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ASSESSING MORPHOLOGICAL FACTORS AND ITS IMPACT ON URBAN FLOODING

By

Aashray Kapali (079MScUrP001)

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DECLARATION

I hereby declare that the thesis entitled " **Assessing morphological factors and its impact on flooding: A Case Study of Dhobi Khola** ", submitted to the Department of Architecture in partial fulfillment of the requirement for the degree of Masers of Science in Urban Planning, is a record of an original work done under the guidance of Dr. Ajay Chandra lal, Institute of Engineering, Pulchowk Campus. This thesis contains only work completed by me except for the consulted material which has been duly referenced and acknowledged.

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079MSCURP001

Abstract

The rapid urbanization of the Kathmandu Valley has significantly altered its river systems, influencing flood dynamics and exacerbating flood risks. This research examines the impact of urban morphological changes, driven by infrastructure development, land use transformation, and increased urban density, on flooding within river basins in the Kathmandu Valley. The study explores how modifications in urban form, such as impervious surfaces, road networks, building density, and drainage infrastructure, disrupt natural water flow patterns and drainage efficiency. By analyzing key urban morphological indicators—such as surface permeability, road density, and building configurations—this research aims to assess their contribution to increased flood volume, runoff, and overall flood vulnerability in urbanized catchments. The findings will offer crucial insights into how urban development interacts with river morphology and inform more effective flood management strategies in rapidly urbanizing regions like the Kathmandu Valley.

Keywords: Urban Morphology, River Basin, Impervious Surfaces, Building Density, Surface Permeability, Runoff, Flood Management

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Acronyms and Abbreviations

EA	Environmental Assessment
LULCC	Land Use and Land Cover Change
GIS	Geographic Information Systems
RS	Remote Sensing
MBV	Mean Building Volume
SDBV	Standard Deviation of Building Volume
IR	Impervious Rate
RD	Road Density
DEM	Digital Elevation Model
BFE	Building Footprint Edge Density

1. Introduction

The Kathmandu Valley's rivers, once dynamic floodplains, have undergone significant morphological changes primarily driven by land cover changes due to rapid urbanization, deforestation, and alterations in agricultural practices. These shifts in land use disrupt natural hydrological processes, significantly impacting flooding dynamics. Urban expansion has replaced permeable surfaces with impervious materials such as concrete and asphalt, increasing surface runoff, reducing water absorption, and overwhelming drainage systems. The impacts of these changes are particularly evident along the Bagmati and Dhobi Khola rivers, where urban encroachment has impaired natural river flows, preventing proper floodwater dispersal. As Gautam et al. (2013) and Dhital & Kayastha (2013) note, urbanization in the Bagmati River Basin has led to frequent flooding, exacerbated by the loss of natural vegetation, which typically enhances infiltration and reduces runoff. Similarly, infrastructure development along the river corridors has altered sediment dynamics, further reducing flood resilience (Thapa et al., 2024). Urban morphology, including building density, road configurations, and drainage systems, plays a critical role in shaping flood risks. High-density urban development and the associated increase in impervious surfaces further concentrate water runoff, leading to more severe flooding (Walsh et al., 2012; Shepherd, 2005). Drainage system inadequacies, combined with the encroachment on water bodies, limit the capacity to manage floodwaters (Sugianto et al., 2022). Moreover, climate change intensifies rainfall patterns, placing additional strain on these already stressed systems. As Huang and Fan (2025) emphasize, effective flood management must account for the complex interactions between land cover changes, urban morphology, and river dynamics. This study aims to examine how these evolving factors, including urban form, land use changes, and climate impacts, influence flood resilience in Kathmandu Valley and other similarly urbanized regions, offering insights into better flood management strategies.

2. Need for research

Flooding in rapidly urbanizing areas is increasingly influenced by morphological transformations of the built environment, particularly building density, impervious surface cover, and urban form. Existing literature establishes that peak discharge during extreme events is primarily driven by catchment imperviousness, built density, and the effects of climate change. However, most development visions and regulatory frameworks inadequately address these morphological variables in the context of flood resilience.

A larger mean building volume typically indicates more built-up mass and, by extension, greater imperviousness, which contributes to higher surface runoff. At the same time, areas with higher vertical development (greater mean building volume but compact footprint) may actually reduce urban sprawl and preserve green, permeable surfaces—showing that urban morphology has complex, dual effects on hydrological responses. These nuances are often missing from conventional land use and zoning policies, which focus primarily on height restrictions and setback regulations, with minimal attention to building density, volume, or their spatial configuration.

Current planning practices also lack integration with flood-responsive design, especially in flood-prone catchments such as Dhobi Khola, where new development is expected. Despite the availability of policies like the river setback strategy and the Bagmati Action Plan, these are rarely linked with morphological data and spatially explicit hydrological assessments. As such, there is a pressing need for catchment-specific studies that incorporate urban form variables (building volume, density, road density) alongside land use plans to guide sustainable and flood-resilient development. This type of research can provides actionable insights for developing flood-resilient urban designs.

