Climate Change and Flood Vulnerability Analysis in the Narayani River of Nepal

Kiran Maharjan (Ph.D.)[1], Susheel Dangol[2]
kiran0maharjan@gmail.com, susheeldangol@gmail.com
[1]University of New South Wales, Australia, [2]Survey Department, Nepal

KEYWORDS

Climate change, Vulnerability, Flood analysis, Disaster

ABSTRACT

Flood disasters annually devastate livelihoods, particularly during the monsoon season, with no apparent reduction in impacts in low-lying regions of developing countries like Nepal. Given the increasing effects of climate change globally, this study aims to assess climate change effects and biophysical vulnerability of riverine communities to floods in the Narayani River of Nepal, elucidating the interrelationship between these phenomena. This paper presents an analysis of trends and extreme events of climatological variables, such as temperature, precipitation, and daily river discharge and hazard mapping and risk assessments in the river stretch of two Village Development Committees (VDCs) in the country's inner Terai region of Nawalparasi district for different return-period floods, with the aid of the HEC-RAS (Hydrologic Engineering Centre's River Analysis System) and HEC-GeoRAS. A long-term climatological data was collected from the Department of Hydrology and Meteorology, Kathmandu, and the analysis was performed using statistical softwares, SigmaStat, and SigmaPlot. In addition, flood conditions representing 2, and 100-year periods were determined using Gumbel's distribution. The study revealed a narrowing temperature range, with increasing minimum temperatures and decreasing maximum temperatures, precipitation, and river discharge. However, there was a notable increase in extreme events. The hazard mapping indicated the people's vulnerability to inundation and soil erosion along the low-lying riverbanks. The findings underscore the necessity for reliable technological and socio-economic vulnerability mapping to provide early warnings to at-risk populations. This paper argues that unplanned and mismanaged settlements in riverine areas may lead to population displacements, creating environmental refugees.

1. BACKGROUND

Flood disasters are a prevalent global phenomenon that pose intricate challenges stemming from a combination of human vulnerabilities, insufficient development planning, and climate variability (Bubeck et al., 2012). The absence of adequate development planning, changes in land use, haphazard construction of infrastructure in flood-prone areas, and river obstructions all elevate the risk of flooding occurrences. Noteworthy natural disasters such as the Indonesian Tsunami, Hurricane Katrina in the USA (Hoggan, 1997), and the floods in the UK in 2000 and 2007 (Wilby et al., 2008) serve as poignant reminders of the catastrophic consequences floods can inflict on both human lives and economies. Recent flood events in the southern slope of the Himalayas, affecting countries like Pakistan, Bangladesh, India, and other South Asian nations, have resulted in significant human casualties, displacement of populations, and extensive economic losses (Sahoo et al., 2019; Gaire et al., 2015).

Nepal, in particular, faces devastating floods annually, accounting for a significant portion of both human casualties and property damage (Bhattarai & Ghimire, 2023; Gautam et al., 2016). Historical flood occurrences in Nepal have shown that the most significant losses occur along river and rivulet channels, with devastating flood events, for instance, in the years 1993, 2002 in central Nepal, 2008 in the Koshi River, 2008 in western Nepal, 2012 in the Seti River, and 2017 all over the country highlighting the vulnerabilities along riverbanks (Shrestha et al., 2020). These events have resulted in substantial human casualties, property damage, and economic losses, emphasizing the urgent need for effective flood risk management strategies in the region (Devkota, 2021). The country's vulnerability to these disasters is also influenced by factors such as increasing population, poor economic conditions, and unplanned settlements.

The impacts of global climate change further exacerbate the fragility of Nepal's geomorphology. The frequency and intensity of extreme events like floods, and heavy precipitation are projected to increase in South Asia due to global warming (Hasson et al., 2015). Studies indicate that the warming trend in the Himalayas exceeds the global average, emphasizing the region's heightened susceptibility to climate variations (IPCC, 2007a; Meehl et al., 2007; Shrestha et al., 2016).

A combination of structural and non-structural measures is essential for effective flood hazard reduction to address the negative impacts of flooding. While structural measures like culverts, dams, and dykes are considered hard approaches to flood control, they may pose environmental and societal risks (Binns, 2020). In contrast, soft measures, including hazard mapping, risk zonation, and improved flood forecasting systems, are crucial for minimizing flood risks and enhancing resilience, enabling timely decision-making and response efforts (Kvočka et al., 2016; Wang et al., 2018; Binns, 2020; Mostafiz et al., 2022). Studies focusing on categorizing and prioritizing these measures are imperative for developing comprehensive flood control strategies.

While developed nations employ advanced flood forecasting models to manage flood risks effectively, developing countries like Nepal struggle to mitigate the adverse impacts of flooding (Chidi et al., 2022; Shreevastav et al., 2021). Although there are some efforts to mitigate floods involving flood mitigation strategies and green infrastructure like low impact development, localized floods often do not receive adequate attention from policymakers despite their severe impact on rural communities (Sudalaimuthu et al., 2022).

In Nepal, limited research has been conducted on soft measures, particularly in the Narayani River basin, to establish early warning systems and inundation mapping for effective flood control (Dhital et al, 2005; Gautam and Kharbuja, 2006; Dangol, 2014; Banstola et al., 2019; Bhattarai et al., 2019; Thapa et al., 2020; Chidi et al., 2022). Enhancing the understanding of flood risk management through a combination of hard and soft measures is vital for reducing the socio-economic impacts of flooding in vulnerable regions (Quirogaa et al., 2016). By integrating advanced modeling techniques, such as the HEC-RAS (Hydrologic Engineering Centre's River Analysis System) model, with innovative flood control strategies, countries can enhance their preparedness and response mechanisms to mitigate the devastating effects of floods on communities and infrastructure (Sarhadi *et al*., 2012).

