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Research Article

# River channel dynamics and flooding: A case of motorable bridge collapse due to abrupt flood in Chhabdi Khola, Tanahun, Nepal

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## Abstract
The monsoon season in Nepal brings calamitous events like riverbank erosion, toe cutting, and the structural failure of bridges due to floods. In July 2021, a motorable bridge in Bhadgaun, Tanahun district, Nepal, collapsed during a massive flood in Chhabdi Khola. The study aims to comprehensively document the aftermath, specifically focusing on the causal factors that led to the damage of the Chhabdi Khola Dovan Bridge. The study delves into an in-depth analysis of the stream's channel morphology, with the 5.85 kilometers Chhabdi Khola partitioned into 28 distinct segments, each spanning approximately 200 meters. These segments, sequentially labeled from Site 1 to Site 28, encompass the area extending from the upstream at Chhabdi Barah temple to the downstream at bridge's location. Rigorous measurements of length, breadth, and depth at each site form the basis for volumetric assessments of the stream. The study revolves around contrasting paleo channel attributes with contemporary alterations within the Chhabdi Khola catchment. The analysis leverages precipitation data sourced from the Department of Hydrology and Meteorology (DHM) to discern precipitation trends within the Chhabdi Khola catchment area. The hydrographic data underwent trend analysis utilizing Mann-Kendall and Sen's slope method through R software (version 4.3.2). The collapse of the Chhabdi Khola Dovan Bridge resulted from intense water flow and debris due to heavy rainfall and a narrow outlet near the bridge, impacting the local population and land users facing the enduring aftermath of a catastrophic monsoon event. The study highlights the significance of understanding river dynamics in small streams and advocates for proactive disaster preparedness measures, even in seemingly small river channels.

***Keywords***: Bridge collapse, Chhabdi Khola, paleochannel, rainfall

## Introduction
In the Nepalese context, water stands as a crucial natural resource, bearing substantial ecological significance and concurrently harboring significant environmental threats that have the potential to unleash catastrophic consequences, ultimately impacting the region's biodiversity and the integrity of its natural surroundings (Hasnat et al., 2018; Thomas, 2017). This research focuses on water-related hazards, such as flooding which occurs when river water levels exceed the flood control capacity, leading to erosion and sediment deposition in low-lying areas (Ciszewski & Grygar, 2016; Devkota et al., 2014). Altered and unpredictable precipitation patterns may lead to riverbank inundation, culminating in flooding events that could compromise prior flood mitigation initiatives (Papagiannaki et al., 2015).

Extreme weather, like heavy rainfall, can lead to unexpected disasters (Batten et al., 2020) which links the annual floods in Nepal cause 29% of fatalities and 43% of property losses (Aryal et al., 2020) among which human decisions on construction contribute to most natural disasters (Gurung, 2019). Climate-induced disaster, such as flood due to heavy rainfall, have significantly impacted various sectors, including infrastructure like settlements, roads, and bridges (Abdul & Yu, 2020; Aryal et al., 2020). While past bridge collapses have expanded our understanding of bridge engineering, the unique characteristics of each collapse make it challenging to provide precise failure explanations (Choudhury & Hasnat, 2015).

In 2019, Nepal began constructing road networks and bridges with support from donor and government agencies 60 years ago. The Department of Roads (DoR) constructs 250-300 bridges annually, and similar projects are undertaken by local and provincial governments. However, some of these constructions fail before reaching their intended design life. The structural issues of bridges in Nepal are probably the result of mountainous country having high-water flow rates contributing in bridges scour (Li et al., 2020). During the monsoon season (June to September), however, geo-hazards and hydro-hazards wash away a significant number of bridges (Gurung et al., 2020). Many bridges have been demolished as a result of geo- and hydro-hazards, but all cases may not have been documented or reported in the media (Gurung, 2019).

Nepal faces hazards due to unplanned settlements, poor infrastructure, and socio-economic challenges (Brogden & Kennedy, 2018). These are worsened by issues like weak disaster management, limited resources, and bridge failures due to design and construction flaws (Choudhury & Hasnat, 2015; McAdoo et al., 2018).

A motorable reinforced cement concrete (RCC) bridge collapsed on 1st of July 2021 in Bhadgaun, connecting two wards of Vyas Municipality (Vyas-1 and Vyas-13) of

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Tanahun district, Nepal which is the major focus of this research. The stream passing through this bridge is Chhabdi Khola which is the tributary of Seti River. It is 5.85 kilometers in length extending from Chhabdi Baraha temple upstream to Chhabdi Dovan downstream. This is the first-time floods have caused such severe damage, according to the events experienced by local people of the area.

This research endeavors to contribute to the mitigation of flood-related challenges in Bhadgaun, Damauli, Tanahun. Its core objective is the identification of key factors that contribute to bridge collapses in Bhadgaun and the provision of recommendations to address these concerns. Furthermore, the study's findings will enhance awareness and preparedness levels in high-risk areas, fostering effective solutions that can benefit the local people. By leveraging the insights generated through this research, the local government can undertake informed measures to mitigate and manage flood risks in the Tanahun region.

The primary aim of this study is to comprehensively document the aftermath of a flood event, specifically examining the causal factors that led to the damage of the Chhabdi Khola Dovan Bridge in Tanahun. This study is particularly dedicated to the analysis and discourse surrounding the broader impacts of the flood on the livelihoods of the Chhabdi community. The insights gained from this analysis have the potential to provide the community with valuable guidance for addressing these issues in the future.

## Materials and Methods

### Study area

Chhabdi Khola catchment of Tanahun district of Gandaki province was selected for the study. This catchment occupied 20.5 square kilometers (sq. km.) area of the Lesser Himalayan zone. Geomorphologically, the catchment area consists of several hills in its boundary region and a plain area in its central region, forming a valley. Tanahun district has a subtropical, temperate, and subalpine climate, with temperatures ranging from 3 to 41 degrees Celsius in the winter and summer respectively. With an annual average precipitation of 1761 millimeters, it is one of the representative districts of Nepal's Mid-hill region (Paudyal et al., 2012; Tripathi et al., 2020).

