Regmi *et al.* (2017)
	NO_{3-}	45	100	1	0.13	CCME (2001)
	PO_{43-}	0.1	100	1	0.13	BBWMSIP (1994) in Regmi *et al.* (2017)
	DO	5	100	1	0.13	CBS (2019); CCME (2001)

$\sum wi = 8$

Table 5. Subindex of each chemical parameter (Sli), WQI and water classification of each water sample of Marshyangdi watershed for pre-monsoon.

				SIi					Total SIi=WQI	Water classification
Sites	**TDS**	**pH**	**DO**	**EC**	**NH_3**	**NO_{3-}**	**PO_{42-}**	**Cl^-**		
MA01	1.87	12.71	15.86	3.72	0.41	0.31	3.85	0.85	39.58	Excellent

MA02	1.58	12.57	18.36	3.27	0.73	0.21	8.05	2.21	46.97	Excellent
MA03	1.48	12.86	16.58	2.94	0.46	0.01	2.45	0.31	37.08	Excellent
MA04	2.06	12.92	17.23	4.11	1.11	0.27	0.70	0.51	38.90	Excellent
MA05	1.98	12.73	17.97	4.00	1.95	0.29	1.05	0.49	40.46	Excellent
MA06	1.22	12.95	13.47	2.42	0.65	0.25	1.40	0.22	32.58	Excellent
MA07	1.26	12.51	19.21	3.87	0.51	0.32	0.70	0.41	38.79	Excellent
MA08	0.67	12.22	16.65	1.38	0.51	0.17	1.40	0.18	33.19	Excellent
MA09	0.79	13.00	14.69	1.60	0.76	0.08	2.10	0.30	33.32	Excellent
MA10	1.89	12.32	18.73	3.63	0.27	0.30	0.70	0.52	38.36	Excellent
MA11	0.52	12.05	18.33	1.92	0.27	0.32	0.70	0.30	34.40	Excellent
MA12	1.93	12.29	18.85	3.84	1.22	0.17	1.05	0.50	39.84	Excellent
MA13	1.59	12.72	17.73	3.23	0.27	0.35	2.80	0.93	39.63	Excellent
MA14	0.64	12.32	17.00	1.30	0.27	0.40	14.00	0.26	46.20	Excellent
MA15	2.28	12.09	17.29	4.57	0.27	0.32	7.00	0.66	44.47	Excellent
MA16	2.28	12.74	15.34	4.68	0.27	0.19	3.15	0.59	39.25	Excellent
MA17	2.15	12.81	13.22	4.27	0.27	0.36	5.60	0.47	39.15	Excellent
MA18	1.99	12.91	11.91	4.06	0.27	0.39	5.60	0.31	37.44	Excellent
MA19	1.37	12.88	17.42	3.89	0.27	0.41	5.60	0.30	42.13	Excellent
MA20	1.66	12.91	15.34	3.24	0.27	0.33	5.60	0.35	39.69	Excellent
MA21	2.18	12.60	16.77	4.65	0.27	0.22	5.60	0.33	42.62	Excellent

The water flow is one of the important variables which significantly impact water quality due to its natural capacity of diluting the pollutants (Darapu *et al.*, 2011;

Iticescu *et al.*,2019). Thus, the excellent water quality in the Marshyangdi River may be due to the high flow, which helps in diluting the pollutants. During field visits, while observing the site conditions at each of the locations we don't observe dumping of waste except at the site (Turture; M07) which falls outside the Annapurna conservation area. Further due to the absence of any industrial activities, intensive agriculture runoff in and around the river may help to possess the present water quality status of the Marshyangdi River.

CONCLUSIONS

This study presents an assessment of water quality based on the water quality index (WQI) in one of the least studied rivers, Marshyangdi, where many hydropower projects are planned, and three of them are already in operation. The concentrations of all the studied physicochemical parameters such as pH, EC, TDS, DO, NO_3^-, PO_4^{3-}, NH_3, and Cl^- were within the prescribed limit and in compliance with national and international standards. Based on WQI, we can conclude that river water is favorable for aquatic biota, with respect to parameters chosen, thus indicating the healthy state of river at all the studied locations during pre-monsoon season of 2019. The excellent water quality in the Marshyangdi River is likely due to the high flow that helps in diluting the water. Further spatial and altitudinal variation has not been observed in the present study, justified by the same water quality class across all the stations.

