ORIGINAL ARTICLE

Hydrologic modeling and flood-frequency analysis under climate change scenario

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Abstract

Assessing flood frequency in a changing climate is crucial for evaluating and managing flood risk in river basins. Often, rivers lack sufficient observational streamflow data, particularly for annual maximum flood discharge analysis, either due to ungauged or inadequate record lengths. However, most river basins have access to rainfall data with longer records. Hydrologic modeling, a valuable tool for simulating streamflows using available rainfall data, can address the lack of longer peak discharge values necessary for reliable flood-frequency analysis. A popular hydrologic model, HEC-HMS, was employed to establish rainfall-runoff relationships and develop a flood discharge simulation tool for the Bagmati river basin in Nepal. The Bagmati river basin, encompassing 593 km² catchment area upstream of the Khokana hydrological station, includes Kathmandu valley which has faced frequent flooding in recent years. The flood discharge simulation model was calibrated and validated using daily discharge data of three largest flood events between 1995 and 2015. The performance of the flood simulation model was found satisfactory based on visual (hydrographs) and statistical (Nash-Sutcliffe Efficiency and Percentage Bias) parameters. To simulate annual maximum discharge values and assess flood frequency under climate change scenario, NHRCM precipitation data with 2-km spatial resolution was utilized. Comparing flood-frequency analysis results between current (1981–2000) and future (2080–2099), annual daily maximum discharge values for various return periods revealed a significant increase in extreme flood events in future. The increase in maximum discharge for current and future climate conditions can be reflected with the values of 1362 m³/s and 1818 m³/s, respectively. The extreme flood events are expected to be higher in future considering similar flood discharge values of 1707 m³/s and 1771 m³/s for 100-year return period in the current climate and 25-year return period in the future climate conditions respectively. This underscores the pressing need for flood managers and policy makers to focus on reducing the heightened flood risks due to climate change.

Keywords Bagmati river basin · Climate change · Flood-frequency · HEC-HMS · NHRCM

Introduction

In recent years, there has been a notable surge in natural and man-made disasters worldwide causing significant loss of life, livelihoods, injuries, and property damage (Sato et al. 2021; Kefi et al. 2020). The rise in these disasters is largely attributed to global environmental changes (Sahu et al. 2012, 2020). This is a particularly serious concern for developing countries, which often have inadequate infrastructure and limited adaptation capabilities. Among the

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various natural disasters, hydro-meteorological disasters are increasingly reported with substantial loss of life and property each year (Thomas and Lopez 2015). The World Disaster Report (2020) warns that weather-related disasters are projected to escalate in frequency and intensity in the future. Flood disasters, in particular, stand out as the most damaging with significant human and economic losses annually (CRED 2023). The rise in flood disasters is predominantly attributed to global change processes such as urbanization and climate change. Urbanization alters hydrological process with reduced amount of infiltration, groundwater flow and lag time; and increased volume of surface runoff with quick peak flows (Ogden et al. 2011; Smith et al. 2005). Rate of urbanization in developing countries like Nepal is quite higher. Likewise, frequent extreme rainfall events are reported with the climate change causing greater surface runoff volume and rapid rise in the peak discharge.

The rise in flood disasters in cities, marked by increased frequency and intensity, has become a pressing concern given that more than half of the global population now resides in urban areas (Salike and Pokharel 2017). Consequently, it is imperative to conduct scientific investigations to comprehend, devise, and implement sustainable countermeasures aimed at mitigating future flood risks in the context of global change. Effective flood risk reduction strategies require information on the probable flood discharge patterns and inundation characteristics in the study area. Numerous studies have been conducted on modelling flood events resulting from the impact of haphazard urbanization and climate change (Callaghan and Hughes 2022; Rahman et al. 2021; Tabari 2020; Saraswat et al. 2016; Mishra and Herath 2015).

Numerous initiatives have emerged across different spatial scales, ranging from global to national and local levels, focusing on adaptation and mitigation strategies for both natural and man-made disasters. The Sendai Framework for Disaster Risk Reduction, adopted in 2015, is a significant milestone outlining a diverse range of structural and non-structural measures to be implemented by 2030 (UNISDR 2015). Structural measures include the construction of embankments and excess water storage facilities. On the other hand, non-structural measures involve activities such as flood hazard and risk mapping, along with the delineation of various risk zones for the construction of settlements, buildings, offices, schools, and other infrastructure. In cities like Kathmandu, large-scale structural interventions may not be feasible for mitigating urban flood challenges due to the substantial investments and large land space they require.

In these context, non-structural measures, such as hydrological modelling for flood hazard and risk mapping, emerge as pivotal strategies for reducing urban flood risks. The

hydrological modelling approach can play a crucial role, particularly in the face of uncertain future land cover and climate change scenarios (Marfai et al. 2015). Hydrologic modelling is a popular tool for streamflow simulations, both low and high flows. The high flow simulations are used to reflect flood characteristics in the form of peak discharge, its time of occurrence; and flood inundation depths and extents under alternative conditions. A number of hydrologic models are found in the literature for the simulation of peak flood hydrographs. These hydrological models have been applied worldwide for studying the impacts of climate and land cover change on hydrologic behaviour of a river basin. Hydrologic models such as HEC-HMS, MIKE-SHE, TOPMODEL and SWMM were extensively used for studying urban river basins (Kawamura et al. 2023; Yilma and Kebede 2023; Juma et al. 2022; Maung et al. 2020; Elliott and Trowsdale 2007). These models are well capable in demonstrating various physical processes which govern flood discharge generation. Using these models, flood discharge simulations are carried out for various extreme rainfall events and return periods.

HEC-HMS is one of the widely used hydrological models for transforming rainfall into both event and continuous streamflow simulations in urban area (Timilsina et al. 2023; USACE 2023; Emam et al. 2016). The use of HEC-HMS is found world-wide for simulations of peak discharge considering its flexibility, simplicity and applicability under different spatial, temporal and data availability conditions. The use of HEC-HMS model is found across various domains, from water resources assessment to flood discharge simulations, and the design of urban drainage systems. The widespread use of the HEC-HMS model is well-documented in the literature. The model was applied for investigating the impacts of urbanization, land cover change, and climate change on hydrological systems, including flooding (Ahmadi et al. 2022; Gumindoga et al. 2017; Olechnowicz and Weinerowska-Bords 2014). Du et al. (2012) utilized the HEC-HMS model in the Qinhuai River watershed, China, to study the effects of urbanization on flood events. Mahmood et al. (2016) applied the HEC-HMS model in Pakistan to assess the impacts of climate change on its water resource system.