3. Importance of research

The importance of this research lies in its potential to significantly enhance flood management and resilience in the Kathmandu Valley, especially given the rapid urbanization and changing river dynamics in the region. Despite existing studies on flooding and urbanization (Dhital & Kayastha, 2013; Pradhan-Salike & Pokharel, 2017), there is a critical gap in understanding how urban morphology—such as building density, road networks, and drainage systems—interacts with river morphology to influence flood resilience. This research is essential to bridge this gap, offering insights that can inform urban planning and flood mitigation strategies. By exploring the relationship between urban development and flood dynamics, the study will help improve urban planning practices, ensuring that building configurations and infrastructure are optimized to reduce flood risks. Additionally, it will provide valuable data on how urbanization's effects, particularly increased impervious surfaces and altered drainage systems, contribute to surface runoff and flooding. This research will also emphasize the need for integrated flood management strategies that incorporate both structural interventions and the natural functions of river corridors, ensuring sustainable flood resilience in the long term. With climate change exacerbating rainfall patterns, this study will also contribute to climate adaptation strategies by offering insights into how urbanization and river systems interact under changing environmental conditions. Furthermore, by refining flood risk mapping and assessing how morphological factors affects flood risks, particularly in tributaries like the Dhobi Khola, this research will improve the accuracy of flood vulnerability assessments, enhancing preparedness for future flood events.

4. Problem Statement

One of the key challenges in managing flood risks in the Kathmandu Valley is the lack of research on how urban morphology can be modified to reduce flood vulnerability, despite its proven potential to mitigate flood volumes by up to 7.8% (Zhu et al., 2024). Urban morphology, which encompasses the physical layout of cities, plays a significant role in shaping flood dynamics by influencing water flow patterns and drainage efficiency. In rapidly urbanizing areas like the Kathmandu Valley, where land use changes have replaced permeable surfaces with impervious materials, surface runoff has increased dramatically, overwhelming drainage systems and exacerbating flood risks. Furthermore, urban planning elements such as building density, road configurations, and drainage systems directly impact the ability of the landscape to manage water during heavy rainfall events.

For instance, the geometric configuration of buildings—such as the mean building volume (MBV) and the standard deviation of building volume (SDBV)—can significantly affect runoff and localized flooding (Bruwier et al., 2020; Wang et al., 2023). Additionally, urban surface features like road density and impervious surface edge density also have a profound impact on flood susceptibility, with higher road densities and impervious surfaces contributing to greater flood volumes (Rahman et al., 2021). Research has shown that even modest modifications to urban morphology, such as adjusting the placement of impervious surfaces or enhancing permeability, can lead to a reduction in flood water accumulation and mitigate flood impacts (Zhu et al., 2024).

Despite these insights, the Kathmandu Valley lacks a comprehensive understanding of how urban morphology interacts with river morphology to influence flood dynamics. The region's river corridors, once dynamic floodplains, have been significantly altered by urban encroachment, with infrastructure developments and land use changes that restrict water flow and reduce natural floodwater management capacity. The need for research that integrates urban morphology and river dynamics is critical in understanding how these changes affect flood resilience, particularly in areas like the Dhobi Khola, where urban development has disrupted the natural flow of the river. By examining how changes in land use, building configurations, and drainage systems contribute to flooding, this research will provide valuable insights for creating integrated flood management strategies that balance urban development with flood resilience.

5. Research Question

- How do urban morphological factors impact the flooding in Kathmandu Valley?

6. Research Objectives

- To explore how morphological variables relate to each other
- To quantify relationship between flooding variables and morphological indicators
- To assess how changes in morphological indicators impact flooding patterns
- To develop strategies for flood resilient development in the future

7. Research Gap

The research gap in this study lies in the limited understanding of how changes in the urban morphology of river catchments specifically influence flooding in the Kathmandu Valley. While urbanization and infrastructure development are recognized as key factors in flood risk, there is insufficient research on how alterations in the catchment's physical structure—such as changes in land use, building density, road networks, and drainage systems—directly affect flood dynamics. These changes impact the natural water flow, runoff patterns, and sediment transport within the catchment, leading to altered flood behavior. A deeper exploration of how urban morphology within catchments drives flooding in the Kathmandu Valley is crucial for developing targeted flood resilience strategies and improving flood risk management.

8. Research Paradigm

Post-positivism allows you to **test hypotheses** and look for causal relationships, but with an understanding that all findings are approximate and subject to revision as new evidence emerges. The research follows a **post positivism** research philosophy. The research tries to correlate various variables relating to urban and river morphology linked with flooding.

- **Objective Measurements:** Rely on measurable variables (land cover, runoff, discharge).

- **Probabilistic Modeling:** Recognizes uncertainty and variability in natural processes.

Both **qualitative and quantitative approaches** will be followed, for which the quantitative approach was used in the simulation while the qualitative approach will be used in the validation of the results from the simulation in the field, through questionnaires.

9. Ontology and epistemology

Ontology refers to the philosophical study of the nature of being, existence, or reality. In the context of research, it concerns the assumptions and beliefs about the nature of reality and what can be known about it. It addresses questions such as "What is the nature of the phenomena being studied?" and "What kinds of entities or things exist in the domain of study?" In social and physical sciences, ontology refers to the way in which researchers conceptualize and categorize the world, including the classification of objects, entities, and their relationships. (Crotty,1998)

- **Objective Reality**: The physical aspects of urban morphology (such as the layout of buildings, roads, drainage systems, and changes in land use) exist as real, measurable entities within the environment. These urban elements directly influence flood dynamics in the Kathmandu Valley catchments. The physical changes to the landscape (e.g., the conversion of permeable surfaces to impervious ones, changes in water flow paths due to infrastructure) are the core focus.
- **Urban Morphology and Physical Systems**: The research assumes that changes in the physical urban environment, such as increased building density, road networks, and altered drainage systems, create tangible impacts on flood behavior. These changes in land cover and land use alter natural water drainage patterns and runoff characteristics.
- **Natural and Built Environment Interaction**: The research focuses on the interaction between urban infrastructure and natural hydrological systems, emphasizing how human-made changes to the landscape impact flood processes in the river catchments.