This paper aims to analyze the patterns of climatological variables, including temperature, precipitation, and daily river discharge, in addition to performing hazard mapping and risk evaluations along the Narayani River segment within two former Village Development Committees (VDCs) situated in the inner Terai region of what was then Nawalparasi district (now Nawalpur district) in Nepal, being the locations of frequent flooding and severe losses and damages. The investigation focuses on assessing various return-period floods with the support of the HEC-RAS and HEC-GeoRAS tools. The paper firstly reviews literature on climate change and flood vulnerability, followed by a discussion of hazard mapping techniques, specifically in Nepal. The next section includes the methodology used for data collection and analysis of the climatological data and conducting hazard mapping. Next, the findings are presented via climatological pattern graphs and flood vulnerability maps for various return periods. The final section will provide the concluding remarks by providing suggestions on effective land-use planning strategies.

2. CLIMATE CHANGE AND FLOOD VULNERABILITY

Recent studies have emphasized the critical association between Nepal's vulnerability and changes in the water regime, particularly highlighting the impact of floods on human lives, infrastructure, and natural assets, especially during the monsoon season (see Khanal et al., 2019; Aryal et al., 2020; Thapa & Prasai, 2022 etc.). The primary trigger for floods is often attributed to high-intensity rainfall events. Understanding the link between floods and climate change necessitates an analysis of hydrological and meteorological data to assess the extent to which climate change contributes to these devastating flooding occurrences. The repercussions of floods, particularly on communities residing near riverbanks, result in displacements and tragic loss of life, underscoring the socio-economic vulnerability of these populations (Aryal et al. 2020). Despite the implementation of disaster risk reduction and adaptation strategies, the resilience of affected individuals remains a critical concern, as some strategies have proven inadequate in addressing the targeted disasters. Flood forecasting and warning systems emerge as pivotal nonstructural measures in comprehensive flood management, essential for minimizing flood-related damages and preserving human lives (Lin et. al., 1995). Additionally, hazard mapping is identified as a crucial nonstructural measure for disaster mitigation, providing valuable insights into vulnerable areas and populations (Mahato et. al., 1996). The delineation between biophysical and social vulnerabilities, as defined by various scholars, underscores the importance of understanding vulnerability in terms of human capacity to anticipate, cope with, resist, and recover from natural hazards, emphasizing the need for comprehensive approaches to disaster risk reduction and climate change adaptation (Blaikie et. al. 1994).

2.1 Climate change effects on floods

Recent studies have highlighted the intricate relationship between total precipitation and heavy or extreme precipitation events, such as floods, in various regions. While it is very likely that regions experiencing increased total precipitation also witness more pronounced heavy and extreme precipitation events, the opposite can also occur in regions where total precipitation has decreased or remained constant (Alfieri et al., 2013). Despite these findings, changes in extreme events have not received adequate attention, despite their significant implications (Alfieri et al., 2023). Climate change is increasingly manifesting through extreme events like droughts, floods, and heatwaves rather than gradual shifts in average conditions over extended periods (Schröter et al., 2015).

Changes in precipitation patterns can have significant implications, leading to severe water shortages or flooding. The accumulation of continuous yet fluctuating precipitation eventually leads to river flow surpassing a critical threshold, causing breaches in riverbanks or previously implemented flood mitigation measures, consequently resulting in inundation (Smit & Pilifosova, 2002; Bubeck et al., 2012). Additionally, the melting of glaciers can contribute to increased flooding and soil erosion (Siddique & Rahman, 2023). With global warming, extreme events such as droughts, hurricanes, tropical cyclones, typhoons, floods, and heavy precipitation events are expected to become more frequent and intense, despite slight increases in average temperature (Li et al., 2015). Observations have already shown more frequent and intense heatwaves and heavy precipitation events (Nie et al., 2010).

In Nepal, rising temperatures have been recorded at a rate of 0.6°C per decade between 1977 and 2000 (Shrestha et. al., 1999). Moreover, warming trends in Nepal and Tibet have been more pronounced at higher elevations (Talchabhadel *et al*., 2021). Many glaciers in Nepal are experiencing rapid deglaciation, with reported rates of glacial retreat ranging from several meters to 20 meters per year (Chand *et al.*, 2017). This rapid deglaciation poses a significant concern for regions dependent on the Himalayan Rivers (Eugster *et al.,* 2016). The country's hazard landscape varies elevation, with snow avalanches and glacial lake outburst floods (GLOFs) being predominant at very high altitudes, giving way to landslides, debris flows, and their outburst floods in the middle mountains, before riverine floods reign supreme in the lower valleys and plains (Nie et al., 2017).

2.2 Flood vulnerability mapping

The evolving field of flood vulnerability mapping and assessment has seen advancements in methodologies and technologies. Studies like those by Wang & Xie (2018) have explored the applications of remote sensing and GIS in water resources and flood risk management, offering insights into flood modeling and forecasting techniques. Tian et al. (2019) have conducted hazard assessments of riverbank flooding and backward flows, utilizing GIS and digital elevation model technology for flood inundation connectivity and evolution simulations. Merwade *et al.* (2008) have addressed the uncertainties in flood inundation mapping, highlighting the need to consider various uncertain variables in producing deterministic flood extent maps.

Numerous studies conducted since 1990 have been dedicated to identifying floodplains and assessing flood hazards across various regions globally. The Hydrologic Engineering Center's River Analysis System (HEC-RAS) model, developed by the U.S. Army Corps of Engineers (USACE), has emerged as a widely utilized tool for investigating flooding and associated hazards, as well as for mapping floodplains on a global scale (Chaudhary & Piracha, 2021). Integrating the HEC-RAS model with ArcGIS has proven effective in floodplain delineation and risk assessment in diverse geographical contexts (Zope et al., 2016; Shafique & Kim, 2018; Bakare et al., 2019; Muhadi et al., 2020; Atanga & Tankpa, 2021). The HEC-RAS model has been instrumental in simulating flood flows, determining inundation levels, and mapping flood hazards worldwide. For instance, studies have applied this model in regions such as Ottawa, Canada, Los Alamos, New Mexico, USA, Bhutan, Morocco, and Vietnam, showcasing its versatility in flood risk management and mitigation efforts (Earles et al., 2004; Yang et al., 2006; Adhikari, 2015; Mai et al., 2017; Azouagh, 2018). In Nepal, the utilization of the HEC-RAS model, along with its ArcGIS extension (HEC-GeoRAS), has enabled the mapping of flood hazards in critical river systems (Dangol, 2014; Dangol & Bormudoi, 2015). These studies underscore the pivotal role of geo-informatics in enhancing urban river management practices during flood events.