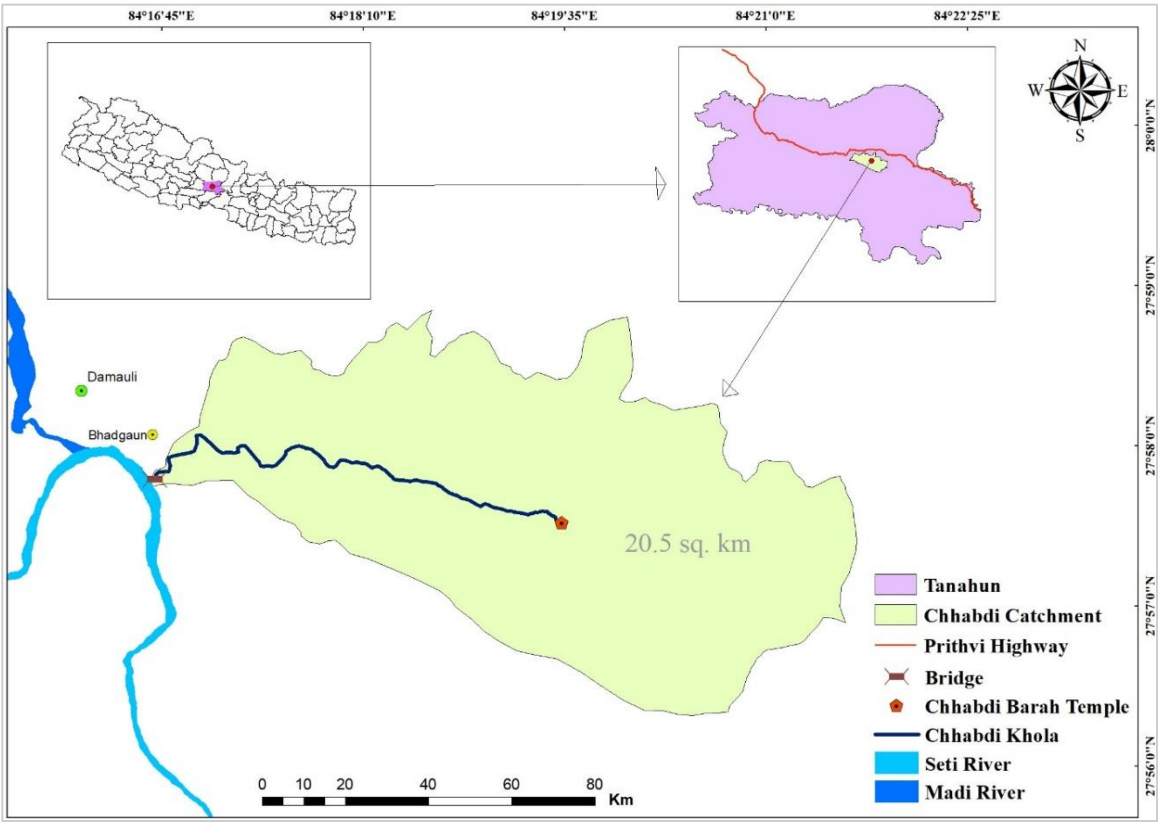


**Figure 1** General view of study area featuring Tanahun District in Nepal, emphasizing the Chhabdi Khola, its catchment area, and the confluence bridge connecting Chhabdi Khola to Seti River near another Seti River's confluence with Madi River.

The Chhabdi Khola Bridge, situated near the outlet of Chhabdi Khola catchment which lies under the Chhabdi Barah temple region, is vulnerable to flooding due to the steep terrain on its surroundings. The Chhabdi Khola catchment has 20.5 sq. km. area. The bridge, a 12.8-meter span connecting Tanahun's Vyas-1 and Vyas-13 municipalities, located at Chhabdi Khola Dovan (27°57'57.60"N & 84°16'36.55"E), approximately 1.5 kilometers southeast of Prithvi highway from Damauli Bazar, collapsed on July 1, 2021. Chhabdi Khola flows for 5.85 kilometers from Chhabdi Barah temple (upstream) to Chhabdi Khola Dovan (downstream), Bhadgaun, confluence to the Seti River about 115 meters south of the bridge as represented in Fig. 1.

**Data collection method**
**Pre-field method**
The study's foundation was laid with an extensive review of existing literature, particularly focusing on stream channel dynamics and flood events in the region. This literature review helped shape the methodological framework underpinning the research as represented in Fig. 3.

The comprehensive compilation of precipitation data pertaining to the Damauli station (Index number 817) during the period from January 2012 to August 2021 was assiduously acquired from the Department of Hydrology and Meteorology (DHM) in Kathmandu.

**Hydrographic survey during baseflow conditions (field method)**
The dataset related with hydrograph of Chhabdi Khlola was acquired under baseflow conditions, enabling the comprehensive analysis of Chhabdi Khola's average depth, breadth (width), length, and volume using a systematic sampling approach. The Chhabdi Khola, extending over 5.85 kilometers, was meticulously segmented into 28 specific sites, spanning from the Chhabdi Barah temple area (upstream) to Chhabdi Khola Dovan; collapsed bridge area (downstream). Each site was labeled from site 1 through site 28, with approximate intervals of 200 meters, progressing from upstream to downstream as illustrated in Fig. 2. During the fieldwork phase, data concerning volume status and post-flood scenarios in the Chhabdi Khola region were diligently documented. The paleochannel areas along Chhabdi Khola were delineated by creating polygons in the sections of the riverbed where the flow of water is no longer active. The recent channel areas were delineated by generating polygons in the segment of the riverbed where both water flow and river sediments are present. This process was facilitated using the Google Earth Pro software, integrated with QGIS, an open-source cross-platform desktop application for geographic information systems.

To ascertain the stream's volume in each section, a meticulous approach was employed. At every 5-meter interval within each site along the stream, measurements and recordings were made for the average widths and average depths, as depicted in Fig. 2. For depth measurements within a site, assessments were conducted by averaging measurements from five distinct areas: two on the left bank, two on the right bank, and three in the midstream area. Regarding breadth measurements in each site, the average was calculated across five measurements, covering the 5-meter section. The depth and breadth of the stream were measured with the help of wooden stick and measuring tape. Fig. 2 illustrates the specific sampling sites and the precise measurement techniques.

**Post Field Method**
Data gleaned from both pre-field and fieldwork phases underwent a rigorous evaluation, leading to the generation of diverse charts and graphs. The Mann-Kendall test is a non-parametric statistical method which can be used for sequentially ordered datasets over time. The Mann-Kendall test was extensively utilized integrating with R software of version 4.3.2 to identify monotonic trends, whether increasing or decreasing, in environmental and time series data (Neupane & Dhakal, 2017; Yue & Wang, 2004). This test assesses trends with a null hypothesis of no trend and an alternative suggesting a trend. Kendall's tau, ranging from -1 to +1, measures correlation, with positive indicating both variables rise together and negative showing an inverse relationship (Neupane & Dhakal, 2017). A Mann-Kendall test with a 95% confidence level was utilized as a monotonic trend test, and in testing, $H_0$ assumes no trend in the dataset's population, with $H_1$ suggesting the presence of a trend; $H_0$ is rejected if $p \leq 0.05$. Similarly, the trend was measured using Sen's slope, a nonparametric method developed by Sen (Poudel & Shaw, 2016) and the slope is calculated using equation 1.

$$Q_i = \frac{X_j - X_k}{j-k} \quad \text{for } i = 1,2,3,\ldots N \qquad (1)$$

Where, $x_j$ and $x_k$ are data values at time j and k (j > k), respectively. Sen's estimator of slope is determined by calculating the median of N values of Qi. If N is odd, the computation involves $Q_{med} = Q\,(N + 1)/2$; for even N, it's calculated as $Q_{med} = [QN/2 + Q\,(N + 2)/2]/2$. The resulting $Q_{med}$ is subjected to a two-sided test at a 100% (1 - α) confidence interval to ascertain the true slope.