Epistemology is the branch of philosophy that deals with the theory of knowledge, focusing on the nature, scope, and limitations of what can be known. In research, epistemology concerns the assumptions about how knowledge is constructed, what constitutes valid knowledge, and how we come to know and understand reality. It addresses questions such as "How can knowledge be acquired?" and "What are the acceptable methods for gathering and interpreting data?" In social and physical sciences, epistemology helps define the relationship between the researcher and the researched, determining the methods and tools used to generate knowledge. (Crotty,1998)

- **Empiricism**: The research adopts an **empirical** approach to acquiring knowledge, where data will be collected directly from the physical environment. This includes satellite images, land use maps, hydrological data, and flood records to understand how urbanization affects the flow of water and the capacity of the catchment to manage floodwaters.
- **Quantitative Methods**: The epistemological stance is **positivist**, relying heavily on quantitative methods, such as spatial analysis, flood modeling, and the measurement of physical features like road density, building footprint, and impervious surface area. This will allow for the generation of objective, measurable data that can be used to assess the impact of urban morphology on flooding.

10. Methodology

The methodology would be more focused on empirical data collection, measurement, and statistical analysis.This research involves several key steps. First, **data collection** will focus on gathering spatial data (via GIS and remote sensing), historical flood data (such as rainfall, river discharge, and flood events), and urban morphological data (including land use and infrastructure). Next, **GIS analysis** will be used to assess urban growth patterns, identify flood-prone areas, and examine river morphology changes. **Statistical analysis** will apply correlation and regression techniques to quantify the relationship between urban morphology and flood risk. **Flood modeling** will simulate flood scenarios using hydrological models based on the collected data. Finally, the research will provide **policy implications** and propose actionable recommendations for urban planning, flood management strategies, and infrastructure development based on the findings.

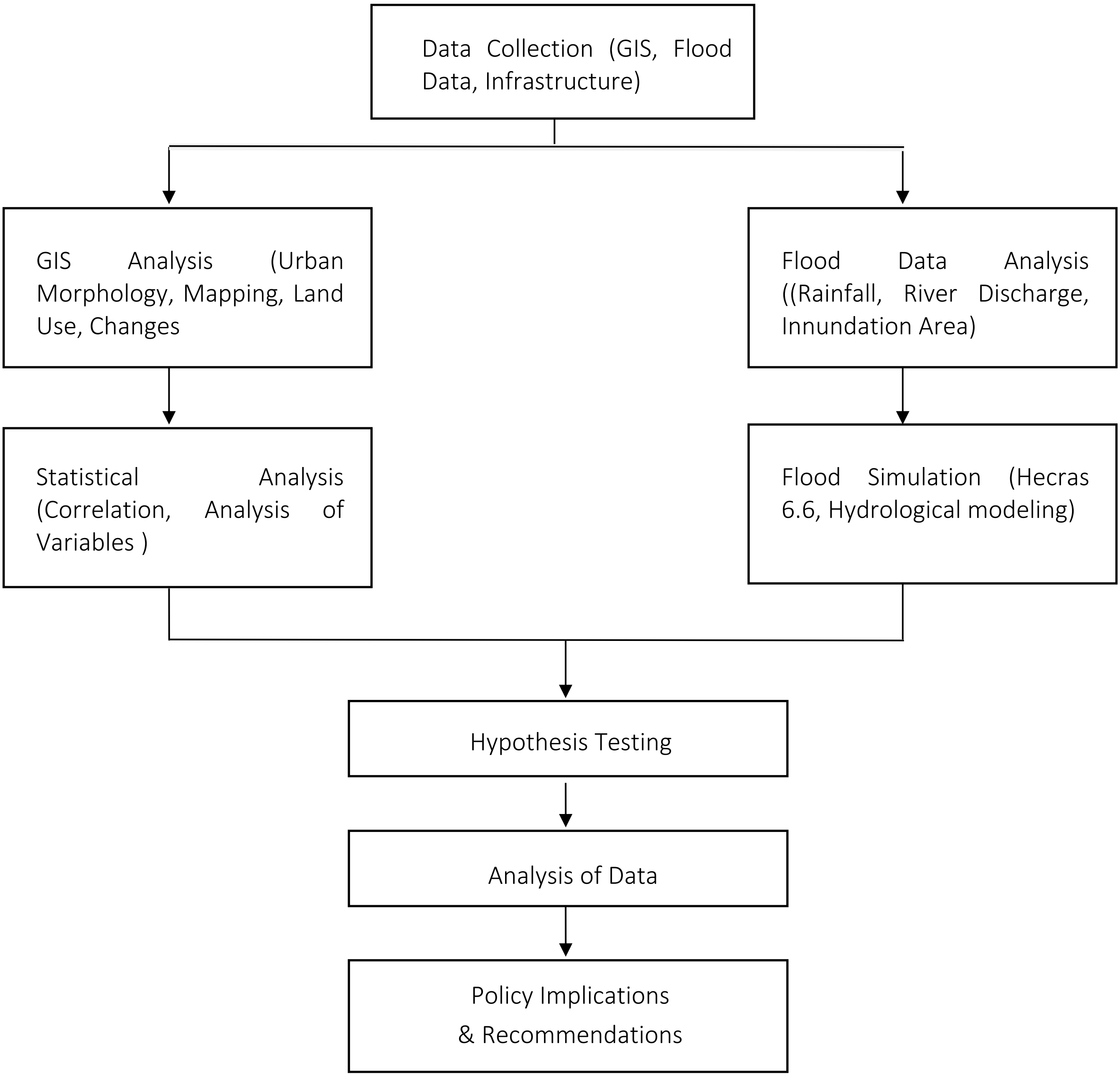
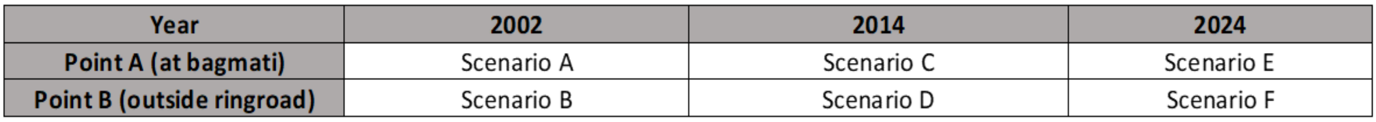