Flood vulnerability mapping in Nepal has been a subject of diverse methodologies and approaches, as evidenced by various studies. Gautam (2017) has emphasized the importance of vulnerability mapping in assessing social vulnerability to natural hazards in Nepal, advocating for decentralized frameworks and inter-district coordination. Additionally, research by Sarkar & Mondal (2019) and Basri et al. (2019) has underscored the importance of utilizing scientifically justified past flood occurrence data for estimating future flood vulnerability and mapping flood-prone areas using remote sensing techniques and Shrestha et al. (2020) have specifically delved into flood risk mapping and hazard assessment in specific regions of Nepal, providing insights into the distribution of flood risk areas and quantifying hazards and vulnerabilities. Aryal et al. (2020) have focused on model-based flood hazard mapping on the southern slope of the Himalayas, offering valuable insights for water resource management and flood control planning. Despite these advancements, there remains a gap in studies that incorporate climate change analysis, and flood inundation mapping using GIS in flood vulnerability analysis, particularly in Nepal. The interdisciplinary nature of flood vulnerability mapping necessitates a holistic approach that integrates diverse methodologies and technologies to effectively assess and mitigate flood risks in Nepal and other vulnerable regions.

3. METHODOLOGY

The research was carried out in the two then VDCs of Kolhuwa and Narayani, situated in the inner Terai region of what was called Nawalparasi district (now Nawalpur). These VDCs were frequently impacted by severe flooding events originating from the river.

3.1. Data collection

Secondary data were obtained from different organizations pertinent to the research. Data on precipitation, temperature, and water discharge were acquired from the Department of Hydrology and Meteorology (DHM), Nepal to investigate the correlation between climate change and flooding in the study area. Furthermore, topographical maps of the study site were obtained from the Department of Survey, Nepal to facilitate flood hazard analysis.

3.2. Analyzing the relationship between floods and climate change

To examine the relationship between climate change and flood occurrences in the study area, long-term climatological data including temperature and precipitation were obtained from the nearest weather station, Dumkauli, through the Department of Hydrology and Meteorology (DHM). Due to the considerable distance of other weather stations from the study sites, they were not included in the analysis. Daily discharge data for the Narayani River at Narayanghat were specifically acquired as this station is in close proximity and serves as a primary confluence of major rivers in the region. Subsequent data analysis was conducted using statistical software packages such as SPSS, SigmaStat, and SigmaPlot. A normality test (Kolmogorov-Smirnov) was performed in SigmaStat to determine the appropriate analytical approach, revealing that the data obtained from DHM were not normally distributed. Consequently, non-parametric analysis methods were employed for the study.

The study conducted trend and mean analyses on variables including temperature and precipitation in the study area, as well as daily discharge in the Narayani River. Analysis of extreme events, such as extreme precipitation and significant floods in the river, was performed to assess the occurrence of climate change in the study area. Correlation coefficients were calculated between the aforementioned variables to determine their significant relationships. Additionally, trend patterns of the variables for corresponding time periods were compared to further support the correlation between them.

3.3. Flood vulnerability analysis

The Hydrologic Engineering Center's River Analysis System (HEC-RAS) has been extensively employed for the computation of one-dimensional water surface elevations and profiles to facilitate flood level prognostication. This software model has gained credibility globally among various entities, including organizations, researchers, and professionals (Knebl et al., 2005). Renowned for its efficacy in river analysis, HEC-RAS has solidified its reputation, and continuous improvements to HEC-RAS have contributed to its ongoing relevance in river analysis (Dangol, 2008). Furthermore, HEC-GeoRAS has been utilized for the preprocessing and postprocessing of data, serving as an intermediary tool bridging HEC-RAS and Geographic Information Systems (GIS), allowing for the extraction of essential spatial information from topographic base maps to support comprehensive analysis (Knebl et al., 2005).

This study used the Sharma and Adhikari (2004)-estimated flood frequency analysis for the Narayani River at Narayanghat for the standard 2-year, and 100-year return periods directly from the flood frequency table. The study area covered 44.75 km^2, including the villages within the study area and a 6.65 km stretch of the river at the study site.

To estimate floods for return periods not explicitly provided in the frequency table, the relationship outlined by WECS and DHM (1990) was employed. This approach enhanced the flood analysis by enabling the extrapolation of flood estimates for additional return periods beyond those directly available from the frequency table.

This methodology aligns with the broader context of flood frequency analysis, where leveraging established relationships and methodologies from prior studies contributes to a more comprehensive understanding of flood occurrences and their implications for risk assessment and management. The integration of such relationships aids in extending the analysis to encompass a wider range of return periods, thereby enhancing the robustness of flood frequency estimations (see table 1). Following relations are used for analysis.

$$Qf = \exp(\ln Q_2 + s\sigma 1) \quad \ldots\ldots\ldots\ldots\ldots\ldots \; i$$

$$\sigma 1 = \ln (Q_{100}/Q_2)/2.326 \quad \ldots\ldots\ldots\ldots\ldots \; ii$$

where ‘s’ is the standard normal variate having different value for different return period;

Q is the flood discharge in m^3/sec;

f is flood return period; Subscript 2 and 100 denote 2-year and 100-year flood return periods respectively.

Table 1: Discharge values for different return periods

S.N.	***Return Period***	***Discharge (m^3s^{-1})***
1.	*2*	*9360.00*
2.	*10*	*12200.00*
3.	*20*	*13249.77*
4.	*50*	*14445.58*
5.	*100*	*15300.00*

4. RESULTS AND DISCUSSIONS

Flood hazard modeling was undertaken to assess the vulnerability of the area to flooding, while statistical analysis was employed to investigate the correlation between various meteorological factors and flood occurrences.

4.1. Relation between climate change and floods

4.1.1. Statistical analysis and results

Correlation analysis was conducted to explore the interconnections among various climatological variables. Spearman Rank Order Correlations, a non-parametric method, were employed to assess the relationships between the variables. The outcomes of the correlation analysis are presented in Table 2.