Global Climate Model (GCM) projections are primarily employed for simulating future flood discharge and investigating likely change in flood-frequency under climate change. The GCM projections are available for a range of Shared Socio-economic Pathways (SSP) and Representative Concentration Pathways (RCP). These combinations represent different scenarios of climate change up to the year 2100 (IPCC 2021). Of the various potential climate change scenarios, SSP5-8.5 portrays a scenario characterized by very high levels of Greenhouse Gas (GHG) emissions.

Coarse-resolution GCM projections are primarily available to assess the effects of climate change on future flood occurrences. However, relying on coarse-resolution GCM projections cannot provide accurate insights into future floods, particularly in smaller river basins. High-resolution dynamically downscaled precipitation data from the Non-Hydrostatic Regional Climate Model (NHRCM) developed by the Meteorological Research Institute (MRI), Japan is accessible for various regions under the SSP5-8.5 climate change scenario (Yamamoto et al. 2021; Saito et al. 2006). This makes NHRCM projections suitable for simulating annual daily maximum flood series and assessing the impacts of climate change on future flood frequency.

In recent years, the increasing occurrence of frequent floods during the monsoon season has become a significant concern for residents and water managers in the Kathmandu Valley. The Bagmati River and its upstream tributaries, extending from Shivpuri hill to Khokana in Lalitpur, encompass the Kathmandu Valley. High river flow rates and extensive encroachment along the riverbanks have led to frequent flooding in the valley. These recurring flood events result in substantial socio-economic losses every monsoon, including hours of traffic disruptions, the evacuation of riverside communities, and loss of life and property (Basnyat et al. 2020). Therefore, it is imperative to investigate and model the Bagmati River Basin, which encompasses the Kathmandu Valley, to better understand and mitigate these frequent flood occurrences.

While various researchers have studied this issue, there remains a need for a thorough assessment of the climate change impact on future flood frequency in the Bagmati River Basin encompassing the Kathmandu Valley. The objective of this study was to establish a rainfall-runoff simulation model and assess flood frequency under climate change scenario in the Bagmati River Basin covering the Kathmandu Valley. By establishing a calibrated and validated HEC-HMS model, annual daily maximum discharge series was simulated to conduct flood frequency analysis in the context of climate change. This study primarily focuses on identifying relative changes in flood frequency. Therefore, instead of emphasizing bias correction, the high-resolution NHRCM precipitation data was directly applied to the calibrated and validated HEC-HMS model to simulate streamflow under current and future climate conditions. NHRCM precipitation data for current (1981–2000) and future (2080–2099) climates was employed to generate annual daily maximum discharge and anticipate relative changes in future flood frequency. SSP5-8.5 NHRCM precipitation projections with a spatial resolution of 2 km and daily temporal resolution were utilized for the climate change impact assessment in this study.

Study area

The study involves setting up a hydrological model to simulate peak discharge and assess flood frequency in the Bagmati River basin with outlet at the Khokana hydrological station. Kathmandu valley is covered by Bagmati river system with major tributaries as Manohara, Hanumante, Dhobikhola, Tukucha and Bishnumati. The Bagmati basin is fan shaped as shown in Fig. 1. Kathmandu valley has experienced significant changes in the hydrological regime in the past three decades due to rapid urbanization and face several damaging floods in recent years (Chaulagain et al. 2023). Recent floods in the Kathmandu valley produce extensive inundation and induce considerable damage including deaths; and destruction of public and private property. The rapid urbanization has also altered groundwater recharge system. Depletion in groundwater table has led in drying of several shallow wells which is highly important for domestic water uses in the Kathmandu valley.

The Bagmati River Basin is located between 85°11'00" E and 85°31'59" E; and 27°31'51" N and 27°50'49" N. Altitude of the study area varies from 1257 m to 2726 m. The basin area upstream of Khokana is approximately 593 km^2. Streamflow is largely characterised by the occurrence pattern of rainfall over the year. The study area gets approximately 1550 mm of annual rainfall. Out of this, nearly 80% of total annual rainfall occurs during June-September. Mean annual temperature in the study area is about 18 °C. The study area consists of 3 major land cover types: forest, agriculture and urban land.

The basin consists of steep and valley terrains, which constitute the surrounding hills and central highly populated regions, respectively. The surrounding upper part of the basin is largely forested or farmland. During monsoon, the valley region receives excessive water from the upper hilly basin and results flooding in the densely populated region. Compounded by the poor drainage systems, flooding occurs frequently in the valley area. As the central valley region is densely populated and serves as capital of Nepal, it is highly important to understand flood water characteristics from the upper hilly region. Peak discharge generated from the upper hills together with extreme rainfall over the valley region can help in assessing flood generation in the lower populated region for mitigating flood risks in the Kathmandu valley.