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AUTHOR CONTRIBUTIONS

RS conceptualized, performed fieldwork, analyzed the data and wrote the first draft of the manuscript. SPK contributed to research conceptualization, data curation, review and editing. VP contributed to conceptualization, review and editing the manuscript.

CONFLICT OF INTEREST

The authors declare no competing interests.

DAT AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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Annex-20 Extended abstract "Assessment of hydrologic alteration: a case of Marshyangdi Watershed

Proceedings of the 18th Annual Meeting of the Asia Oceania Geosciences Society (AOGS 2021), August 1-6, 2021, Singapore

ASSESSMENT OF HYDROLOGIC ALTERATION: A CASE OF MARSHYANGDI WATERSHED

Reeta Singh[1], Vishnu Prasad Pandey[2] and Sadhana Pradhanang Kayastha[3]

ABSTRACT: Hydrologic regime plays a vital role in the sustainable ecosystem. However, its alterations due to various climatic and anthropogenic activities cause significant impacts on river health. Hence, in this paper, we have analyzed the degree of hydrologic alterations in a snow-fed Marshyangdi watershed, Nepal, using the Indicators of Hydrologic Alteration tool which is based on the range of variability approaches. Hydrologic alterations in the basin vary among the groups from low to moderate with an overall mean hydrologic alteration of 30% based on 32 hydrologic indices. An increase in the median flow values during the period of March-August and consequent statistically significant increasing trend in the 30-day and 90-day maximum values indicate the possibility of flood in the future. Further, increases in anthropogenic influences could alter the natural flow regime of the *Marshyangdi* watershed with severe ecological consequences in river health.

Keywords: Indicators of Hydrologic Alteration, Marshyangdi, Streamflow.

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INTRODUCTION

The flow regime of a river namely magnitude, frequency, duration, timing, and rate of change is recognized as central to sustaining biodiversity and ecosystem integrity (Poff and Ward 1989; Richter et al., 1997; Rosenberg et al., 2000). These components characterize the entire range of flows and specific hydrologic phenomena, such as floods or low flows, which are critical to the integrity of river ecosystems. Global climate change along with

MATERIALS AND METHOD

Marshyangdi watershed is located between Latitude 27°50'42" N to 28° 54'11" N and Longitude: 83°47'24" E to 84°48'04" E with an area of approximately 4,787 sq. km. Due to variation in altitude from 200 to 8,042 masl climate too varies from tropical savanna at the lower belt to polar frost at a higher altitude (Karki et al., 2016).

Hydrologic data from the Department of Hydrology and Meteorology was analyzed with exploratory data analysis.

The pre-and post-impact periods were determined as per Pettitt's (1979) test on the annual average data to identify any abrupt change points in the streamflow time series in the Marshyangdi watershed. Then, all 33 indices of hydrologic alterations were analyzed by Indicators of Hydrologic Alterations(IHA 7.1; Richter et al.,1997 ; Na ture Conservancy2009). Further hydrologic alterations (HA) were calculated with the following equation (Xue et al., 2017).

$$Pi\ (\%) = \frac{(Mpost - Mpre)}{Mpre} * 100 \ldots\ldots\ldots\ldots\ldots (i)$$

M_{post} is the median for Post-CP

anthropogenic activities possess the greatest emerging threat to global biodiversity and the functioning of local ecosystems including hydrological regimes. However, its alterations over time in a watershed cause a significant impact on river health. Hence, this paper analyzed the degree of hydrologic alterations in a snow-fed Marshyangdi watershed, Central Nepal, which has a greater potential for hydropower development (Jha,2010).

M_{pre} is the median for Pre-CP.

Finally, trend analysis was performed by Mann Kendall's and Sen's slope (Mann 1945;Sens's Slope 1968) method.