Table 2: Spearman rank order correlation.

S.N.	Variable	Precipitation	Min. Temp	Max. Temp
1	Daily discharge	0.534	0.331	0.755
	p-value	0	0	0
2	Precipitation	--------	0.171	0.480
	p-value	--------	0	0
3	Max temp	--------	--------	0.714
	p-value	--------	--------	0

The correlation analysis presented in Table 2 indicates significant positive correlations among all variables at a significance level of p=0. Notably, daily discharge exhibits a very high correlation with minimum temperature and a high correlation with precipitation. Given that the Narayani River is influenced by both rainfall and snowmelt, the correlation between precipitation and daily discharge is not as pronounced. Furthermore, daily discharge shows a positive correlation with maximum temperature, albeit to a lesser extent compared to other variables.

Likewise, precipitation demonstrates positive correlations with maximum temperature and a strong correlation with minimum temperature. Additionally, maximum temperature exhibits a high correlation with minimum temperature. The positive correlation between temperature and precipitation suggests a degree of interdependence between these variables, indicating a mutual relationship where one variable influences the other. As temperatures rise, precipitation levels increase, subsequently elevating daily discharge and, consequently, river discharge. This underscores the potential for temperature-induced flood events resulting from climate change.

4.1.2. Analyzing precipitation patterns

Table 3 illustrates a rise in mean precipitation levels from 6.49 mm in the period 1976-1985 to 7.2 mm in 1996-2006. Comparing these values to the mean precipitation over a thirty-year span (1974-2006) of 6.76 mm, it appears that the mean precipitation during 1996-2006 has increased. However, when considering the standard deviations, the mean precipitation values for the respective decades remain relatively consistent. Contrary to this tabular data, previous findings suggest a declining trend in precipitation, attributed to sporadic occurrences of intense precipitation events.

Table 3: Precipitation pattern from 1974-2006 in mm

Year	Min	Max	Mean	St. Dev
1974-1984	0	242.0	6.49	19.34
1985-1995	0	289.0	6.57	19.37
1996-2006	0	324.5	7.20	20.68
1974-2006	0	324.5	6.76	19.81

Data source: DHM, 2008

Moreover, the table indicates an upward trend in the frequency of heavy precipitation events, with the maximum intensity recorded at 242 mm in the initial decade, escalating to 324.5 mm in the third decade, with a consistent increase in the second decade as well. Consequently, although the mean precipitation levels do not exhibit a notable increase over the thirty-year period, there is a discernible rise in the occurrence of extreme precipitation events.

4.1.3. Analyzing discharge patterns

The trend of daily discharge within the Narayani River exhibits an upward trajectory. Table 4 delineates a progression in the mean daily discharge, escalating from 1539.96 m^3s^{-1} in the initial decade to 1573.13 m^3s^{-1} in the third decade. Concurrently, the maximum daily discharge within the river has surged from 10700 m^3s^{-1} in the first decade to 12100 m^3s^{-1} in the third decade. However, when juxtaposed with the mean daily discharge spanning 1971-2006, totaling 1570.53 m^3s^{-1}, the mean daily discharge for the period 2001-2006 showcases a decline. This rise in mean daily discharge is primarily attributed to the heightened occurrence of extreme flood events in recent years.

Table 4: Mean daily discharge in the Narayani River from 1971-2006 in m^3sec^{-1}.

Year	Min	Max	Mean	St. Dev
1971-1980	163	10700	1539.96	1716.52
1981-1990	160	11400	1574.39	1729.81
1991-2000	214	12100	1573.13	1751.87
2001-2006	163	11300	1450.99	1626.77
1971-2006	160	12100	1570.53	1729.37

Data source: DHM, 2008

4.1.4. Analyzing temperature patterns

The graphical representation in Figure 1 illustrates a declining trend in maximum temperature over a span of three decades from 1976 to 2006, while Figure 2 depicts an increasing trend in minimum temperature during the same period.

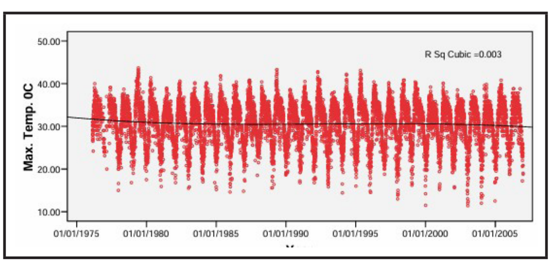

Figure 1: Trend of maximum temperature (1976-2006)

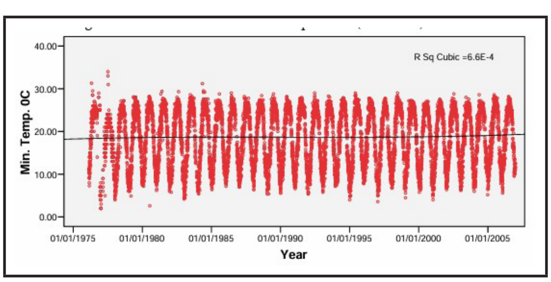

Figure 2: Trend of minimum temperature (1976-2006)

Table 5 presents a decline in the mean maximum temperature from 30.75°C in the period 1976-1985 to 30.35°C in 1996-2006. The mean maximum temperature for the decade 1996-2006, is also lower than the thirty-year mean maximum temperature spanning 1976-2006, which stands at 30.60°C. Conversely, the mean minimum temperature exhibits an increasing trend, rising from 18.63°C in 1976-1985 to 18.81°C in 1996-2006, with an intermediate value of 18.68°C in 1986-1995. The mean minimum temperature for the period 1996-2006 surpasses the thirty-year mean minimum temperature of 18.71°C for 1976-2006, indicating an increase of 0.18°C in the minimum temperature and a decrease of 0.40°C in the maximum temperature over the three decades. Consequently, the table also indicates a narrowing range between the maximum and minimum temperatures.

Table 5: Temperature patterns from 1976-2006.