## Results and Discussion
**Hydrographic analysis**
The Mann-Kendall trend analysis, conducted with hydrographic data including stream breadth, depth and volume ratio, exposes variations in the pattern across the study area. Table 1 presents the trends in hydrographic data along with its Sen's slope, including breadth, depth, and volume ratio, across various sites. In this study, only the ratio's behavior is observed in case of volume as the data is presented in proportion format, checking for fluctuations.

The trend of breadths and depths of the Chhabdi Khola from upstream to downstream up to bridge area at different 28 sites are in increasing and decreasing trend respectively as obtained from the field and further data analysis as presented in Figs. 4 and 5. The depths of the stream are found almost less than 1 meter from upstream to downstream as represented in Fig. 5. The average breadths and depths of the stream are 17.45 m and 0.25 m respectively, where the maximum and minimum breadth are found to be 28.8 m and 12.5 m respectively whereas maximum and minimum depths are found to be 0.31 m & 0.195 m as shown in Figs. 4 and 5.

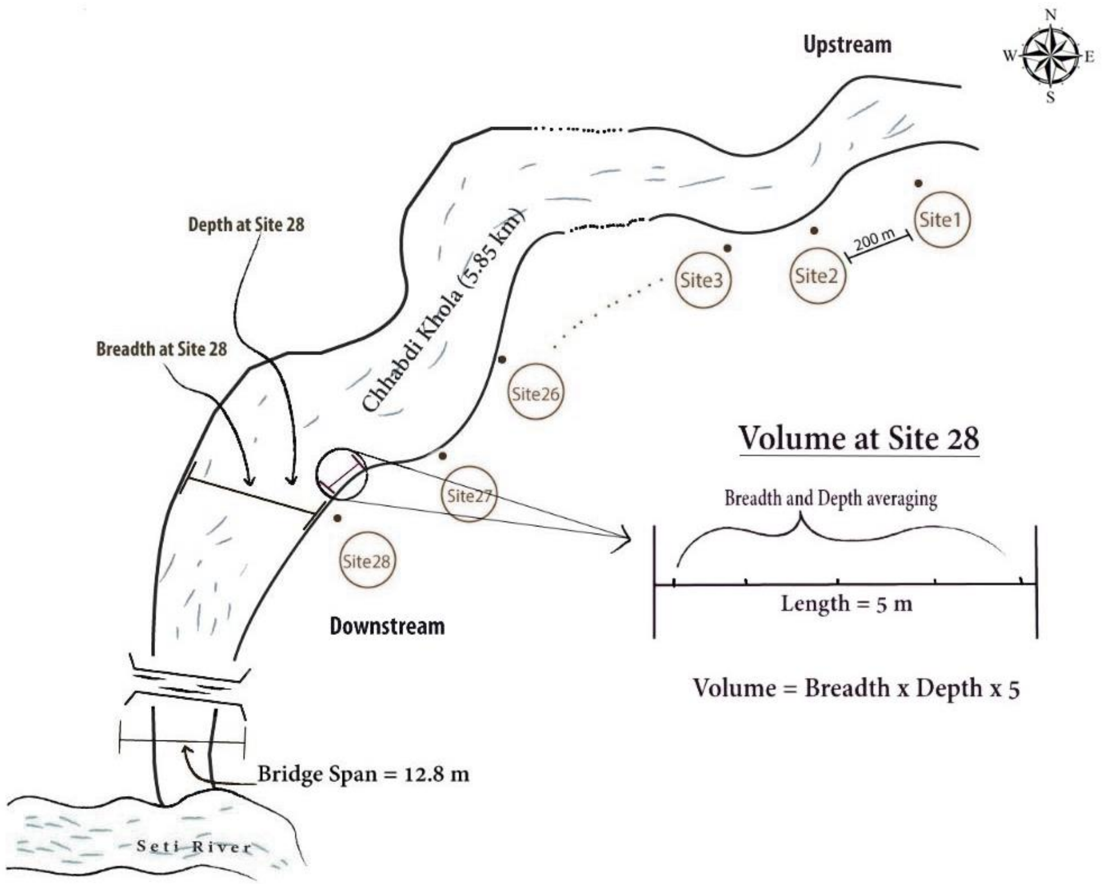


**Figure 2** Illustration of geographical distribution of sampling sites from site 1 to site 28, spanning upstream to downstream of Chhabdi Khola, inclusive of bridge location along with example of data collection method for Site 28.

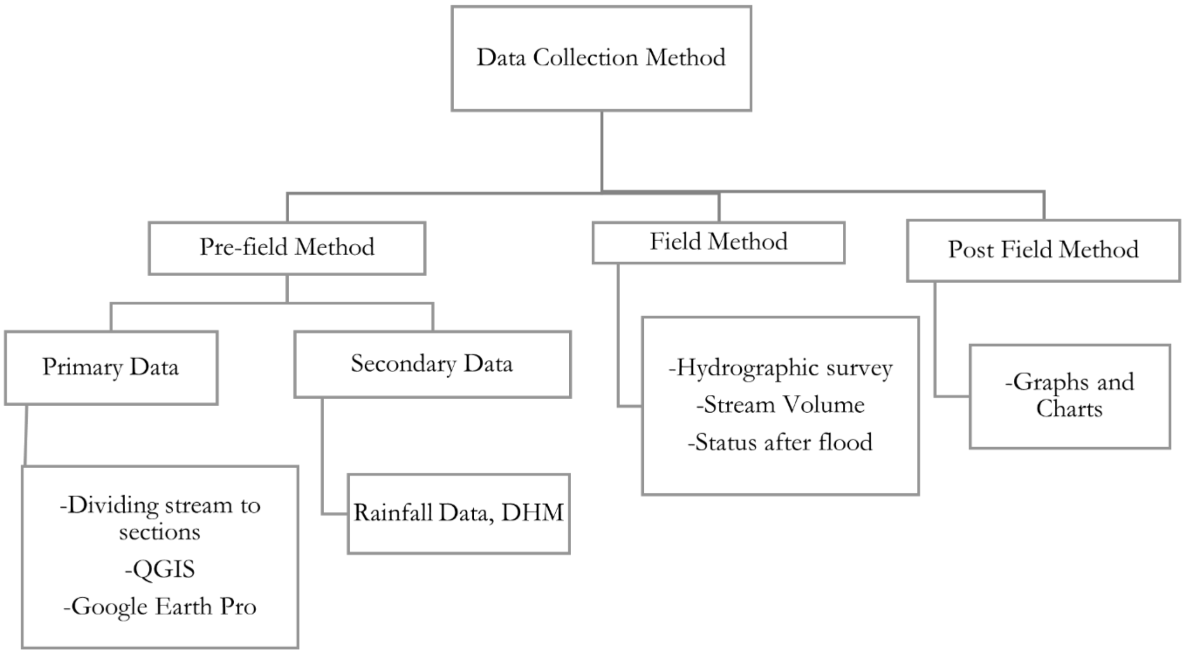


**Figure 3** Methodological framework encompassing comprehensive data gathering, hydrographic survey and post field survey.