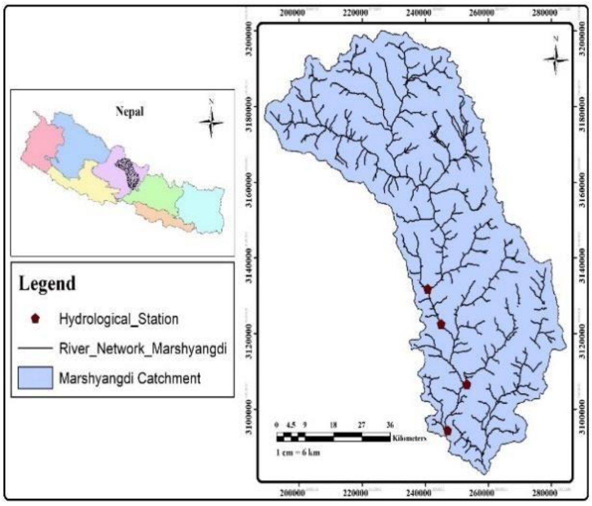

Fig.1 Marshyangdi Basin

Table 1: Ecological Implications of selected hydrologic indices (m^3/s/year)

IHA Statistics Group	**Name of parameter**	**From pre to post impact period**	**Ecological Implication**	**HA (%)**	**Trend**	**Reference**
Group 1	Median flow	Increases during Monsoon a nd pre-monsoon	✦ Susceptible to flooding	Low, except January: High	-0.08, NS	Xue et al. 2017
Group 2	3-day 7-day 30-day Max flow	Changes in floodplains	✦ Low oxygen and prolongation of duration of stressful high temperatures	High: 62.5 Low: 21.9 Low: 7.1	7.5, NS 4.4, NS 5.5, NS	Graf, 2006
	1-day 90-day Max flow	Increase	✦ Beneficial and harmful effects	Low: 21.9 Low: 7.1	0.4, S 4.8, S	Stefanidis et al. 2016
Group 3	Date of minimum: Jmin	Lagging of Julian date Shift in occurrence of low flows	✦Earlier drying up of the downstream channel ✦Adverse effects on the flood plain habitats,ecology, and navigability of the river. ✦Threaten the riverine environment.	M: 36.8	-0.26, S	Sharma et al. 2019 Xue et al. 2017

Group 4	Low pulse count	Frequent dry & wet situation	✦Stress for plants due to changes in frequency and magnitude of soil moistu e, which causes anaerobic conditions. ✦Lack of availability of floodpl ain for aquatic organisms.	M: 36.8	0.23, S	Xue et al. 2017 Graf,2006
Group 4	High pulse count	Not favor the riverine ecosystem	✦ Limited nutrient availabi lity for plants along the r iverbank affecting the pr omotion of river biodiversity.	Low: 0.7	0,S	Xue et al. 2017
Group 5	Rise rate and fall rate	Increase abruptnes s of streamflow	✦ Trapping of aquatic organisms in floodplains affects plants' and animal habitat stability.	Low: 27.8 M: 57.5	0.01, NS -0.12, NS	Sharma et al. 2019

Note: HA: Hydrologic Alteration; S: Significant; S: Significant, NS: Insignificant; M: Moderate

RESULTS AND DISCUSSION

The mean annual streamflow in the basin is 222 m^3/s which is insignificantly increasing with a trend of 0.6 $m^3/s/y$. Hydrologic alterations (HA) in the basin vary from low to moderate within five groups. An increase in the median flow values during the period of monsoon and post-monsoon values (Fig.2) and consequent statistically significant increasing trend in the 30-day and 90-day maximum values indicate the possibility of flood in the basin in the future (Table1). Poff and Zimmerman (2010) had also mentioned that almost all published research found negative ecological changes to alteration in the flow variability.

However further increases in anthropogenic influences and climate change may affect the natural flow regime of the *Marshyangdi* watershed which may exacerbate in the future and the implications pointed out could have severe ecological consequences with the high degree of hydrologic alteration.

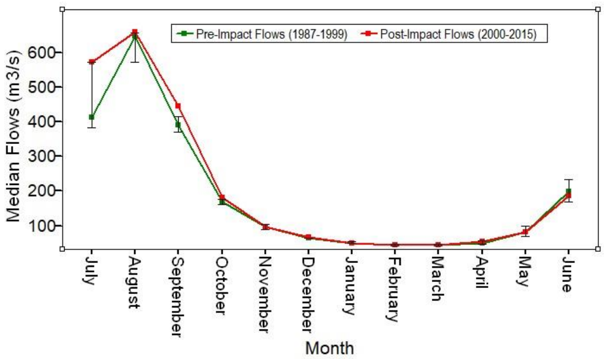

Fig.2 Median Monthly Flow

CONCLUSION

The hydrologic alteration was low with an overall mean of 30% in the Marshyangdi basin. However, in the future, alteration in a flow regime due to climatic and anthropogenic activities could impact river health.