Table 1 Theoretical framework of research



Year	2002	2014	2024
Point A (at bagmati)	Scenario A	Scenario C	Scenario E
Point B (outside ringroad)	Scenario B	Scenario D	Scenario F

11. Study Area : Dhobi Khola, Kathmandu Valley

Why Dhobikhola is Ideal for Studying River Morphology and Flood Resilience

Dhobi Khola presents a highly suitable and unique case study for investigating the evolution of morphology and its impact on flood dynamics for several compelling reasons. The river basin is characterized by two distinct regions with contrasting urbanization patterns: one area lies inside the Kathmandu Valley’s ring road, which has experienced rapid urbanization and infrastructure development, while the other area is outside the ring road, where urbanization is occurring at a slower pace. This provides an excellent opportunity to compare the hydrological responses of different morphological settings within the same river system, allowing for a scenario-based analysis of flood dynamics.

1. **Urbanization Contrast**: The inside-the-ring-road portion of Dhobi Khola has undergone significant urban development, including infrastructure like roads, buildings, and drainage systems, which have significantly altered the natural flow and drainage patterns. The region outside the ring road is less developed, retaining more natural land cover and hydrological characteristics. This stark contrast allows for a clear assessment of how varying rates of urbanization impact flood risks and the evolution of morphological features like land cover, channel structure, and runoff characteristics.
2. **Flood Vulnerability During Monsoons**: Dhobi Khola is highly prone to flooding during the monsoon season, which poses a significant challenge for both urban and rural areas along its path. The river's susceptibility to flooding, exacerbated by rapid urbanization and seasonal rainfall variability, makes it an ideal location to explore the correlation between morphological evolution, land cover, discharge, and flooding. The monsoon rains cause varying impacts across the two regions of the river, offering valuable insights into how different land uses and morphologies interact with hydrological processes during extreme weather events.
3. **Dynamic Hydrological Processes**: The river’s catchment area and the corresponding morphological features evolve differently on either side of the ring road, with factors such as land cover, urbanization, and natural terrain affecting the river's discharge, flow patterns, and inundation. This variability in hydrological behavior within the same river system allows for a more nuanced understanding of how landform complexity (measured through fractal dimension) and human development shape flood risk, runoff behavior, and flood extent.
4. **Accessibility and Data Availability**: Dhobi Khola is located in a region with adequate access for field studies and data collection, including satellite imagery, land cover classification, rainfall data, and discharge records. This accessibility makes it possible to gather both historical and real-time data that are crucial for assessing the long-term evolution of morphology and flood risks.

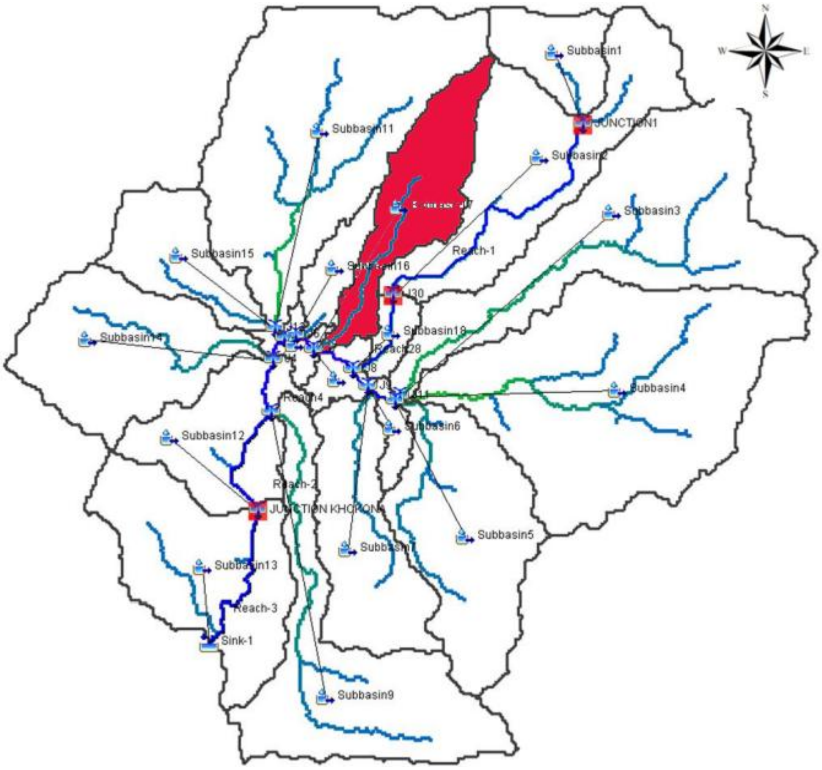


Figure 1 Sub Basins of Bagmati River in Kathmandu Valley. (Source:Preparation of Bagmati Action Plan Supplementary Volume (II) - Hydrological & Flood Modelling Report.)