Year	Temp	Min	Max	Mean	St Dev
1976-1985	Max	14.60	43.70	30.75	4.83
	Min	2.00	34.00	18.63	6.75
1986-1995	Max	14.40	43.30	30.74	4.92
	Min	4.00	29.00	18.68	6.49
1996-2006	Max	11.40	40.80	30.35	4.99
	Min	3.60	29.00	18.81	6.36
1976-2006	Max	11.40	43.70	30.60	4.92
	Min	2.00	34.00	18.71	6.47

4.2. Flood vulnerability analysis

The flood vulnerability maps were generated through the intersection of the land use map of the floodplain with the flood area polygon corresponding to each modeled flood event. This process facilitated the assessment of the physical vulnerability of people to flood disasters (see Figure 3 and 4; Table 6).

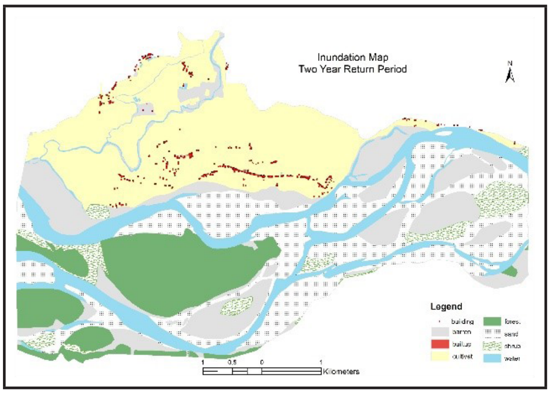

Figure 3: 2-year return period inundation area.

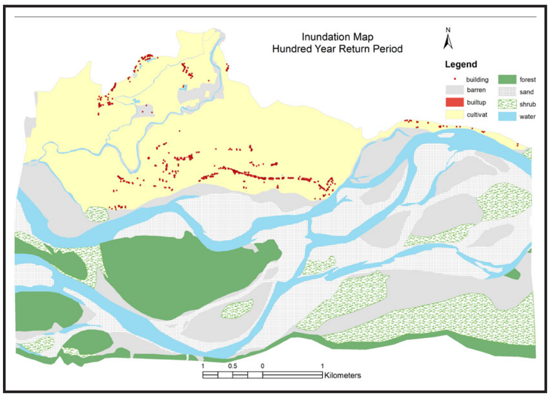

Figure 4: 100-year return period inundation area

Table 2 presents an overview of the impact of simulated floods on land use patterns. The evaluation of the flood-affected area reveals that a significant portion of cultivated land, sand area, barren land and forested areas are situated within the vulnerable zone. Specifically, during the 2-year return period, approximately 8.923 km^2 of cultivated land is submerged, a figure that escalates to 9.889 km^2 for the 100-year return period, rendering the land unsuitable for agricultural purposes. The extent of inundation spans from 27.179 km^2 to 32.641 km^2 across various land categories, encompassing shrub lands, forests, barren lands, and water bodies (excluding the Narayani River) over return periods ranging from 2 to 100 years. However, the data indicates that the inundation of forested and barren areas remains relatively stable despite increasing return periods. This phenomenon can be attributed to the elevated elevation of these forested and barren lands within the study area, placing them beyond the reach of flood inundation at higher return periods. Consequently, these lands are deemed resilient to inundation by floods during extended return periods.

Table 6: Land use vulnerability for different return periods

Land Use Class	Total vulnerable area (km^2)				
	2-yr	10-yr	20-yr	50-yr	100-yr
Barren	5.372	5.397	5.419	6.528	6.772
Built up	0.080	0.081	0.082	0.083	0.086
Cultivation	8.923	9.461	9.657	9.797	9.889
Forest	4.390	4.390	4.390	4.391	4.980
Sand	6.761	6.917	6.932	6.932	6.932
Shrub	1.384	1.384	1.384	2.006	3.713
Water	0.270	0.270	0.270	0.270	0.270
Total	27.179	27.899	28.135	30.006	32.641

The analysis reveals that cultivated land, forest areas, shrub lands, and barren land are subject to inundation by floods, leading to the degradation of cultivated land and a subsequent decline in food productivity and availability within the region. Despite owning agricultural land, many villagers are compelled to purchase food grains for their families, as their hard work and resources are compromised alongside the deterioration of their cultivated plots. Furthermore, the degradation of forest and shrub lands restricts villagers' access to essential natural resources in close proximity.

A considerable expanse of cultivated land falls within the vulnerable zone across various flood frequencies, necessitating the implementation of effective disaster risk reduction strategies to safeguard the area's productivity. Additionally, the study highlights that numerous residences constructed in floodplain areas are at heightened risk of flood hazards, including inundation and soil erosion. Natural calamities do not provide forewarning, underscoring the imperative need for the development of robust mechanisms to mitigate and alleviate the impacts of such disasters to enhance community resilience.

Table 7 illustrates that the count of houses submerged during the 2-year return period amounts to 477, progressively escalating to 529 in the 100-year return period. Assuming an average household size of approximately 6 individuals, the total population at risk due to flood inundations is estimated at 2862, 2970, 3024, 3084 and 3174 individuals for return periods of 2, 10, 20, 50, and 100 years, respectively. It is important to note that the figures denoting the number of houses susceptible to inundation are approximations, as they are derived from google maps and not field verified. Enhanced accuracy in these estimations can be achieved through the generation of large-scale building footprints for more precise calculations.

Table 7: Number of vulnerable houses for different return periods

S.N.	Return period	No. of vulnerable houses
1	2-year	477
2	10-year	495
3	20 year	504
4	50-year	514
5	100-year	529

5. CONCLUSION AND RECOMMENDATION

This paper presented an analysis of climatological variables for trends and extreme events and conducted hazard mapping and risk assessments in the river stretch lying in Nawalparasi district for different return-period floods, using the HEC-RAS and HEC-GeoRAS. It has contributed to the interdisciplinarity of flood vulnerability analysis by incorporating climate change analysis and flood inundation mapping using GIS.

The analysis of temperature trends revealed a gradual convergence between maximum and minimum temperatures. Concurrently, while there was a declining pattern in precipitation trends, there was a notable increase in the frequency of intense precipitation events. A similar scenario was observed in the daily discharge patterns of the Narayani River, where despite a decreasing trend, occurrences of high-volume discharges were conspicuous. These trend dynamics, coupled with the prevalence of extreme events, underscored the manifestation of climate change impacts within the study area. This escalation in the frequency of extreme events, alongside the uncertain trend patterns, signified a growing vulnerability to the effects of climate change.