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Annex-21 Certificate of participation in the National Conference

HIMALAYAN KNOWLEDGE CONCLAVE

7TH GRADUATE CONFERENCE ON ENVIRONMENT AND SUSTAINABLE DEVELOPMENT

Sustainability beyond Pandemic: Youth Innovation for Environment and Spirituality

Himalayan Knowledge Conclave

CERTIFICATE OF APPRECIATION

This certificate is awarded to

Ms REETA SINGH

in recognition as a PAPER PRESENTER in the Seventh Graduate Conference held on May 24-25, 2021.

Mr Ukesh Raj Bhuju
Dean, School of Development Studies & Applied Sciences
Lumbini Buddhist University

Sharada Poudel, PhD
Conference Secretary
Assistant Professor, Lumbini Buddhist University

Annex– 22 Certificate of participation in the International Conference

Asia Oceania Geosciences Society

ROS 0198/2003 TAP

PROOF OF ATTENDANCE

This is to certify that

Reeta SINGH

Patan Multiple College

has participated in the

18th Annual Meeting of the
Asia Oceania Geosciences Society

during the period
02 Aug to 06 Aug, 2021

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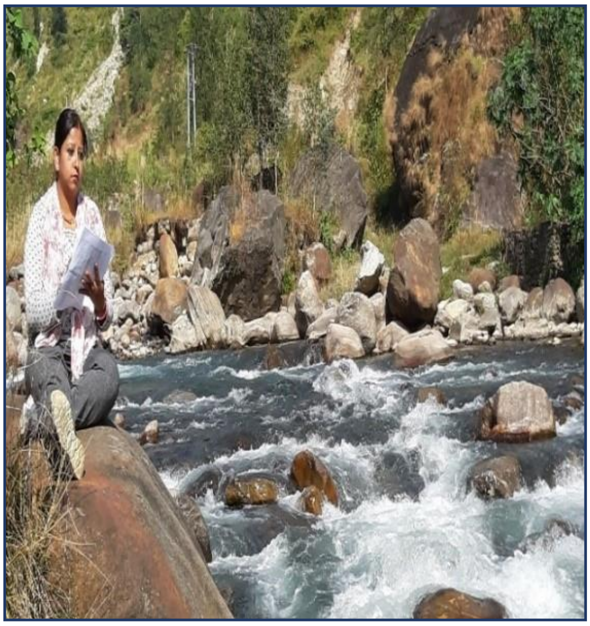
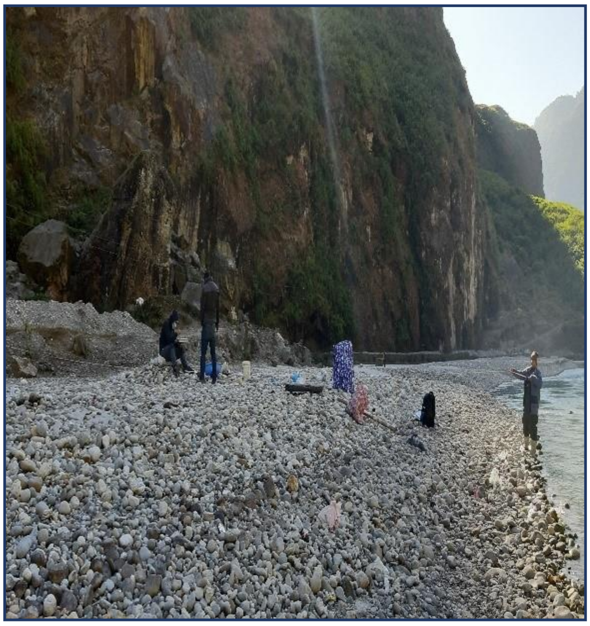
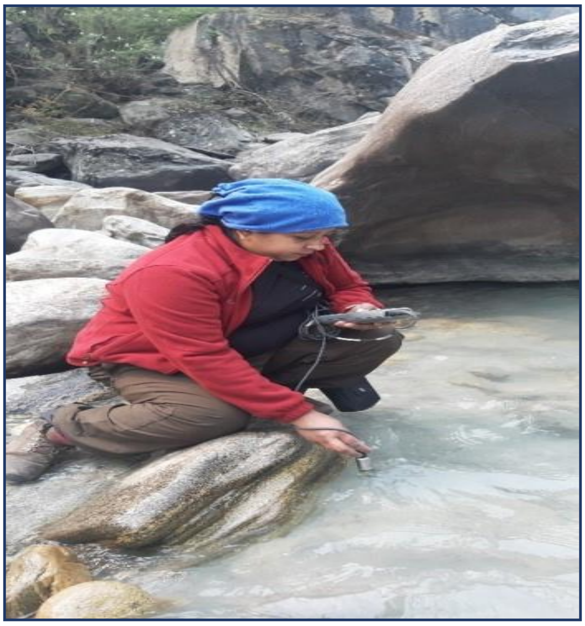
Annex–23 Field photographs