12. Literature Review

12.1 River Morphology :

12.1.1 Introduction

Rivers transport water, sediment, and solutes from the drainage area to the sea, making them important to hydraulic engineers, geomorphologists, and sedimentologists. Engineers focus on the practical implications, such as erosion, sediment transport, and deposition, which cause problems in rivers and catchments. They study changes in river channels over short periods (10–100 years), including shifts in size, shape, and composition, with the goal of understanding erosion and sediment dynamics. This field, known as fluvial hydraulics or river dynamics, has been developed over the past 200–300 years.

Geomorphologists, on the other hand, are concerned with the long-term changes (thousands to millions of years) in the earth’s surface due to both internal processes (like volcanism and diastrophism) and external forces (such as water, weathering, and glaciers). Geomorphology studies these landform changes and is often used interchangeably with physiography, especially in Europe. Fluvial morphology, or river morphology, a subfield of geomorphology, examines landforms shaped by river action through erosion, sediment transport, and deposition. While both fields are descriptive and observational, hydraulic engineers, hydrologists, and geographers have also contributed to understanding river morphology in recent decades. (Garde, 2006)

Rivers play a crucial role in shaping the Earth's surface through erosion and sediment transport. Annually, around 100 x 10^{12} m^3 of precipitation falls on the Earth, with two-thirds evaporating and the rest flowing to the sea. Water forms small rills, floods, streams, and rivers, continuously altering landforms. Geomorphology, which describes and categorizes Earth's surface configurations, includes a subfield called river morphology that focuses on the formation and development of rivers. This field combines knowledge from hydraulic engineering, geology, climatology, and landscape ecology. Channel hydraulics and sediment transport are essential for understanding river dynamics, and empirical methods are used to solve problems in river morphology. Rivers are three-dimensional systems, and their geometry, which changes over time, must be studied from multiple perspectives. The hardness of rocks influences sediment transport, with harder rocks becoming more significant in the bedload over time. Rivers are classified based on climate and rock type, though most display a mix of morphological patterns. River history reflects changes in climate and landscapes over geological periods, driven by tectonic activity and climatic forces, with rivers acting as either erosive or accumulative forces in response. (Mangelsdorf, Scheurmann, & Weiß, 1990)

12.1.2 Some problems in river morphology

1. **Human Impact on Rivers**: Since ancient times, humans have altered rivers for water, navigation, power, and irrigation, disturbing the river’s stability.
2. **Graded Stream**: A "graded" or "equilibrium" stream, as defined by Mackin (1948), is one where channel dimensions and slope adjust to carry sediment and water without significant erosion or deposition. In the short term, most rivers are in equilibrium, except for unstable rivers like the Koshi, Brahmaputra, and Yellow River.
3. **Disturbances to River Equilibrium**:
    - **Dams**: Reduce sediment transport upstream, causing aggradation in reservoirs and degradation downstream, potentially leading to channel widening.
    - **Navigation**: Modifications for navigation (dams, dredging, channel straightening) disturb river stability.
    - **Irrigation Works**: Barrages and sediment excluders change sediment flow, leading to downstream aggradation.
    - **Mining**: Sand and gravel extraction causes degradation downstream, affecting the river and its tributaries.
    - **Water Transfers**: Large-scale water transfers can disrupt the balance between water and sediment loads.
    - **Flood Control Works**: Embankments and other structures can disturb river equilibrium.
    - **Dredging**: Sediment balance is disrupted, affecting river stability.
    - **Land Use Changes**: Deforestation, urbanization, and construction increase runoff and sediment load, triggering changes in river characteristics.
4. **Urbanization**: Leads to increased runoff, sedimentation, pollution, and encroachment on flood plains, raising flood levels and affecting river stability.
5. **Climate and Hydrologic Changes**: Long-term climate shifts can alter discharge, sediment type, and river morphology, potentially causing rivers to change course or cease to exist.
6. **Tectonic Activity**: Earthquakes and tectonic movements (e.g., subsidence or uplift) can significantly impact river stability. For example, the 1950 Brahmaputra earthquake caused massive landslides, blocked rivers, and changed river courses.

These factors disrupt the natural equilibrium of rivers and require careful consideration in river management and engineering projects. (Garde, 2006)

12.1.3 Investigations in River Morphology

The methods and scope of investigations into river morphology, as well as the strategies developed for stabilizing degraded river sections, necessitate a fundamental understanding of the processes involved in bed formation. This understanding should encompass both geological and river morphological perspectives, along with engineering considerations (Lane, 1955). Collaborating between geologists and engineers has proven to be not only beneficial but essential in this context.

In addition to geomorphological analyses of valley and river system development, three primary hydrological methods have proven effective for studying bed erosion.

Hydrographs of Annual Mean Water Level at Gages

For an initial investigation of erosive river sections, it is sufficient to monitor the changes in bed levels at a few selected locations. Hydrographs of the annual mean water level at official gaging stations are particularly useful for such localized studies, provided long-term, continuous data is available for the river reach in question.