Moreover, the proliferation of settlements along riverbanks accentuated the heightened vulnerability to such impacts, exacerbated by unplanned and mismanaged settlements. It is imperative that stringent measures, such as the implementation of effective embankments and the relocation of at-risk populations to safer locales, be promptly initiated to mitigate the vulnerability of individuals to flood hazards. Until such measures are implemented, the loss of lives, properties, and livelihoods will persist, exacerbated by incidents of inundation and riverbank erosion exacerbated by the effects of climate change. It is crucial to recognize that the low-lying areas along riverbanks are best suited for cultivation with adequate protective measures, rather than for habitation in a resource-poor country like Nepal. Therefore, construction of houses without proper planning and management should be avoided as far as possible.

Soft measures of flood hazard reduction techniques are very essential in the context of rivers of Nepal, as the Nepal government and the policymakers are usually unaware of localized floods despite their severe impacts on people, similar to what was argued by Sudalaimuthu et al., 2022. As many houses have been built in the low-lying riverbeds, the country urgently needs better flood hazard mapping and forecasting systems, along with timely decision-making and response efforts, for significant reducing flood risks and increasing community resilience, as suggested by Mostafiz et al., 2022.

Without stringent policies and reliable technological and socio-economic vulnerability mapping, developing accurate and prompt early warning systems for climate change disasters remains a challenge. This leaves a significant portion of at-risk populations in Nepal and similar developing countries precariously exposed, increasing the likelihood of environmental refugees.

REFERENCES

Adhikari, R. (2015). Application of HEC-RAS model in flood inundation modeling of Wangchu River, Bhutan. Journal of Bhutan Institute of Technology, 2(1), 1-8.

Alfieri, L., Broduch, Z., Ferraris, M., Jakobsen, N., & Dottori, S. (2013). Rainfall extremes and high-resolution inundation modeling in the Po Plain, Italy. Water Resources Research, 49(6), 3886-3899.

Alfieri, L., Dottori, S., & Mazzetti, C. (2023). Unveiling the misleading relationship between total precipitation changes and flood risk across Europe. Geophysical Research Letters, 50(2), e2022GL101290.

Aryal, A., Baniya, C. B., Shrestha, S., Pandey, B., & Shrestha, M. (2020). Assessment of flood vulnerability and its driving forces in the Gandaki River Basin, Nepal. Sustainability Science, 15(2), 377-396.

Asian Disaster Preparedness Center and United Nations Development Program (ADPC and UNDP). (2005). *Integrated Flood Risk Management in Asia. Bangkok: Asian Disaster Preparedness Center and United Nations Development Program*. Accessed on September 13, 2008.

Atanga, A. B., & Tankpa, V. T. (2021). Floodplain delineation and inundation mapping of Mayo-Danai River using HEC-RAS and GIS. International Journal of River Research and Applications, 37(1), 121-132.

Bakare, A. A., Ibrahim, A. L., Pradhan, B., & Yusof, M. L. (2019). Flood Susceptibility Mapping and Mitigation Strategies in Kelantan River Basin. *Malaysia. Environmental Earth Sciences*, 78(10), 290.

Banstola, N., Ngai, V., Adnan, S. F., & Tang, J. Y. (2019). *Assessing the Effectiveness of Flood Early Warning Systems (EWS) – A Case Study of the Gandaki River Basin, Nepal.* https://www.researchgate.net/publication/255947664_Effectiveness_and_Efficiency_of_Early_Warning_Systems_for_Flash-Floods_EWASE

Basri, H., Anuar, M. K., Abdullah, R., & Yusop, Z. (2019). Assessment of Flood Vulnerability Using Remote Sensing and Spatial Multi-Criteria Evaluation Approach. *Sensors,* 19(1), 180.

Bhattarai, T., & Ghimire, M. N. (2023). *Flood Hazard Assessment in Gandaki River Basin, Nepal.* https://www.mdpi.com/2076-3263/8/2/50

Binns, A. R. (2020). *Floodplain Ecosystems: A Short Review of Their Services and Management.* Wiley Online Library. https://link.springer.com/article/10.1007/s10750-022-04916-7

Blaikie, P. M., Cannon, T., Davis, I., and Wisner, B. (1994). *At Risk: Natural Hazards, People's Vulnerability and Disasters.* London: Routledge.

Bohle, H. G., Downing, T. E., and Watts, M. (1994). Climate Change and Social Vulnerability: Toward a Sociology and Geography of Food Insecurity. *Global Environmental Change*, 4(1), 37-48.

Bubeck, P., Newell, B., & Dessai, S. (2012). *Flood Risk, Resilience and Adaptation & Decision-Making Under Uncertainty in Europe.* https://www.merit.unu.edu/publications/uploads/1684850075.pdf

Buttle, J. M., and Xu, F. (1988). Snowmelt Runoff in Suburban Environments. *Nordic Hydrology*, 18, 19-40.

Chaudhary, A., & Piracha, A. M. (2021). Application of HEC-RAS Model for Flood Inundation Mapping in Chenab River, Pakistan. *Journal of Applied Environmental and Biological Sciences*, 11(1s), 31-39.

Chidi, Z., Ndomba, P., & Rabearison, J. (2022). Flood Vulnerability Assessment and Early Warning System: A Case Study for Data-Scarce Regions. *Natural Hazards*, 1-22. https://www.preventionweb.net/publication/flood-early-warning-system-development-case-study

Dangol, B. (2008). *Application of HEC-RAS Model for Flood Inundation Mapping in Rapti River, Nepal*.