Materials and methods

This research primarily involves simulation of peak streamflow values and flood-frequency analysis under climate change scenario. In the beginning, HEC-HMS model was
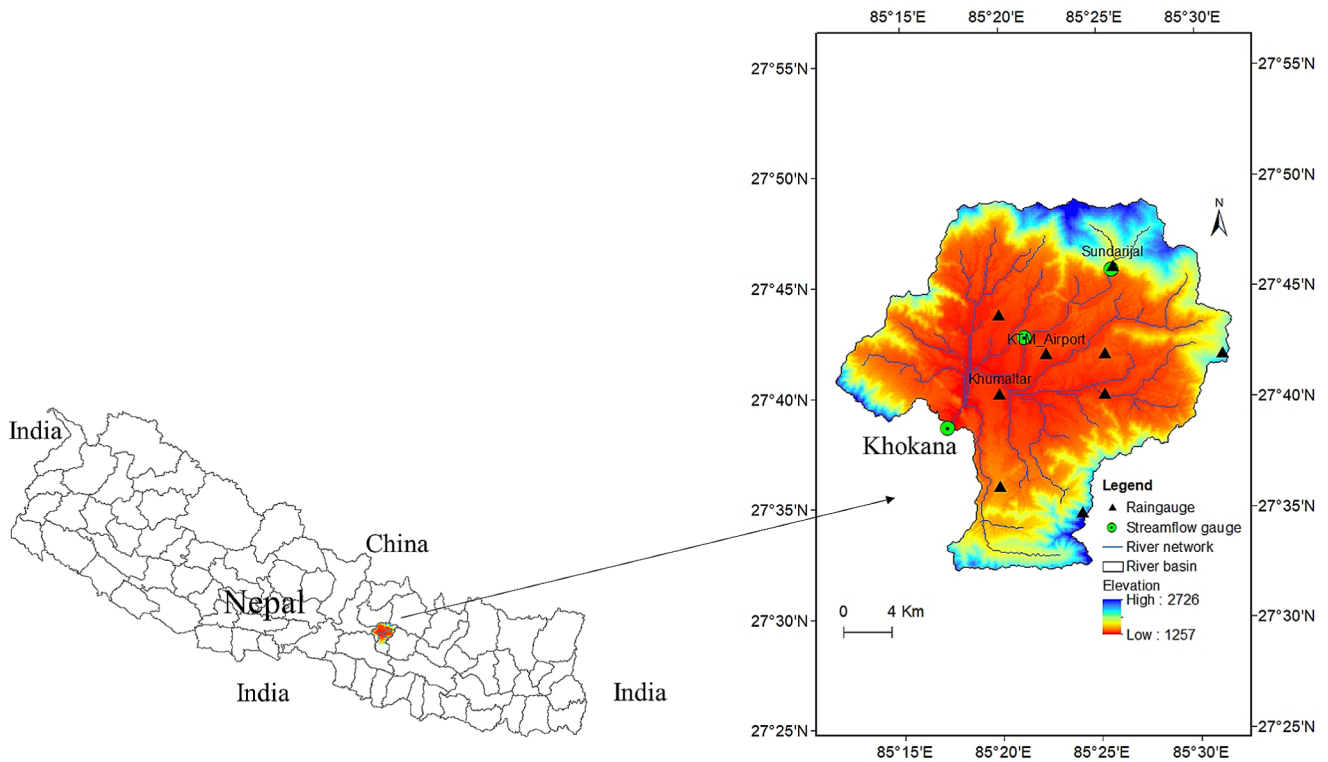
Fig. 1 Location of Bagmati river system upstream of Khokana hydrological station (not to scale)

set-up for peak streamflow simulation in Bagmati river basin. Hydrologic modelling set-up is primarily aimed for estimating flood discharge at the inlet locations for the inundation simulation modelling over lower valley region. The HEC-HMS model is expected to provide flood discharge values from the upper mountainous region to lower valley region under different land cover and climatic conditions. Later, Gumbel frequency distribution was applied to annual daily maximum streamflow values for current and future conditions for estimating flood magnitudes of various return periods.

Data acquisition

Different datasets such as elevation, land use land cover, soil, and hydro-climatic data are necessary for streamflow simulation modeling and flood frequency analysis. The Digital Elevation Model (DEM) for the study area utilizes ALOS-PALSAR data with a spatial resolution of 12.5 m. GIS tools are widely used to prepare spatial data in the required format. ArcGIS enabled to delineate river basin and extract several other topographic parameters using the DEM. Land cover change, as the time elapses, can significantly affect runoff generation. In this case, Landsat images enabled to obtain the land cover maps for different time periods. Food and Agriculture (FAO) global soil map was downloaded and extracted for the study area for preparing soil data.

Observational rainfall and discharge data were obtained from Department of Hydrology and Meteorology, Nepal. Daily rainfall data of Kathmandu airport (Station index: 1030), Sundarijal (Station index: 1077) and Khumaltar (Station index: 1029) were used for reflecting spatial variations of rainfall over the basin. Daily discharge data of Khokana hydrological station with station index: 550.05; latitude: 27° 37'48" and longitude: 85°17'24" were used for calibration and validation of the HEC-HMS model. NHRCM daily precipitation data for 1981–2000 and 2080–2099 periods representing current and future climate respectively were applied for the assessment of climate change impacts on flood-frequency. NHRCM precipitation projections from MRI, Japan offer very high-resolution data over the Nepal domain. The NHRCM precipitation output, with a spatial resolution of 2 km, corresponds to the SSP5-8.5 climate change scenario, representing the most critical conditions of global warming in the future. The NHRCM precipitation corresponding to Sundarijal, Kathmandu airport and Khumaltar meteorological stations were extracted for the current and future climate conditions.

HEC-HMS simulation process

HEC-HMS model consists of several components as basin model, meteorological model, control specifications, and time series data components. The basin model represents

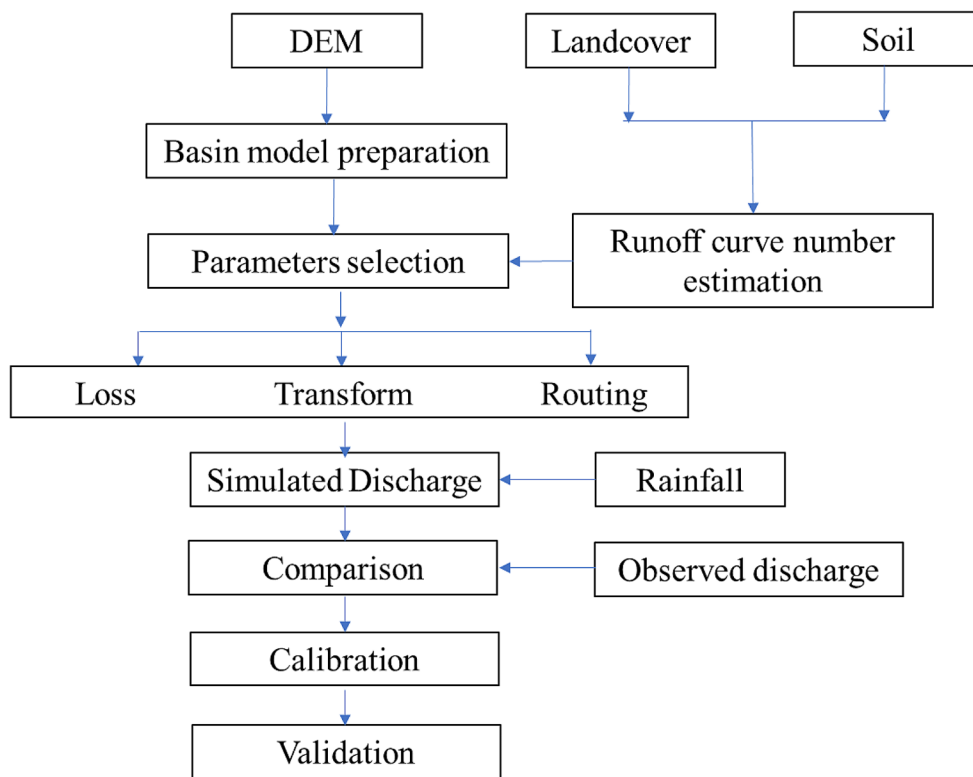**Fig. 2** Flow chart for setting the HEC-HMS model

Table 1 Selected methods for HEC-HMS model parameters

No.	Parameters	Method
1	Loss	SCS Cuve Number
2	Transform	SCS Unit Hydrograph
3	Routing	Muskingum

the physical description of the watershed in a HEC-HMS project. Using DEM, outlet locations and appropriate threshold values; sub-basins and reaches are created. The meteorologic model enables to define location and analysis of precipitation data for each sub-basin. Meteorological information is presented as time-series data. The Control Specification feature empowers users to set the start and end of HEC-HMS simulations, along with the computational time interval for the simulation process.