**Table 1** Hydrographic data trend for Chhabdi Khola.

| Hydrographic Data | p-Value | Tau | Sen's slope | Significance |
|---|---|---|---|---|
| Breadth of stream | 0.0008693 | 0.45498 | 0.2708333 | Yes |
| Depth of stream | 0.0194 | -0.32037 | -0.001842105 | Yes |
| Volume ratio of stream | 0.5402 | -0.08465 | -0.003512135 | No |

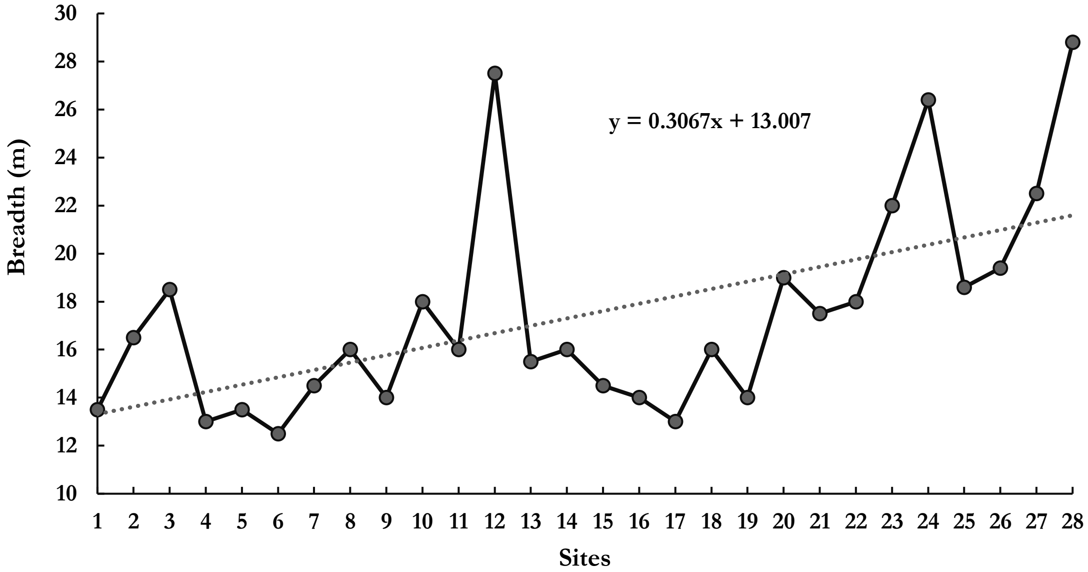


**Figure 4** Gradual expansion of breadth of Chhabdi Khola as progressing from upstream to downstream section, spanning from site 1 to site 28, respectively.

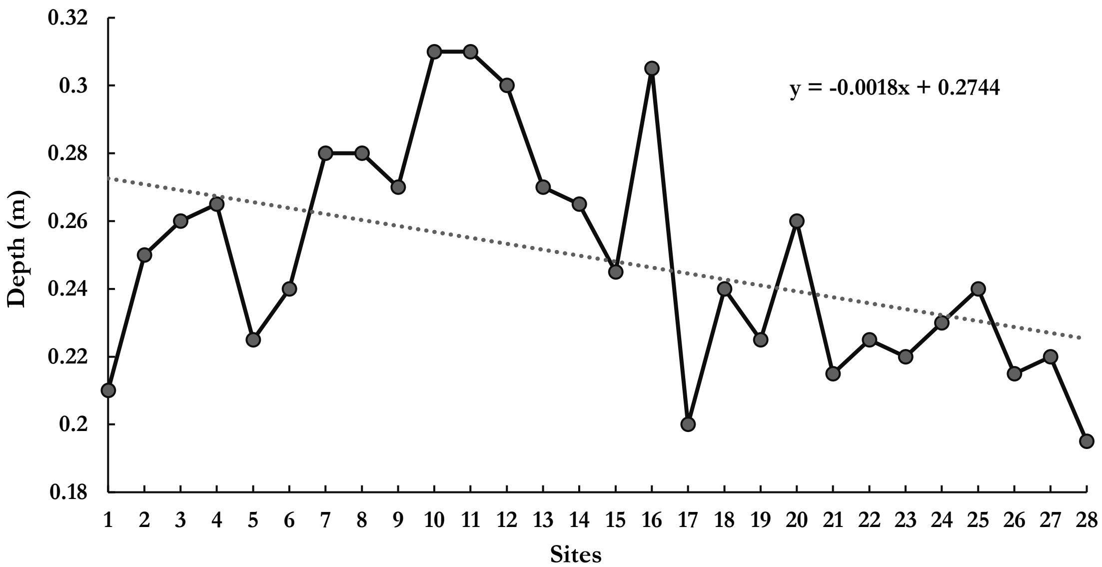


**Figure 5** Reduction in depth of Chhabdi Khola as moving from the upstream to the downstream section, spanning from site 1 to site 28, respectively.

According to field and further data analysis, the volume ratio of the Chhabdi Khola fluctuates along the stream, showing a slight decrease from midstream to downstream at various 28 sites, particularly near the bridge area sites as presented in Fig. 6.

Paleochannel and recent channel are compared and analyzed that how much area of the stream are decreased and flowing in the recent time. The paleochannel regions of the Chhabdi Khola is vastly greater than the size of the Chhabdi Khola's recent channel as illustrated in Figs. 7 and 8.