Dangol, B. (2014). *Community Based Flood Risk Reduction Program, Budhikhola Watershed, Nepal*. https://www.scirp.org/journal/paperinformation?paperid=109886

Dangol, B., & Bormudoi, S. (2015). *Flood Hazard Assessment in The Gandaki River Basin Using HEC-RAS Model.*

Dangol, S. (2014). Use of Geo-informatics in Flood Hazard Mapping: A Case of Balkhu River. *Nepalese Journal on Geoinformatics* (13), pp 52-57, DOI: https://doi.org/10.3126/njg.v13i0.16937

Dangol, S., and Bormudoi, A. (2015). Flood Hazard Mapping and Vulnerability Analysis of Bishnumati River, Nepal. *Journal of Geoinformatics, Nepal* 14, pp 20–24, https://doi.org/10.3126/njg.v14i0.16969

Devkota, L. P. (2021). Flood Risk and Adaptation in Nepal. In A. Dutta & M. L. Khan (Eds.), *Natural Disasters in South Asia* (pp. 87–102). Springer Singapore. https://www.sciencedirect.com/science/article/pii/S2214581818300417

Dhital, M. R., Babel, M. S., & Wahid, S. (2005). Flood Hazard Assessment in The Narayani River Basin, Nepal. *Natural Hazards*, 35(1), 361-381. https://www.sciencedirect.com/science/article/abs/pii/S2212420923000158

Earles, J., Michelsen, P., & Weissmann, D. (2004). HEC-RAS Modeling of Flood Wave Propagation in The Ottawa River. *Canadian Water Resources Journal*, 29(1), 79-92.

Eugster, P., Frey, H., & Haeberli, W. (2016). Amending the Definition of Glaciers and Ice Caps in The Himalayan Region. *The Cryosphere*, 10(5), 1525-1530.

Gaire, S., Delgado, R. C., and Gonzalez, P. A., (2015). Disaster Risk Profile and Existing Legal Framework of Nepal: Floods and Landslide. *Risk Management and Healthcare Policy* (8), 2015.

Gautam, D. (2017). Assessing Social Vulnerability to Natural Hazards in Nepal: A District-Level Analysis Using a Composite Index. *International Journal of Disaster Risk Reduction*, 24, 401-410.

Gautam, D. K., and Kharbuja, R. G. (2006). Flood Hazard Mapping of Bagmati River in Kathmandu valley Using Geo-informatics Tools. *Journal of Hydrology and Meteorology*, 3(1), 1.

Hasson, S., Sanderson, M., & Ahmed, K. (2015). Changes in The Seasonal Cycle of Temperature Over Land and Ocean in The South Asian Monsoon Region From 1979 To 2012. *Journal of Climate*, 28(8), 3231-3248. https://journals.ametsoc.org/doi/abs/10.1175/JCLI-D-14-00808.1

Hoggan, D. H. (1997). *Floodplain Hydrology and Hydraulics.* The McGraw-Hill Companies, Inc.

IPCC (2007a). *Climate change 2007: Impacts, Adaptation and Vulnerability*.

Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (Eds.), UK: Cambridge University Press, Cambridge, pp. 976.

Islam, M., and Sado, K. (2000). Flood Hazard Assessment in Bangladesh Using NOAA AVHRR Data with Geographical Information System. *Hydrological Processes*, 14 (3), 605-620.

Khanal, N., Uchida, K., Hirabayashi, Y., Morimoto, T., Ngo, L. T., Dung, N. V., & Nishio, M. (2019). Flood Hazard Mapping Using Improved Inundation Modeling and High-Resolution Land Use Maps. *Journal of Hydrology and Hydromechanics*, 67(3), 321-331.

Knebl, M. R., Wright, N. G., Sonny, M. B., & Baker, V. W. (2005). *HEC-RAS River Analysis System User's Manual (Version 4.1).* https://www.hec.usace.army.mil/software/hec-ras/documentation/HEC-RAS%20User's%20Manual-v6.4.1.pdf

Kvočka, J., Kašpárek, L., & Hlavčová, K. (2016). Flood Risk Perception of Riverside Population in The Czech Republic: A Case Study. *Water Resources Management*, 30(14), 5525-5541.

Li, C., Zhang, Y., Li, X., Xu, H., & Yu, C. (2015). Assessing the Impacts of Projected Climate Change on Extreme Precipitation Over China. *Journal of Climate*, 28(23), 9203-9215.

Lin, C., Cheng, M. D., & Chau, K. W. (1995). Flood Forecasting Using Radial Basis Function Network. *Journal of Hydrology*, 185(1-2), 323-338.)

Mahato, R. C., Higaki, D., Thapa, T. B., and Paudyal, N. P. (1996). Hazard Mapping Based on The Few Case Studies in The Central Region of Nepal. In *Proceedings of An International Seminar on Water Induced Disaster* (pp. 260), 26-29 November. Kathmandu, Nepal

Meehl, G. A., Stocker, T. F., Collins, W. D., Friedlingstein, P., Gaye, A. T., Gregory, J. M., Kitoh, A., Knutti, R., Murphy, J. M., Noda, A., Raper, S. C. B., Watterson, I. G., Weaver, A. J., and Zhao, Z. C. (2007). Global Climate Projections. In Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M. and Miller, H. L. (Eds.), Climate Change 2007: *The physical Science Basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. UK: Cambridge University Press. Cambridge and USA: New York, NY. Nepal Red Cross Society (NRCS). (2008).

Merwade, V., Romanowicz, R. J., & Raffiani, M. (2008). Uncertainty in Flood Inundation Mapping Using Coupled Hydrologic and Hydraulic Models. *Journal of Hydrology*, 359(3-4), 207-220.

Mostafiz, S., Rahman, M. M., & Oo, A. M. T. (2022). Flood Risk Assessment and Management Using a Combined Approach. *Journal of Flood Risk Management*, 15(6), e12827.

Muhadi, A., Ramli, A. F., Pradhan, B., & Sameen, A. M. (2020). Flood Susceptibility Mapping Using an Ensemble Machine Learning Approach in the Sekayu River Basin, Malaysia. *Sustainable Water Resources Management*, 6(8), 3231-3249.

Nie, D., Wu, H., Kim, J., Kakarla, R., & Robinson, A. (2010). An Assessment of Global Precipitation Changes from 1979 to 2008. *Geophysical Research Letters*, 37(7).

Nie, Y., Ngai, V., Kang, Y., Wu, J., & Wong, M. S. (2017). A Comprehensive Framework for Evaluating Flood Resilience of Urban Areas Using Big Data. *Earthquake Engineering & Structural Dynamics*, 46(12), 2251-2273.