The model set-up process includes importing DEM into the HEC-HMS for watershed delineation; preparing landcover and soil data; providing locations of hydro-meteorological stations and their time-series data; and finally, calibration and validation of the peak flow simulations. The flow chart (Fig. 2) illustrates the various stages involved in establishing the hydrological model for conducting peak discharge simulations.

Runoff generation and routing process are two essential components in setting-up of a hydrologic model. The runoff

generation component estimates the total runoff from a sub-basin during the rainfall event. Total runoff from a sub-basin is computed by subtracting losses, transforming excess rainfall, and adding baseflow. The parameters contributing to runoff generation encompass canopy loss, surface storage loss, infiltration loss, transformation of excess rainfall, and baseflow. For flood modelling purposes, canopy loss, surface storage, and baseflow components are typically negligible and therefore often omitted. HEC-HMS offers various methods to estimate infiltration losses, transform excess rainfall, and route channels. Table 1 presents the methods applied to different processes in this study.

Loss estimation and runoff transformation

The Soil Conservation Service (SCS), also known as the Natural Resource Conservation Service (NRC), devised a technique for estimating infiltration losses and transforming excess rainfall (SCS 1986). This method employs the runoff

curve number (CN), which varies based on combinations of land use, soil types, and antecedent moisture conditions. The SCS-CN method predicts runoff by considering rainfall, soil cover, land use, and antecedent soil moisture. The SCS-CN method is basically an empirical equation for predicting excess rainfall using a number varying between 0 and 100 for different combinations of soil, land use land cover, and antecedent moisture conditions. Equation 1 can be utilized to estimate direct runoff within the SCS-CN method.

$$Q = \frac{(P - I_a)^2}{(P - I_a + S)} \tag{1}$$

where Q is direct runoff (mm); P is rainfall (mm); I_a is initial abstraction (mm); and S is the maximum soil water retention (mm) after runoff begins.

The SCS dimensionless Unit Hydrograph method was created by studying many watersheds in the United States (Rai et al. 2017). In this method, discharges at various time points are described using peak discharge and the time it takes for the hydrograph to rise. By knowing the peak discharge and lag time for a specific duration of rainfall excess, the SCS unit hydrograph is determined.

Flow routing using Muskingum method

Routing plays a crucial role in hydrologic modelling by capturing how the flow hydrograph changes as flood discharge moves downstream. When a large basin is divided into sub-basins, the flood hydrograph needs to be routed from the upper sub-basin to the lower one (Angelidis et al. 2010). A routing model facilitates the transfer of the entire runoff hydrograph from the outlet of a sub-basin to the outlet of the entire basin. The Muskingum method is a commonly utilized flood routing technique. It relies on the principle of conserving mass to guide the routing of an inflow hydrograph. This method estimates two parameters, flood wave travel time (K) and channel storage coefficient (x), to capture changes in the shape of the inflow hydrograph.

Determination of runoff curve number (CN)

The SCS-CN method estimates surface runoff by considering the characteristics of land cover, soil type, and the moisture condition of the river basin (Dwivedi and Tripathi 2020). This method classifies soil into four hydrological soil groups (HSG), labelled A, B, C, and D, representing high, moderate, low, and very low infiltration capacities, respectively. Soil groups A, B, C, and D describe the hydrologic properties of soils, particularly their infiltration rates and runoff potential. These groups help in understanding how different soils behave in terms of water movement. Group A

soils, such as sand, gravel, and loamy sand, have high infiltration rates and low runoff potential due to their coarse texture and well-drained nature. Group B soils, which include sandy loam, loam, and silt loam, have moderate infiltration rates and runoff potential. Group C soils, like clay loam, silty clay loam, and shallow sandy loam, have slow infiltration rates and high runoff potential. Finally, Group D soils, which encompass clay, silty clay, and peat, have very slow infiltration rates and very high runoff potential. The value of CN is determined, taking into account the soil moisture content. Based on the rainfall received in the past five days, three soil moisture conditions are defined: dry, moderate, and wet soil. The SCS-CN values range from 0 to 100. Lower values suggest a low potential for runoff, while higher values indicate a greater potential for runoff (Chow et al. 1988). In a basin with various combinations of land cover, soil type, and antecedent soil moisture conditions, a composite CN value is computed. This composite CN for a sub-basin is determined by weighing the CN values and areas of different combinations of soil, land cover, and soil moisture conditions.

Calibration, validation and performance measures

Calibrating and validating the hydrologic model with observational discharge data improves its predictability and ensures reliability of model simulations (Halwatura and Najim 2013). The model parameters are adjusted so that the simulated streamflow matches the observed values. Some of the model parameters cannot be easily known or guessed for initiating the calibration process. In these cases, default or reasonable values are often used to initiate the calibration process and simulate streamflow The model parameters are adjusted iteratively until the simulated and observed values closely match. Trial-and-error as well as auto-calibration methods were applied to optimize the model parameters. HEC-HMS offers auto-calibration through the optimization trial option. Simplex method was chosen for optimization function available in the HEC-HMS model.

Identifying and applying appropriate criteria to assess the similarity between model and observational values is crucial. Various performance measures are commonly used in hydrologic modelling for this purpose. The Nash-Sutcliffe Efficiency (NSE) is a common criterion in evaluation of hydrologic model simulations (Nash and Sutcliffe 1970). Percentage bias (PBIAS) is another popular criterion to evaluate the "goodness-of-fit" of modelled results. Equations 2–3 provide formula for calculating Nash-Sutcliffe efficiency and percentage bias respectively.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \qquad (2)$$

$$PBIAS = \frac{\sum_{i=1}^{n}(S_i - O_i)}{\sum_{i=1}^{n}O_i} \times 100 \qquad (3)$$

where S_i and O_i are the simulated and observed discharge at time step i respectively; $\bar{O}$ is mean observed discharge; and n is the number of time steps. In general, model simulations are considered satisfactory when NSE is greater than 0.5 and PBIAS falls within the range of ± 25 (Moriasi et al. 2007).