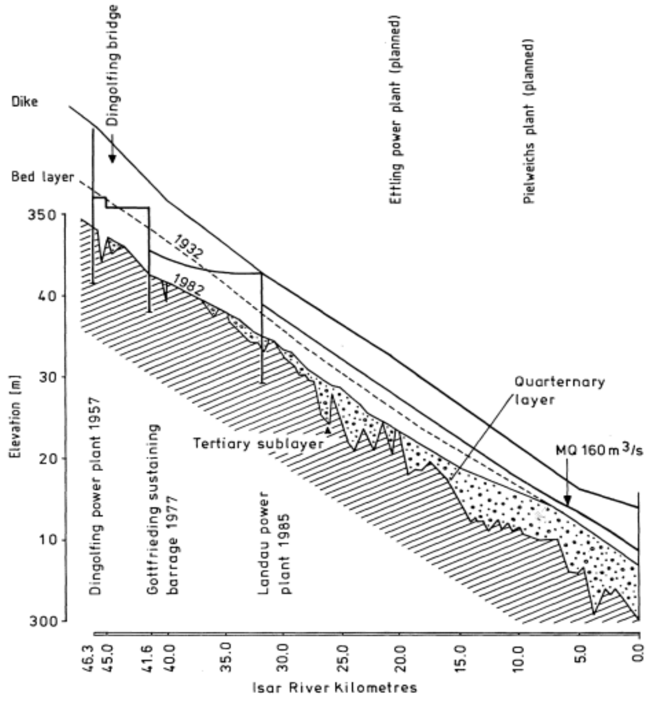


Figure 2 Longitudinal section of the Isar River from Dingolfing to the mouth (Mangelsdorf, Scheurmann, & Weiß, 1990)

Cross-Section Surveys

For a more precise understanding of changes in riverbed levels, particularly in longitudinal sections, cross-section surveys are used. In rivers that are surveyed and calibrated, these are typically conducted at regular intervals, such as every 200 meters. To present changes in elevation along the river's course, either the mean bed level or the thalweg can be used. The mean bed level is a calculated value, not directly observable in nature. It is determined from the area defined by the observed bed profile, two lateral boundaries (often marked by the river's right and left bench), and an assumed horizontal line. However, the mean bed levels are only comparable if the lateral boundaries remain fixed over time.

On the other hand, the **thalweg** represents the line connecting the deepest points of each cross-section along the river. By plotting the thalwegs from multiple cross-section surveys along with borehole data, one can track the excavation process and the penetration into the underlying Quaternary and Tertiary layers.

For identifying a break or discontinuity in gradient, known as a **knick point**—which can indicate a base level in an erosive reach—the mean bed level is more effective due to its smoother, more equalized nature. Finally, cross-section records can be used to generate a **cumulative mass curve**, which plots the changes in the riverbed and can be used to track the position of the knick point in erosional stretches.

Recording of Mean Low Water Level

Periodic recordings of the water level at low discharge are another effective method for investigating erosive stretches of a river. Unlike cross-section surveys, this approach requires the measurement of only a single point, making it less labor-intensive and more cost-effective. However, it is essential to ensure that the low water level is recorded at a consistent discharge level for each measurement to maintain comparability with previous data. This consistency ensures the reliability of the results over time.

Aerial Photogrammetry

Changes in channel morphology resulting from human activities like river regulation, reservoir construction, gravel dredging, or flow diversion can be documented through the comparison of aerial photos. This is done by superimposing two or more aerial images taken at different times, ideally after major floods, and tracing the outlines onto a common map. The differences in the channels over time can then be highlighted using different hatching patterns or colors. This method provides a clear visual representation of how human interventions have altered the river’s morphology.

12.1.4 Manning's n

The value of ‘n’ represents how rough or smooth the surface is in a channel or over a land area, affecting how much the surface impedes water flow. Higher n values correspond to rougher surfaces, which increase resistance and decrease flow velocity. Lower n values indicate smoother surfaces, allowing water to flow more easily.
Here’s a breakdown of how n values relate to land surfaces:

1. **Smooth, hard surfaces** (e.g., concrete, asphalt):
    - These surfaces provide little resistance to water flow, so the nnn value is low, typically ranging between **0.010** to **0.015**.
2. **Vegetated areas** (e.g., grass, shrubs):
    - Areas with short grass or bare soil tend to have moderate nnn values (typically **0.030** to **0.035**), as vegetation or soil provides some resistance but doesn't impede flow as much as rougher surfaces.
3. **Rough surfaces** (e.g., dense vegetation, rocky channels):
    - For areas with dense vegetation, wetlands, or steep rocky riverbeds, the nnn value increases significantly (e.g., **0.50–0.75**). These surfaces introduce significant turbulence, increasing resistance to flow.

12.1.5 Factors Affecting Manning's n:

Several factors can affect the value of n:

- **Vegetation**: Taller, dense vegetation (e.g., forests, tall grass, shrubs) increases roughness, leading to higher n values.
- **Channel shape and condition**: Irregular, rough, or boulder-filled channels have higher n values compared to smooth, straight channels.
- **Surface material**: Smooth surfaces like concrete have lower n values, while rough surfaces like cobblestone or gravel increase n.
- **Flow conditions**: If the channel or land cover is flooded or saturated, n values may increase due to changes in vegetation density or surface roughness.