Quirogaa, S., Booij, M. J., Correa, A. M., He, B., Liang, X., Mejia-Fernandez, A., & Zhao, G. (2016). Ensemble Hydrologic Prediction for Flood Risk Reduction Under Uncertainty in Complex River Basins. *Water Resources Research*, 52(6), 4638-4662.

Sahoo, B. K., Patel, N. R., Sinha, S., & Kumar, P. (2019). Flood Hazard Assessment and Vulnerability Mapping for the Kosi River Basin Using Geospatial Techniques. *Arabian Journal of Geosciences*, 12(3), 88.

Sarkar, S., & Mondal, P. (2019). Application ff Machine Learning for Flood Susceptibility Mapping in a River Basin Using Satellite Remote Sensing Data. *Journal of the Indian Society of Remote Sensing*, 47(6), 963-973.

Schröter, D., Cramer, W., Le Mouel, P., Van der Linden, A., Bussar, A., Bopfenspörger, T., & Estel, S. (2015). What Can Scenarios Tell Us About Future Biodiversity? *Ecology Letters*, 18(1), 34-45.

Shafique, M., & Kim, S. (2018). Floodplain Delineation and Inundation Risk Assessment Using HEC-RAS and GIS in the Lower Mekong River Basin. *Water*, 10(12), 1822.

Sharma, K. P., and Adhikari, N. R. (2004). *Hydrological Estimations in Nepal.* Nepal: Department of Hydrology and Meteorology.

Shreevastav, A., Singh, V. P., & Sharma, A. K. (2021). Flood Susceptibility Assessment Using Machine Learning Models in the Rapti River Basin, Nepal. *Arabian Journal of Geosciences*, 14(18), 1-17.

Shrestha, A. B., Wake, C. P., Mayewski, P. A., and Dibb, J. E. (1999). Maximum Temperature Trends in the Himalaya and its Vicinity: An Analysis Based on Temperature Records from Nepal for the Period 1971-94. *Journal of Climate*, 12, 2775-2787.

Shrestha, A., Babel, M. S., & Pandey, A. D. (2016). Exploring the Nexus of Climate Change, Water, And Security in the Hindu Kush Region. *Ambio*, 45(S3), 347-360.

Shrestha, S., Vaidya, S., Sharma, A., Nakarmi, S., & Basaula, M. (2020). Flood Hazard Assessment and Risk Mapping in the Trishuli River Basin, Nepal. *Natural Hazards*, 101(3), 829-850.

Siddique, A., & Rahman, M. M. (2023). Glacial Lake Outburst Floods in The Hindu Kush Region: A Looming Threat. *Journal of Mountain Science*, 20(3), 825-838.

Singh, M., and Singh, K. N. (1988). *Planning in Integrated Rural Environment.* Deep & Deep Publications.

Smit, B. and Pilifosova, O. (2002). *From Adaption to Adaptive Capacity and Vulnerability Reduction. Enhancing the Capacity of Developing Countries to Adapt to Climate Change.* London: Imperial College Press.

Smit, B., & Pilifosova, O. (2003). From Vulnerability to Adaptation: A Conceptual Framework. *Mitigation and Adaptation Strategies for Global Change*, 8(2), 223-251.

Sudalaimuthu, S., Johan, S. A., & Abdullah, A. M. (2022). A Review on the Role of Green Infrastructure for Flood Risk Mitigation. *Urban Forestry & Urban Greening*, 73, 107921.

Talchabhadel, R., Rai, S., & Aalto, J. (2021).

Elevation-Dependent Warming Pattern in The Himalayas. *Theoretical and Applied Climatology*, 143(1-2), 223-235.

Thapa, R., & Prasai, S. (2022). Spatiotemporal Flood Vulnerability Assessment in the Gandaki River Basin of Nepal. *Journal of Mountain Science*, 19(6), 1803-1822.

Thapa, R., Baniya, C. B., & Murthy, M. S. R. (2020). Flood Inundation Modelling Using HEC-RAS Integrated with GIS and Remote Sensing in Gandaki River Basin, Nepal. *Arabian Journal of Geosciences*, 13(23), 1-13.

Tian, Y., Wu, J., Liu, Y., Ge, Y., & Li, J. (2019). Assessing Flood Inundation Connectivity and Evolution Based on a GIS And Digital Elevation Model (DEM). *Natural Hazards*, 98(3), 1021-1041.

Vivian, R. (2003). *Nepal Country Case Study*. Regional Workshop on NAPA, Bhutan.

Wang, Y., & Xie, H. (2018). Flood Disaster Monitoring and Early Warning Based on Remote Sensing and GIS. *Sustainability*, 10(11), 3822.

Water and Energy Commission Secretariat and Department of Hydrology and Meteorology (WECS and DHM). (1990). *Methodologies for Estimating Hydrologic Characteristics of Ungauged Locations in Nepal.*

Wilby, R., Beven, K. and Reynard, N. S. (2008). Climate Change and Fluvial Flood Risk in the UK: More of the Same? *Hydrological Processes* 22(14):2511-2523, DOI: 10.1002/hyp.6847

World Meteorological Organization (WMO). (2005). Weather Climate, Water and Sustainable Development. *Annual Report WMO*-No 1000, p. 36.

Zope, A. E., Bhakar, R. P., & Khambete, N. D. (2016). Floodplain Delineation and Risk Assessment Using HEC-RAS Coupled with GIS and Remote Sensing Techniques. *Journal of Applied Water Engineering and Research*, 4(2), 142-156.

ACKNOWLEDGEMENT

The research was undertaken as a thesis for the Master of Arts in Humanities and Natural Resources in 2009. Consequently, the data utilized in this study predates this particular year, however, the google map used to overlay on the inundation maps is from April 2024. The author expresses gratitude for the assistance received from both individuals and organizations, who facilitated the provision of essential data and technical guidance essential for the successful execution of this research.

Author's Information

Name	:	Kiran Maharjan
Academic Qualification	:	PhD
Organization	:	University of New South Wales
Current Designation	:	Academic
Work Experience	:	6
Published paper/article	:	7