Flood-frequency analysis

Maximum streamflow of different return periods offers crucial insights into potential future flood events, guiding the planning and design of flood risk mitigation measures. Flood frequency analysis is a commonly employed method for estimating maximum streamflow for different return periods. A suitable frequency distribution function is used to assess the maximum probable flood for a given return period based on annual daily maximum streamflow values. In this study, Gumbel frequency distribution, which is common in hydro-meteorological research, was applied to annual daily maximum streamflow data to estimate flood discharge for different return periods. The impact of climate change on future flood events was assessed by applying the Gumbel frequency distribution to annual daily maximum streamflow values at the Khokana hydrological station. The comparative change in flood frequency under climate change was evaluated by analyzing simulated extreme streamflow values for current and future time periods.

Results and discussion

Basin modeling

HEC-HMS was employed to simulate streamflow data at the Khokana section of the Bagmati River Basin for both current and future climate scenarios. The basin model within the HEC-HMS project provides a detailed physiographic representation, encompassing the shape, size, direction, slope, and junctions of the river system. To account for topographic variations, the river basin was divided into 23 smaller sub-basins, as illustrated in Fig. 3.
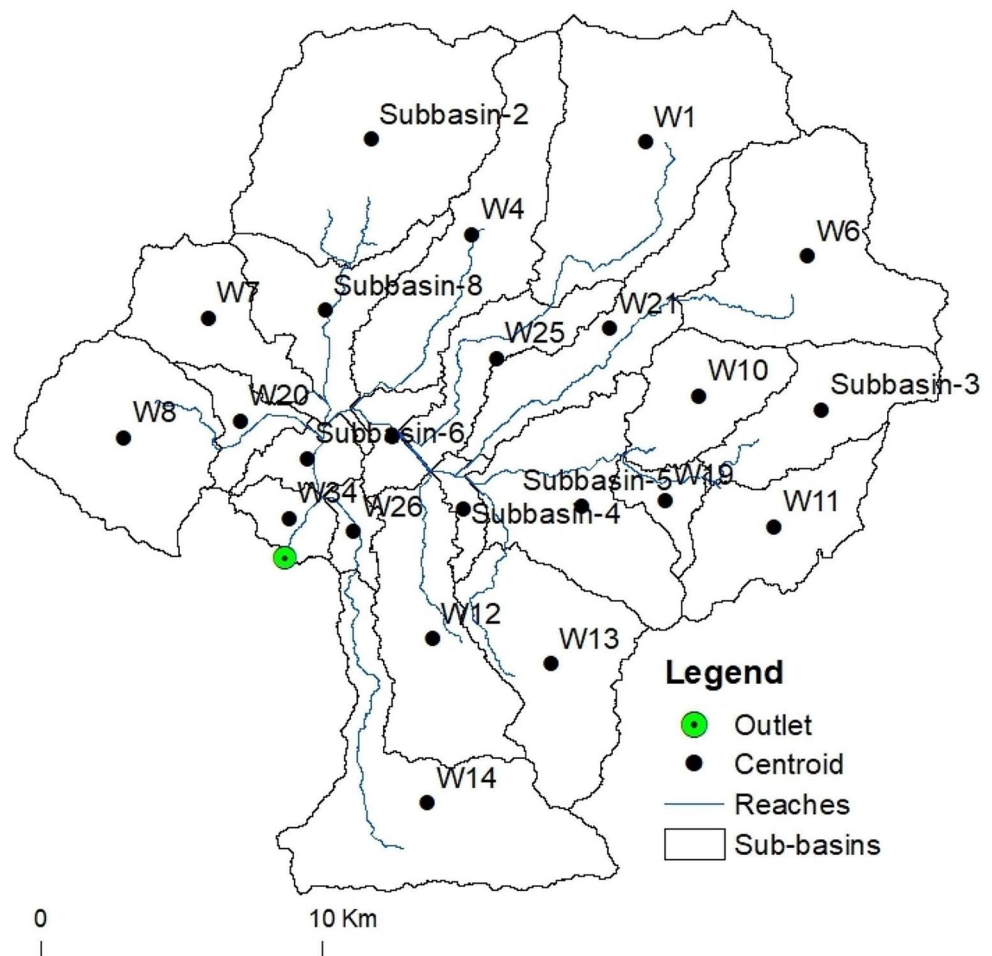
Runoff curve number mapping

Runoff curve number (CN), an index developed by the Soil Conservation Service (SCS), method was used in the HEC-HMS model to estimate the amount of excess rainfall and its transformation in direct runoff hydrograph at sub-basins level. The HEC-HMS simulation model development involved focusing on the three largest flood discharge events between 1995 and 2015. Accordingly, runoff curve number maps were prepared for the years 1998, 2002, and 2011, corresponding to the occurrence of these three major flood events.

Temporal change in soil types is usually found insignificant and thus, it is not important to prepare soil map for all these years. However, temporal change in landcover pattern is reported at higher rate in developing countries. Thus, landcover maps were prepared for all these years for estimating change in runoff curve number values. This involved creating landcover maps for 1998, 2002, and 2011, the years when the three largest flood discharge events occurred. Landsat images were extracted and analyzed for the year 1998 using Landsat 5 captured on April 15, 1998, for the year 2002 using Landsat 7 captured on April 12, 2002, and for the year 2011 using Landsat 5 captured on February 4, 2011. Spatial analysis was employed to obtain landcover maps by analyzing satellite images using unsupervised classification techniques within ArcGIS software. The generated landcover maps were visually analyzed and compared with ground reality to validate the feature classes. This validation involved matching spatial locations of different features with prior knowledge of the study area. Additionally, the accuracy of different landcover classes was checked by visually comparing the generated maps with Google Earth images. The landcover in the Bagmati River Basin primarily comprises three classes: forestland, cropland, and urban regions. Figure 4 displays the landcover maps, indicating the areas for each class and changes over the years. The rise in SCS-CN values in recent years has accelerated runoff processes across the ground surface, resulting in an increase in surface volume.