Filling of water sample for lab analysis   Sampling of macroinvertebrates at Muglin



Filling up protocal at Khudi River   Sampling of water at Bhoteodar

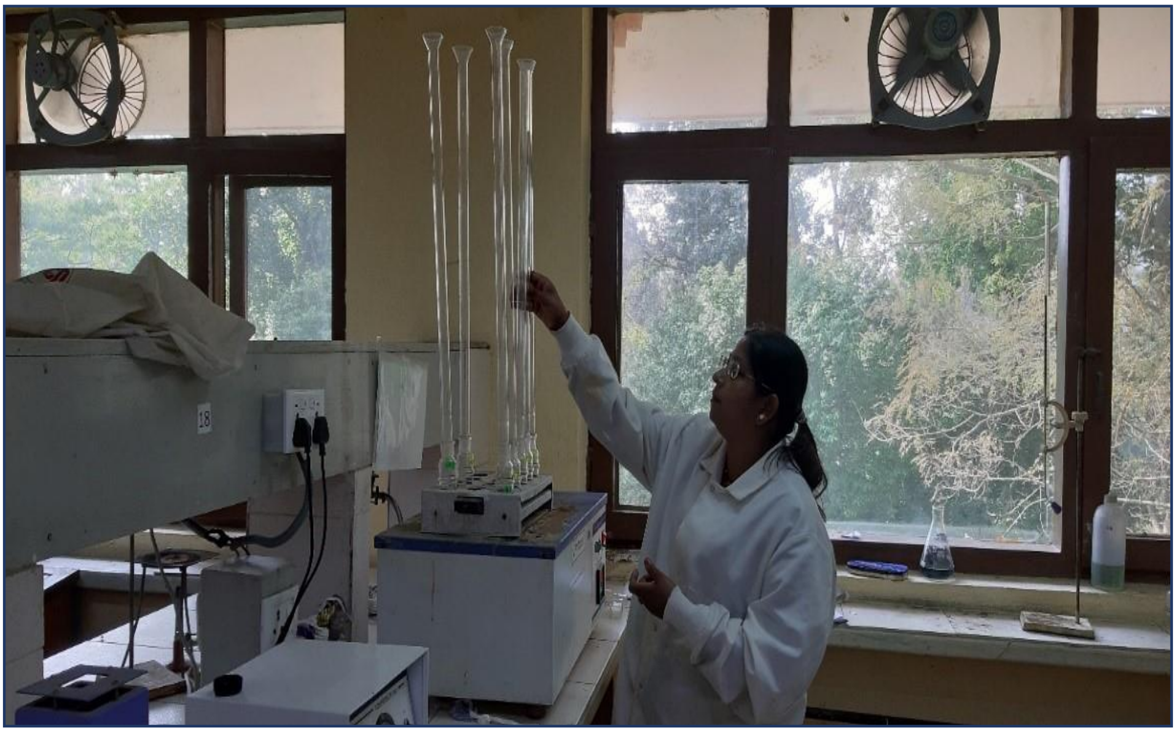




Taking measurements of dry river width at M17

Taking measurement of DO at M20

Taking measurement of velocity at downstream site of Upper Marshyangdi Hydropower



Analysis for chemical oxygen demand at the lab

Identification of macroinvertebrates


Filling of sample bottles