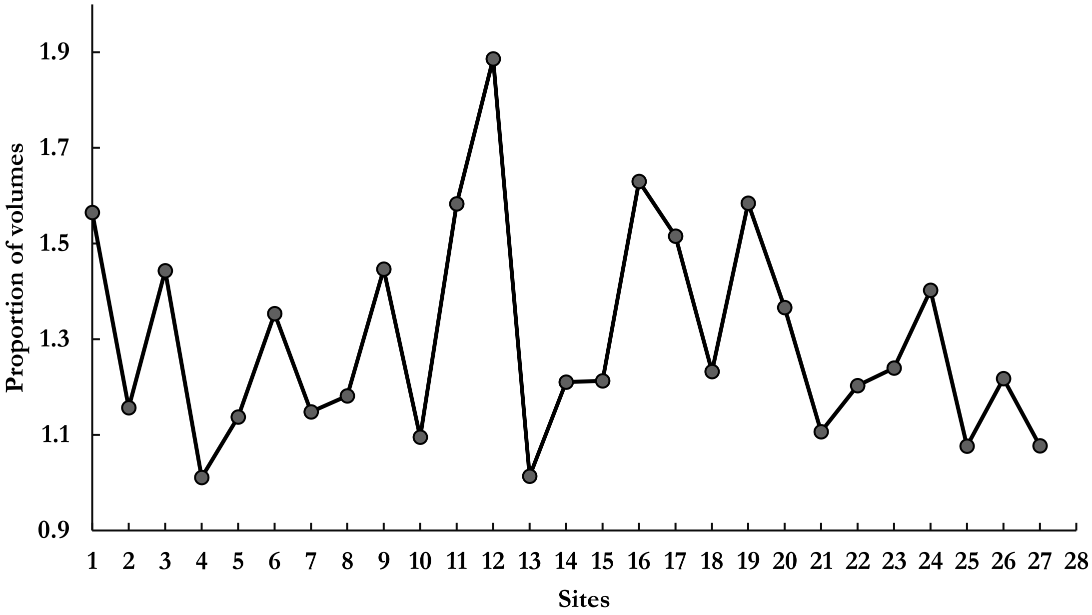


**Figure 6** Reduction in the volume ratio of Chhabdi Khola as moving from upstream to the downstream section, spanning from site 1 to site 28, respectively.

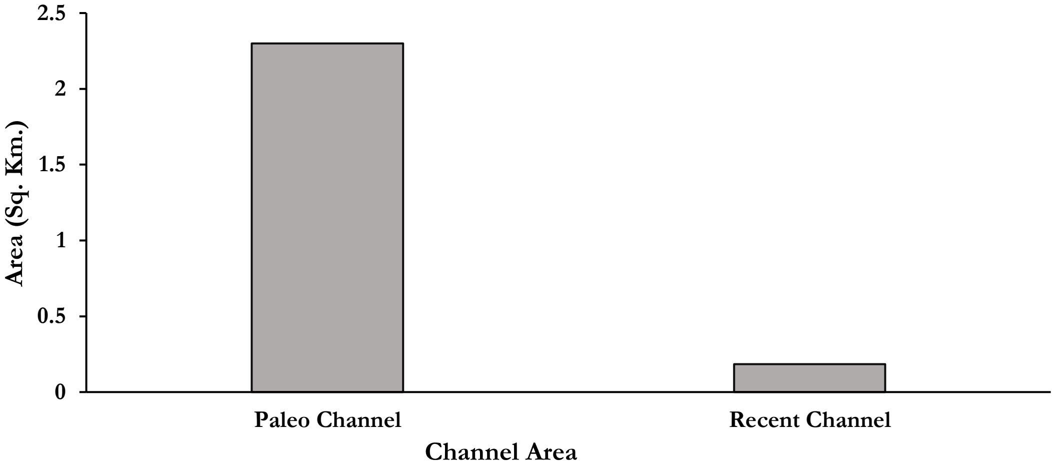


**Figure 7** In-depth exploration of the contrasting conditions between the paleo channel and the recent channel within the Chhabdi Khola catchment.

The Chhabdi Khola catchment, encompassing an area of 20.5 square kilometers, exhibits a paleo channel with an extent of 2.29 square kilometers, in contrast to the current Chhabdi Khola, which occupies a substantially smaller area of only 0.18 square kilometers, as visually represented in Fig. 8. Paleo channel shifts, influenced by natural processes such as erosion and sediment deposition, are evidenced in studies examining river meanders and avulsion events over extended time scales using geomorphological evidence (Pereira & Benedetti, 2013; Romans et al., 2016). Variations in stream width, stemming from natural factors like sediment deposition and avulsion, along with human interventions such as dam construction and channelization, significantly affect floodplain development, habitat diversity, and sediment transport dynamics, thereby influencing erosion and deposition patterns in aquatic and terrestrial ecosystems (Cantonati et al., 2020; Wang et al., 2015).

Additionally, the increased stream width has made streamside dwellings more appealing, thereby contributing to encroachment and associated settlement in the case for Chhabdi catchment. This alteration has, in turn, interfered with the natural stream channel, causing a reduction in stream width (Chou, 2016; Hossain, 2017; Mondal et al., 2018). This scenario may lead to bridge failure due to high flow of water.

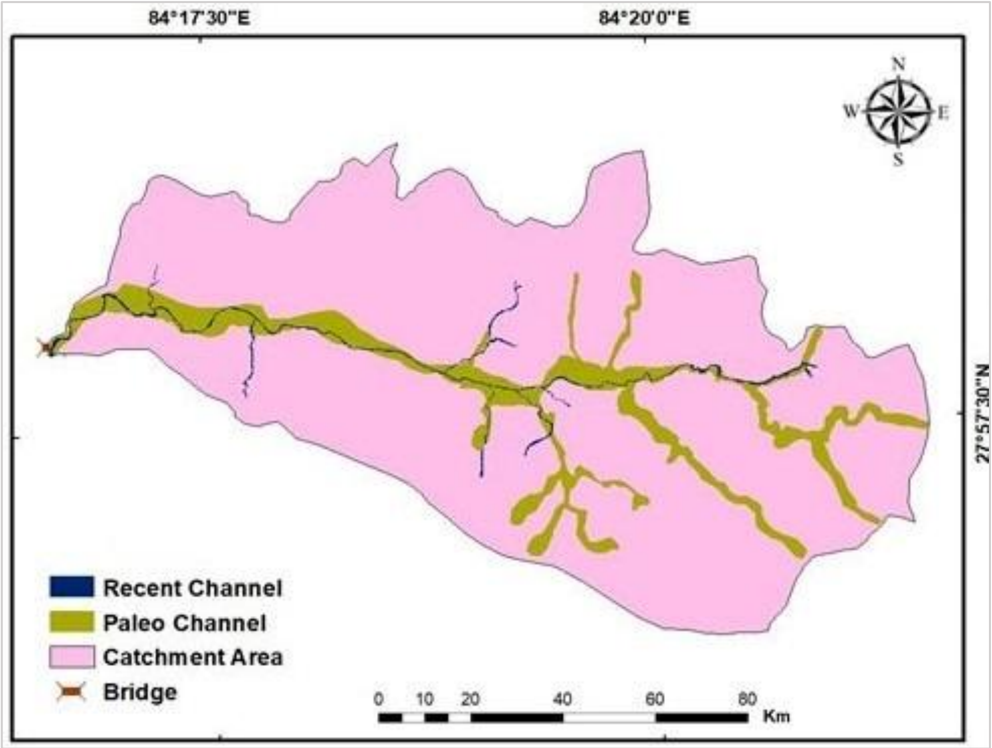


**Figure 8** General view of the entire catchment area, including both the paleo and recent channels, as well as the prominent bridge location.