Soil map of the study area was prepared from Global Hydrologic Soil Groups (HYSOGs250m) for Curve Number-based Runoff Modelling (Ross et al. 2018). In this soil dataset, Hydrological Soil Groups (HSG) were derived from soil depth and texture classes information available in FAO global soil data. HSG indicates the amount of infiltration that occurs in various types of soil. Broadly, there are four hydrologic soil groups: A, B, C and D with "A" soil representing high permeability and little runoff production to "D" soil representing low permeability rates and produce much more runoff. In the Bagmati River Basin, three soil groups: B, C, and D were found (Fig. 5). However, it was observed

Fig. 3 Sub-basins and river networks for HEC-HMS modeling

that the C soil group dominates the basin, covering an area of 528 km², which accounts for 89% of the total basin area.

Figure 6 provides comparative runoff curve number (CN) maps and values for the three largest flood events occurring between 1995 and 2015. The CN values for the Bagmati River Basin were found to range between 68 and 95. The expansion of urban areas has led to an increase in the area with higher SCS-CN values in recent years. As a result, an increase in surface runoff is expected during this period.
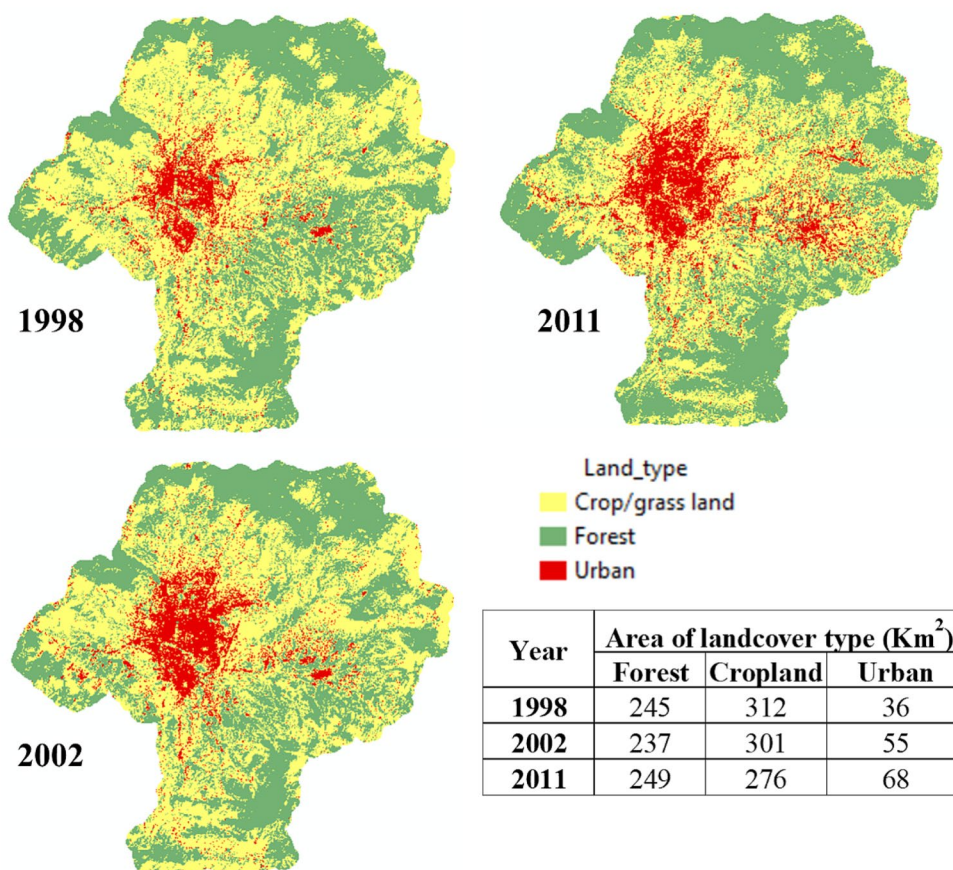
Streamflow simulations

HEC-HMS model was first set-up by calibrating its parameter with flood event of August 2002; and then validated using flood events of July 1998 and September 2011. The year 2002 was chosen for calibration considering highest peak discharge value among three flood events between 1995 and 2015. Figures 7, 8 and 9 provides the results of the calibration and validation process for peak flood events during 2002, 1998 and 2011 respectively. The HEC-HMS model was calibrated and validated using 31-days discharge data with peak value at the centre for each flood event.

Various time periods ranging from 3-days to 30-days were tried for estimating consistent set of model parameters. The model parameters exhibited considerable fluctuations when using smaller time-series data. However, when utilizing discharge datasets spanning longer than 20 days for the calibration of the HEC-HMS model, the model parameters did not demonstrate significant variation. It can be seen that the daily hydrographs of the simulated discharge and observational flood discharge are well matching for the calibration and validation periods.

Different performance measures were applied for comparing the simulated and observed values. The model simulation results were visually examined by comparing the hydrographs of observed discharge with those of the model discharge values to assess their similarity. Moreover, the reliability of the model simulations was evaluated using Nash-Sutcliffe Efficiency (NSE) and percentage bias (PBIAS). During the calibration period (2002), the NSE and PBIAS values were determined as 0.7 and −2.8%, respectively. For the validation periods in 1998 and 2011, the NSE and PBIAS values were 0.6 and 18.3%, and 0.7 and 1.5%, respectively. A model performance is deemed satisfactory for peak flow

Fig. 4 Landcover maps of Bagmati river basin

Year	Area of landcover type (Km^2)		
	Forest	Cropland	Urban
1998	245	312	36
2002	237	301	55
2011	249	276	68

simulations when the NSE value exceeds 0.5 and the PBIAS value is less than 25%. The qualitative (visual) and quantitative statistical analysis show that the developed hydrological model is well performing and suitable for simulation of flood discharge. Additionally, the study tried to determine the sensitive parameters of the HEC-HMS model that significantly influence flood discharge values. It was found that the parameters CN (curve number) and initial abstraction were highly sensitive in simulating peak flows.

Flood-frequency under climate change scenario

Utilizing the calibrated and validated HEC-HMS, the NHRCM precipitation data were employed to simulate daily streamflow values for current and future climate conditions. For this purpose, a runoff curve number map from 2011 was used to simulate streamflow. Flood-frequency analysis commenced with the extraction of annual daily maximum streamflow values for both current and future climate scenarios (Table 2). Gumbel frequency distribution function was applied to these annual daily maximum flood series for flood frequency estimations. Daily maximum floods for 5-, 10-, 25-, 50- and 100-years return period were estimated and compared for the current and future climate conditions.