12.1.6 General Ranges of n Values

- **Smooth (e.g., concrete, asphalt)**: **0.010–0.015**
- **Grasslands (short)**: **0.030–0.035**
- **Vegetated or forested (dense)**: **0.040–0.060**
- **Rough, boulder channels**: **0.040–0.080**
- **Wetlands or dense, tall vegetation**: **0.50–0.75**

Table 2 Manning's Manning’s Value for River bank Environmental Conditions (Chow, 1959)

S. No.	Land Use Type	Manning’s Coefficient
1	Forest	0.15
2	Shrub land	0.05
3	Grassland	0.04
4	Agricultural Area	0.05
5	Barren Land	0.03
6	Water Bodies (River)	0.035
7	Built Up Area	0.15

In summary, Manning's n value helps quantify the influence of surface roughness on water flow, with higher values indicating more resistance and slower flow, and lower values corresponding to smoother, faster flows. It is essential for flood modeling, drainage design, and hydrologic studies. (U.S. Department of Agriculture, 1986)

The **Flow rate equation** often used in hydrology and hydraulics:

$Q = C \times I \times A$

Where:

- Q = Discharge (flow rate), usually in cubic meters per second (m^3/s) or cubic feet per second
- C = Runoff coefficient (dimensionless), which represents the fraction of rainfall that runs off the land surface and contributes to flow in the channel. It varies depending on land cover, soil type, and urbanization.
- I = Rainfall intensity, typically in millimeters per hour (mm/h) or inches per hour (in/h), representing the rate of rainfall during a given storm event.
- A = Area of the watershed or catchment, typically in square kilometers (km^2) or square miles (mi^2), from which the runoff is being generated.

- **Runoff coefficient (C)**: This coefficient varies depending on the land use or cover of the area. For example:
  - **Urban areas** might have higher C values (e.g., 0.7 to 0.9) due to impervious surfaces like roads and buildings.
  - **Forested areas** might have lower C values (e.g., 0.1 to 0.3) since more rainfall infiltrates the ground.
- **Rainfall intensity (I)**: This refers to the rate of rainfall over a specific period, often during a storm event. It is usually determined from local meteorological data or storm event records.
- **Area (A)**: The contributing drainage area or catchment size directly impacts the volume of runoff, as a larger area will generally contribute more runoff.

12.2 Urban morphology

12.2.1 The Elements of Urban Form

This chapter explores the different physical elements that shape cities, focusing on the analysis of urban form. Each element of the city is examined in isolation to better understand its structure and function. This approach, however, is not neutral, as it requires tools and frameworks to organize and interpret these elements. The role of the researcher, and the various instruments used for analysis, will be discussed further in Chapter 6, which addresses how different researchers approach the study of cities.

The Concept of Urban Tissue

Cities are complex entities, composed of various parts or objects. These components are interconnected through a hierarchical structure, where different levels of urban form are recognized and analyzed. Urban morphology often uses this hierarchical perspective to simplify the complexity of cities by breaking them down into fundamental physical elements.

At a broad level, cities are composed of "urban tissues," a term popularized by Karl Kropf in his work ***Urban Tissue and the Character of Towns***. Kropf, influenced by the Italian tradition, defines urban tissue as an organic whole that can be examined at varying levels of detail. At a low level of resolution, urban tissue may only refer to the streets and street blocks, while at a higher level, it could include detailed elements such as construction materials or open space features.

Cities are generally made up of several core elements of urban form, including streets, street blocks, plots, and buildings. However, the specific arrangement of these elements varies across cities, creating distinct types of urban tissue that contribute to a city's unique character. Over time, the development of cities is shaped by layers of construction that accumulate without erasing previous structures, a concept often described as a ***palimpsest***. This ongoing process of urban development means that cities constantly evolve, with each new layer building upon or altering the older one.

Different Urban Tissues Within a Single City

Not only can different urban tissues be found across different cities, but they can also coexist within the same city. Figure 2.2 highlights four distinct urban tissues within the borough of Manhattan in New York City, each with its own unique characteristics.

1. **Downtown (Wall Street Area)**: This area features narrow streets, irregularly shaped street blocks, and large buildings. Wall Street, a historically significant area, has buildings with large footprints and heights, reflecting the economic importance of the area.
2. **Soho**: Soho has a more regular street grid with larger blocks, many of which are occupied by iron buildings built between 1869 and 1895. This area is known for its high mix of uses, contributing to its vibrant urban environment.
3. **Harlem**: Harlem's urban tissue is primarily residential, with the exception of the commercial 125th Street. The street blocks here are larger and contain more buildings, although vacant plots are common, which diminishes the area’s overall urban quality.
4. **Stuyvesant Town**: Unlike the other three areas, Stuyvesant Town is a private residential development where open space predominates over built form. The area has fewer street blocks and buildings, but the existing structures are large and exhibit formal homogeneity.

These examples show how urban tissues vary not just between cities but also within the same city, shaped by different historical, social, and geographical contexts. Each tissue contributes to the overall character of the urban environment, offering distinct spatial experiences and functional arrangements.

12.2.2 The Natural Context

The natural context plays a crucial role in shaping the establishment and organization of urban settlements. The land relief, soil quality, climate, and natural landscapes are all fundamental factors that influence where and how human settlements are formed. From the first paths and streets to the subdivision of land into plots, and even the materials used in construction (especially until the last century), the natural environment plays a key role in defining urban form.

Influence of Land Relief on Urban Form

Land relief is the most immediate natural feature that impacts human settlements. The shape and configuration of the land, including hills, valleys, and rivers, dictate the placement of roads, buildings, and infrastructure. In her theses on urbanism and territory, Rosália Guerreiro (2001, 2011) explores the relationship between land relief and urban settlements, categorizing land relief into two main types: **micro-relief** and **macro-relief**.

1. **Micro-relief**: Refers to small-scale landforms such as individual hills, promontories, and depressions that directly influence how settlements are placed and organized.
2. **Macro-relief**: Involves larger, more structured forms of land, such as ridges and valleys, which are products of geological forces that shape continents. These structural forms divide territories into watersheds and drainage basins.