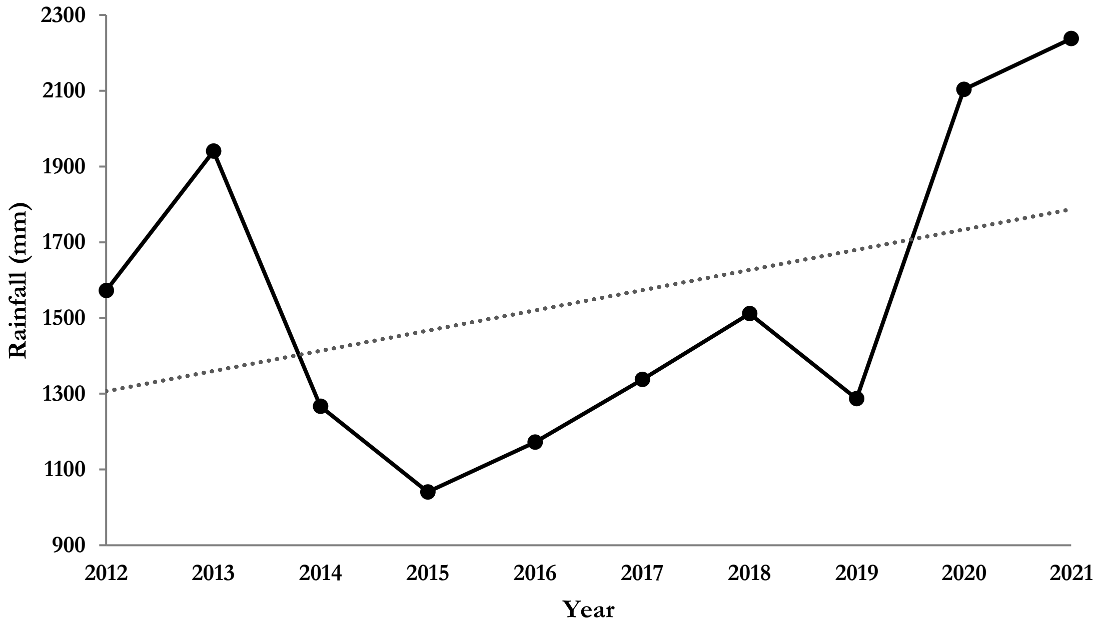


**Figure 9** Upward trend in the annual average rainfall of decade within the Chhabdi Khola catchment.

**Annual Average Rainfall Pattern of Chhabdi Area**
Analyzing the ten-year rainfall data in the Chhabdi catchment, the research focused on short-term cases and did not employ the Mann-Kendall test. Instead, it concentrated on the near-time situation. A comprehensive decade-long analysis of annual average rainfall data in the Chhabdi catchment area revealed a noteworthy upward trend in the overall annual averages. Despite incomplete data for the year 2021, it stands out with the highest annual average rainfall at 2237.45 mm, covering only the period from January to August. In comparison, the annual average rainfall for the year 2012 was 1572.30 mm, representing a notable deviation from the ten-year trend, as illustrated in Fig. 9.

Annual precipitation trends in the basin signal potential challenges for different sub-regions (Shrestha et al., 2019). The Trans-Himalaya and Mountain regions are becoming drier, while the Hill region is getting wetter (Wu et al., 2016). These trends have significant implications for local communities, including an increased risk of flash floods due to extreme precipitation events in the Hill region (Rosenberg et al., 2010). Additionally, the Hill region's vulnerability to soil erosion and landslides is worsened by its fragile geology, deforestation, and intensified precipitation (Dhakal, 2014; Mahapatra et al., 2018; Pokhrel, 2013).

**Average Monthly Rainfall Pattern of Chhabdi Area**
The average monthly rainfall data for the decade are observed and analyzed which shows that the catchment has 130.60 mm. The highest average monthly rainfall data is found to be of July which has 431.96 mm of rainfall and lowest average monthly rainfall data is found to be of November which has 0.94 mm of rainfall as shown in Fig. 10. Furthermore, the monthly rainfall trend highlights July as a month with significantly elevated rainfall levels, making it particularly susceptible to flood occurrences. This observation aligns with the established spatial rainfall patterns prevalent in Nepal, and a comparable finding was reported in previous research by Kansakar et al. (2004).

**Seasonal Precipitation (Rainfall) Trend of Chhabdi Area**
The pre-monsoon and monsoon rainfall pattern of Chhabdi area is found to be in increasing trend as presented in Figs. 11 and 12. The pre-monsoon data for the year 2015 is missing from DHM, so excluding it the trend can still be taken as in increasing order. The highest pre-monsoon rainfall is found to be 483.34 mm in the year 2020 as shown in Fig. 11 whereas the highest monsoon rainfall is found to be 1851.93 mm in the year 2021 as shown in Fig. 12.