The plot depicting current and future flood frequency curves indicates a significant increase in future flood values under climate change scenarios (Fig. 10). The maximum discharge for current and future climate conditions was found to be 1362 m³/s and 1818 m³/s, respectively. Additionally, the number of days with greater flood events was considerably higher for future climate conditions. Table 3 compares annual daily maximum flood values for different return periods with average increase by 32.2% in future floods. Notably, similar flood discharge is observed for 100-year return period in the current climate and 25-year return period in the future climate conditions. Earlier, Lamichhane and Shakya (2019) employed a hydrological model to project future flood scenarios in the Bagmati River basin under various climate change scenarios. The results indicated a significant increase in peak flood discharge, with projections showing that river runoff for RCP4.5 scenarios is expected to rise by 12–37% under future climate conditions. In overall, flood frequency is expected to increase substantially under future climate change scenarios. Consequently, existing flood defense installations may prove inadequate in the future, necessitating a re-evaluation of current flood management systems to mitigate future flood risks.

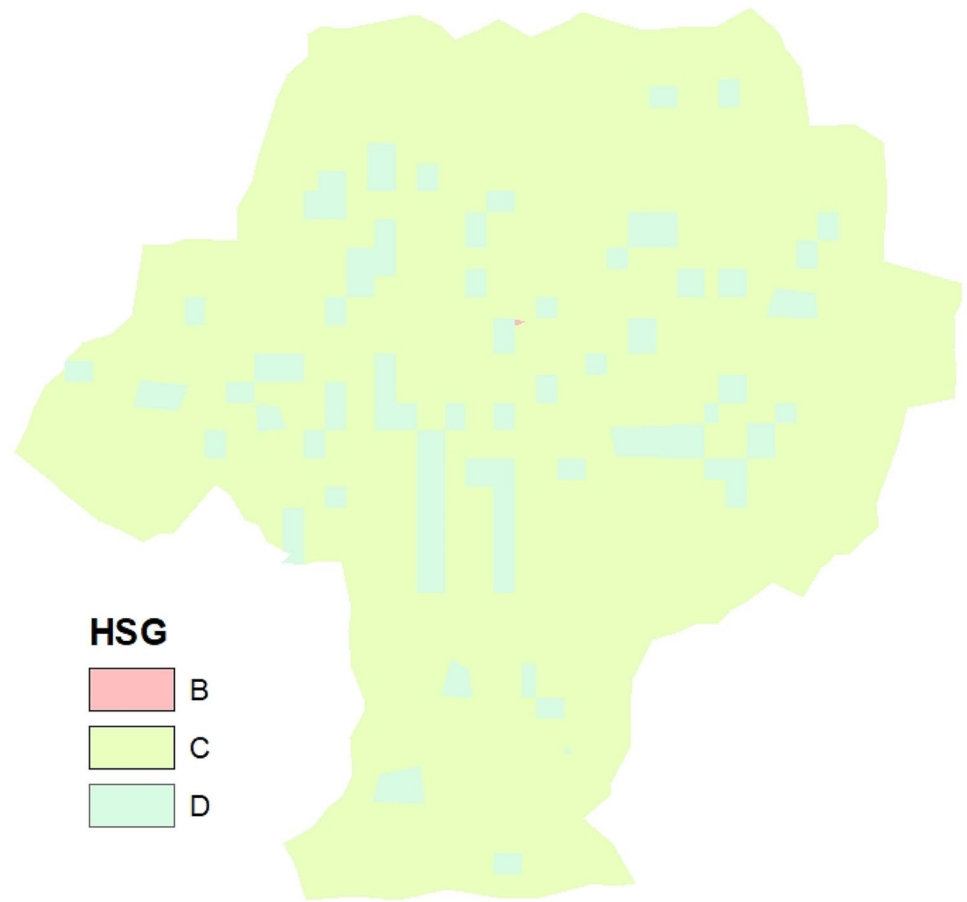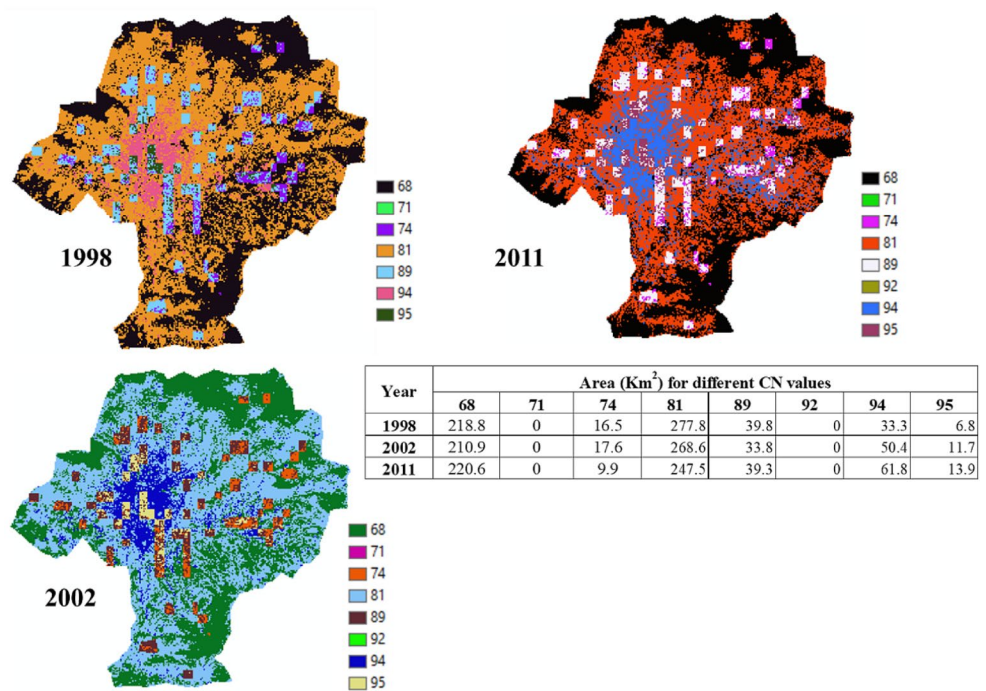Fig. 5 Hydrological soil groups
of Bagmati river basin