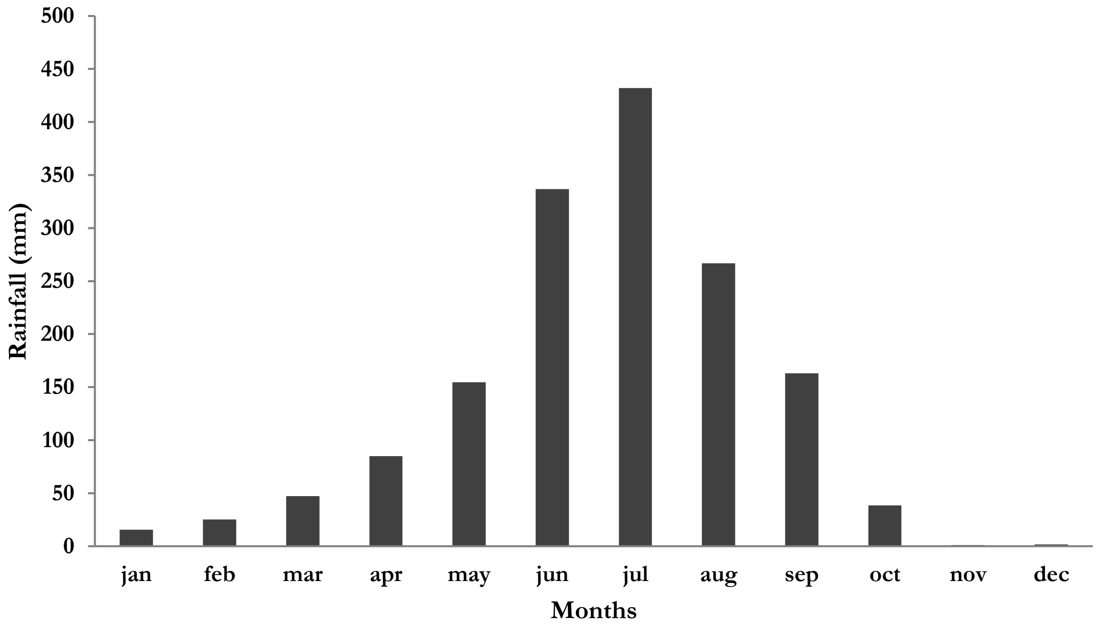


**Figure 10** Distribution of monthly average rainfall within the Chhabdi Khola catchment.

The monsoon season (June-September) in Chhabdi periphery experiences high rainfall, leading to flood and landslide risks. Post-monsoon periods, as shown in Fig. 13 for 2012-2021, experience the lowest rainfall levels. Numerous studies have consistently confirmed that Nepal experiences its monsoon season from June to September, during which approximately 80% of the annual rainfall is received, with the highest precipitation levels occurring in July (Dahal et al., 2018; Perry et al., 2020; Poudel & Shaw, 2016). This pattern of heightened rainfall during the monsoon season corresponds to a higher likelihood of frequent flood events with shorter return periods. It is reported that both the spatial and temporal distribution of rainfall in the Gandaki River Basin of Nepal demonstrates a substantial increase in rainfall during the monsoon season and a significant decrease in the post-monsoon, pre-monsoon, and winter periods across most regions (Panthi et al., 2015).

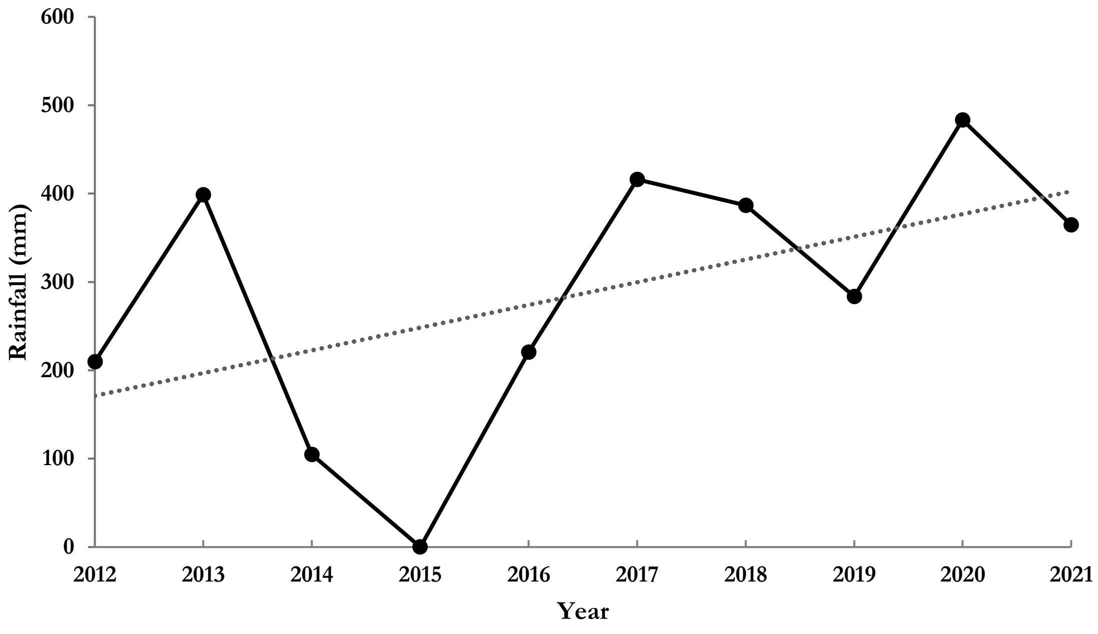


**Figure 11** Increasing trend of Pre-monsoon rainfall from 2012 to 2021 years within the Chhabdi Khola catchment.

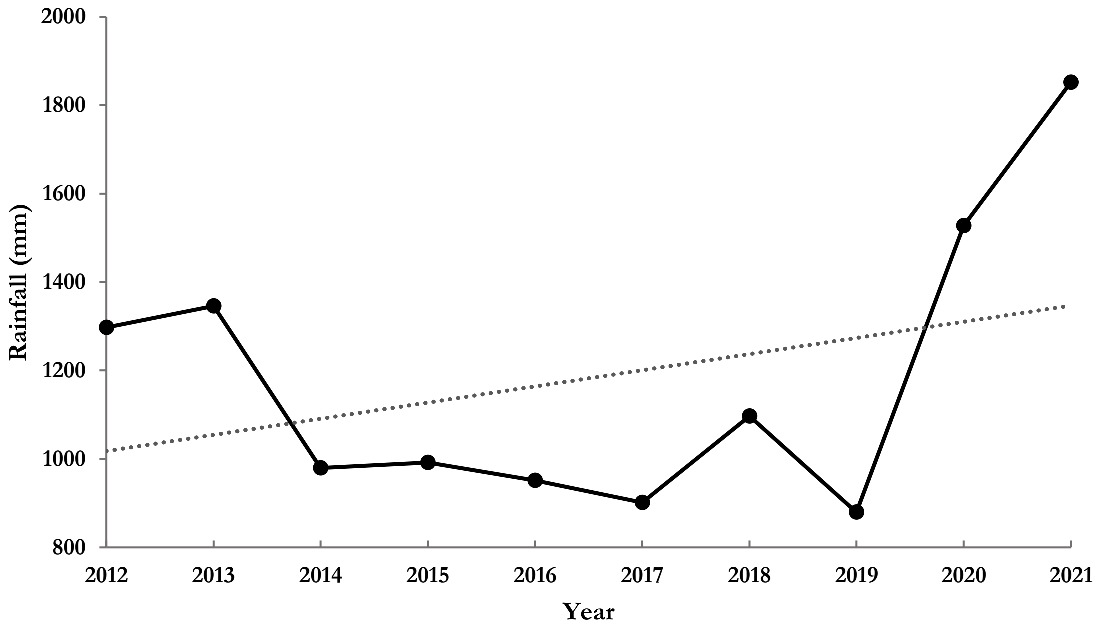


**Figure 12** Increasing trend of monsoon rainfall from 2012 to 2021 years within the Chhabdi Khola catchment.

The average pre-monsoon and monsoon rainfall for the years 2012 to 2021 is 286.836 mm & 1182.295 mm respectively as represented in Table 2.

**Table 2** Average Pre-monsoon & Monsoon rainfall data from 2012 to 2021 of Chhabdi catchment.

| Station | Pre-monsoon (mm) | Monsoon (mm) |
|---|---|---|
| Damauli | 286.836 | 1182.295 |

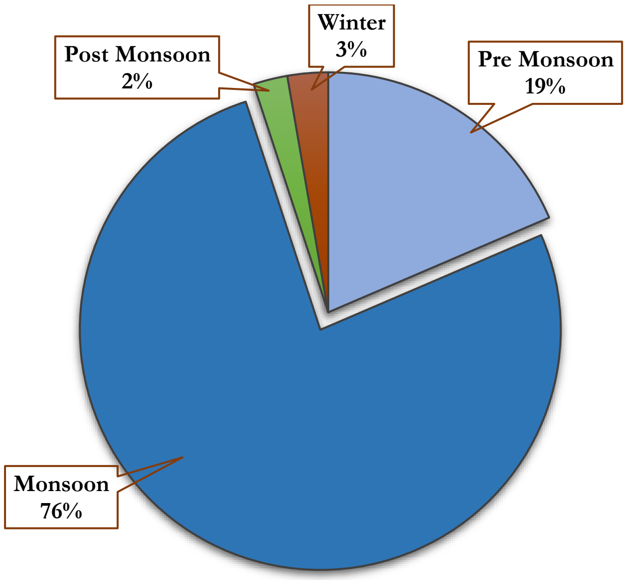


**Figure 13** Overall seasonal rainfall pattern of decade within the Chhabdi Khola catchment.

## Effects of flooding in Chhabdi catchment

### Bridge collapse

The Chhabdi Dovan Bridge collapsed in the year 2021 following a flooding event in the Chhabdi catchment area, an unprecedented occurrence according to local community reports. The bridge's current state can be seen in Fig. 14, with debris and materials scattered around the collapsed structure due to the flood aftermath. Fig. 14 provides a visual overview of the bridge's historical and current conditions, which served as a crucial link between Vyas Municipality's wards 1 and 13, as well as its surrounding environment.


**Figure 14** Comparing before and after condition of Bridge area due to flood; a: Bridge condition assessment of Chhabdi Khola Dovan linking Vyas 1 and Vyas 13 under low-flow conditions b: Bridge infrastructure loss and roadway damage in aftermath of the flood event c: Bridge dimensions indicated by red dotted line and showing location of Seti River area which is mainstem for Chhabdi Khola d: Condition of Chhabdi Dovan Bridge's structural integrity following its submersion by the Chhabdi Khola flood and subsequent debris accumulation (*Note: The photographs featured in Fig. 14 to Fig. 17 were captured by the author.*).

The bridge has an average width of 17.47 meters, but at study site 28, the stream widens to 28.8 meters near the bridge inlet, as shown in Fig. 14. The figure shows the stream flowing narrowly through the bridge, highlighting the insufficiency of the bridge's dimensions, especially its height and length, to accommodate the stream's width and ensure unobstructed flow.

In a comprehensive study by Wardhana and Hadipriono (2003) analyzing 500 bridge failures in the USA from 1989 to 2000, hydraulic factors related to flooding, including insufficient waterway capacity, emerged as the primary causes. Similarly, a study by Lebbe et al. (2014) in Queensland, Australia, identified floods resulting from inadequate waterway capacity as a significant contributor to bridge damages and failures. This scenario parallels the case of the Chhabdi Dovan Bridge.

On the same day, an analogous event transpired in the vicinity of the Chhabdi Barah temple, located approximately 5 kilometers northeast of Chhabdi Khola Dovan, which is within the periphery of study site number 25. This incident entailed the complete dislodging of a crucial wooden bridge, supported by concrete-based pillars, utilized for local transit, as a consequence of an exceptional rainfall-induced deluge. The ramifications of this deluge extended to the detriment of agricultural lands, croplands, and grasslands, as evidenced in Fig. 15.


**Figure 15** Chhabdi flood impact in the upstream area near Chhabdi Barah temple in site 25; a: Photograph showing the bridge pillar scouring during the flood b: Photograph showing complete sweeping away of the same bridge after the flood.

**Rapid Rainfall Impact**

Various incidents transpired during the persistent rainfall period on July 1, 2021, owing to the relentless precipitation in the Chhabdi catchment area. The excessive rainfall in this region gave rise to several critical issues, including human safety concerns, structural and infrastructural damage, as well as significant losses in the agricultural and livestock sectors. Furthermore, it led to soil erosion and landslides, compounding the risks to human life, hindering transportation and communication systems, and further exacerbating damage to buildings and infrastructure, as illustrated in Fig. 16.


**Figure 16** Post-flood condition in Chhabdi Khola; a: Expansion in both banks of Chhabdi Khola affecting agricultural area; highlighted by the red line indicating the original Chhabdi Khola path b: Landslide as indicated by red line and soil erosion resulted from extreme rainfall. *(Photo taken after 24 days of the flood).*

The Chhabdi Khola area faced numerous challenges following a destructive flood event. This led to significant property losses, including farmland, homes, and livestock. Erosion of soil put many houses at risk, and the fast-flowing floodwaters further exacerbated the situation. Fig. 17 illustrates one such at-risk building near the downstream area.

Because of the heavy rainfall and the narrow stream channel near the outlet, a bridge at Chhabdi Dovan was destroyed by the flooded Chhabdi Khola. This caused many problems for the people living in Vyas Municipality. Hearn (2002) stressed the underuse of engineering geomorphology in Nepal, leading to recurring issues, design modifications, and realignment of infrastructure. The interplay between river hydrology and geomorphology is often neglected during design, increasing the risk of bridge failures (Zevenbergen et al., 2011). In the case of Chhabdi Khola, the stream's changing course and widening reduced the width of outlet of the bridge, contributing to its failure.


**Figure 17** Building being exposed to vulnerable due to Chhabdi flood; red line indicating the original Chhabdi Khola path and blue line encircles the immediate structural mitigation (gabion wall) applied after flood event to minimize risk for building.

## Conclusions

The Chhabdi Khola Bridge crumbled under the weight of heavy rainfall, resulting in a devastating flood that severely impacted nearby residents. After the comprehensive hydrographic and paleochannel analysis, the stability of bridge was compromised, resulting to bridge failure. This study emphasizes the importance of concentrating on structural designs like bridge, and buildings particularly in the vicinity of streams, with a focus on river dynamics even in small streams, and advocates for the implementation of proactive disaster preparedness measures even if the river channel is seemingly small.

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**Author Contributions:** Madhav Adhikari: Design and performance of study, data collection and analysis, editing, reviewing, primary manuscript draft, the draft revision and finalizing the manuscript. Bharat Prasad Bhandari: Overall supervision, guiding in data analysis, editing, reviewing, manuscript draft and reviewing the manuscript.

**Conflict of Interests:** The authors declare no conflict of interest.

**Data Availability Statement:** The data that support the finding of this study are available from the corresponding author, upon reasonable request.

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