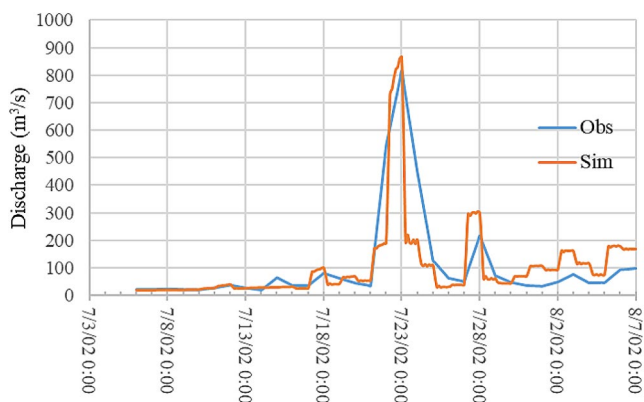Fig. 6 Spatial variation of SCS-
CN values over Bagmati river
basin

Year	Area (Km²) for different CN values						
	68	71	74	81	89	92	94	95
1998	218.8	0	16.5	277.8	39.8	0	33.3	6.8
2002	210.9	0	17.6	268.6	33.8	0	50.4	11.7
2011	220.6	0	9.9	247.5	39.3	0	61.8	13.9

Fig. 7 Comparison of simulated and observed for 2002 flood discharge series
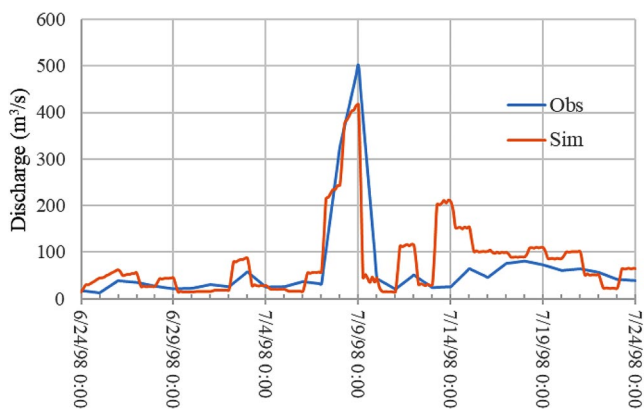
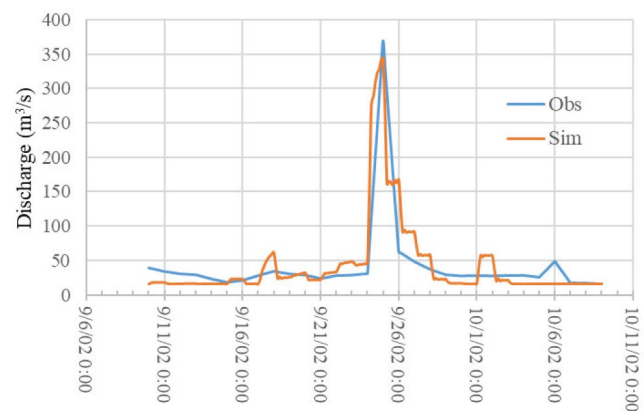**Fig. 8** Comparison of simulated and observed for 1998 flood discharge series

Fig. 9 Comparison of simulated and observed for 2011 flood discharge series

Conclusion

In this study, a rainfall-runoff simulation tool using the HEC-HMS model was successfully established to simulate peak river discharge and address the recurring flood risk in the Kathmandu Valley. The flood simulation model,

Present climate		Future climate	
Year	Q (m³/s)	Year	Q (m³/s)
1981	1350.1	2080	249.1
1982	479.1	2081	1131.7
1983	383.8	2082	1189.3
1984	716.6	2083	533.6
1985	455.6	2084	1294.2
1986	541.8	2085	410.4
1987	793.1	2086	800.4
1988	415.4	2087	510.5
1989	1362.1	2088	519.8
1990	663.2	2089	665.5
1991	379.6	2090	343.7
1992	656.7	2091	434.3
1993	460.4	2092	920.2
1994	469.2	2093	1818.4
1995	317.2	2094	1180.6
1996	462.7	2095	1140.1
1997	713.0	2096	439.4
1998	458.9	2097	426.0
1999	397.7	2098	511.2
2000	817.3	2099	402.0

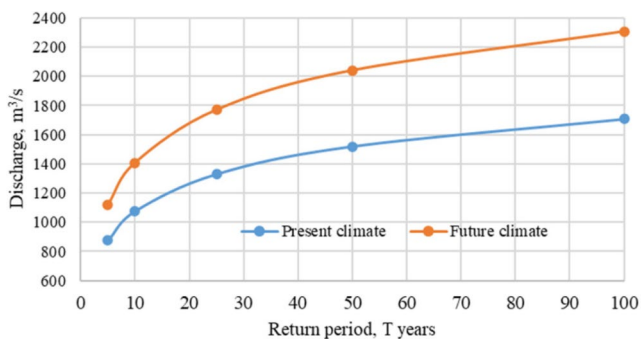**Table 2** Annual daily maximum flood (Q) values for current and future climate

Fig. 10 Flood-frequency curves for current and future climate conditions

Table 3 Comparison of annual daily maximum flood for different return periods

Return period, T years	Discharge, m³/s		Increase (%)
	Present climate	**Future climate**	
5	876	1120	27.9
10	1077	1408	30.7
25	1331	1771	33.1
50	1520	2041	34.3
100	1707	2308	35.2

calibrated and validated with the three largest flood events between 1995 and 2015, demonstrated satisfactory performance through comparison of hydrographs and statistical indicators like NSE and PBIAS. The robustness of the HEC-HMS model, evaluated qualitatively and quantitatively, suggests its reliability for simulating flood discharge within the Bagmati River Basin. With optimized parameters and methodologies identified, peak discharge estimation and assessment are feasible at various locations upstream of Khokana (Lalitpur).

Furthermore, the analysis of land cover, a critical input for peak discharge generation, revealed significant changes within the study area. Examination of land cover maps from 1998 to 2011 showed a notable increase in urban areas, resulting in higher SCS-CN values in recent years. The rise in SCS-CN values and impervious surfaces not only intensify flood discharge but also impede groundwater recharge and water availability.

The high-resolution NHRCM precipitation data in HEC-HMS enabled the simulation of annual daily maximum flood series for current and future climate conditions. Comparison of annual daily maximum discharge at Khokana revealed rising flood risks in the Kathmandu Valley in future. The projected increase in flood risk underscores the imperative for re-evaluating existing flood management systems in the capital city. Large uncertainties are often reported in the projections of GCMs and SSPs. However, the findings of this study are based on a single GCM and SSP. Therefore, it is recommended to consider multiple GCMs and SSPs to obtain more reliable impact studies on streamflow under climate change. Ultimately, this study on hydrological modelling and flood-frequency analysis in the Bagmati River Basin enhances understanding for assessing and mitigating future flood risks under climate change scenario.

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