The Key Structural Lines in the Landscape

Guerreiro identifies three primary systems of territorial lines that guide the formation of settlements:

1. **Ridge Lines**: These are lines that connect the highest points of elevation, dividing the flow of water into opposing slopes. Ridge lines are often natural routes for movement, providing less resistance when traversing the land.
2. **Thalweg Lines**: These are the lines that connect the lowest points in valleys, forming natural drainage routes where water flows downstream. The thalweg lines often mark the routes where settlements are more likely to develop, especially for river-based or water-dependent cities.
3. **Contour Curves**: These lines cut perpendicularly across the ridge and thalweg lines, creating a relationship between elevation points that define the movement of water and the shape of the land.

Together, these lines form the framework of natural movement within the landscape, and historically, settlements have often developed along these lines of least resistance. Areas where ridge and thalweg lines intersect are often key points in the landscape, often developing into **distribution centers** or **encounter centers**. These areas become the focal points of settlements, as they represent easier points for communication and movement across the land.

Historical Examples of Land Relief Influencing Urban Form

The relationship between human settlements and land relief can be seen in various cities around the world. Four notable examples illustrate how landforms shape the built environment:

1. **Machu Picchu (Peru)**: Built in the 15th century by the Inca civilization, Machu Picchu is one of the most remarkable examples of a city that integrates seamlessly with its mountainous natural environment. The city was constructed on a series of terraces, ramps, and stairways, adapting to the rugged relief of the Andes Mountains at nearly 2500 meters above sea level. The settlement was divided into areas for religious, agricultural, industrial, and residential purposes, with a central square around which the city was organized.
2. **Masada (Israel)**: A fortified settlement located in the Judean Desert, Masada was built by King Herod in the first century BCE. Situated on a high plateau above the Dead Sea, its location was chosen for its defensibility and control over the surrounding landscape. The settlement also had an advanced water supply system, adapted to the arid environment.
3. **Lhasa (Tibet)**: The Tibetan city of Lhasa, situated at 3700 meters above sea level, is another example of a settlement that is deeply integrated with its natural context. Built on the Red Mountain, the city's iconic structures like the Potala Palace and Jokhang Temple were constructed to harmonize with the surrounding mountainous terrain.
4. **Saint-Michel (France)**: In Normandy, France, the small settlement of Saint-Michel developed around a Benedictine abbey, with its unique feature being its location on a rocky island. The settlement was built on the Mont Saint-Michel, which becomes isolated from the mainland at high tide, creating an extraordinary dialogue between the settlement and the surrounding water and land relief.

Other Examples: Water and Urban Form

Water, alongside land relief, also plays an essential role in shaping urban form. The cities of **Venice** and **Varanasi** are prime examples:

- **Venice**: Founded in the 5th century, Venice is built on 120 small islands within a lagoon. Its urban form is closely tied to the natural environment, with a network of canals replacing traditional streets. The city's layout evolved in direct response to the lagoon, demonstrating the close relationship between urban form and water.
- **Varanasi**: This ancient city in India is situated on the banks of the Ganges River. The river is integral to the life of the city, with the urban form extending right up to the water's edge.

Figure 3 Relationships between urban forms and natural context—water: Venice and Varanasi (Source Photographs by Sara Guedes (a) and Jorge Correia (b)

Influence on Urban Grid and Development

The natural context can influence the development of cities in varying degrees, depending on the physical features of the land and the concept of city planning. For example, **New York City's** development provides insight into how landforms influence urban form over time:

- **Downtown Manhattan**: The city's older districts, such as the financial center around Wall Street, were influenced by the island's compactness. Over time, as space became limited, buildings grew taller to accommodate the growing population.
- **Midtown and Central Park**: Moving north, the city's regular grid system, introduced in the early 19th century, was largely unaffected by the island's topography. Central Park, on the other hand, was designed to preserve the "natural" look of the land, though it was in fact an artificial landscape, meticulously engineered by human hands. (Oliveira, 2016)

12.3 The Study of Urban Form: Different Approaches

The key morphological approaches developed in recent decades, which are central to understanding urban form. These include:

1. **Historico-Geographical Approach**: This approach, largely shaped by MRG Conzen's seminal work, focuses on the historical development of urban landscapes. It examines how cities evolve over time, emphasizing the relationship between land use, building types, and spatial organization, particularly through the analysis of plot systems.
2. **Process Typological Approach**: Developed by Saverio Muratori, this approach looks at the city as a product of historical and social processes. It classifies urban forms based on their historical development and typology, focusing on how different types of spaces, such as streets and plots, relate to each other and to their functions.
3. **Space Syntax**: This approach, which emerged in the 1970s, uses mathematical models to analyze spatial configurations within cities. It explores how the layout of streets and spaces influences social behavior, movement, and interaction. Key concepts include connectivity, integration, and accessibility of urban spaces.
4. **Spatial Analysis Methods**: These include various forms of modeling such as **fractals**, **cellular automata**, and **agent-based models**. These techniques are used to simulate and analyze spatial interactions, movement patterns, and the impact of different urban configurations on social and environmental outcomes.

These approaches provide different lenses through which urban morphology can be understood, from historical development to modern computational analyses.

Spatial Analysis

This method introduces three key methods of spatial analysis used in urban studies: **Cellular Automata (CA)**, **Agent-Based Models (ABM)**, and **Fractals**. Each method represents a distinct approach to understanding urban phenomena, but they can also be used together to complement one another. Notably, Michael Batty is recognized as a key figure in advancing these approaches, particularly in the study of urban dynamics and the complexity of cities.

<u>Michael Batty's Contribution</u>

Batty has contributed extensively to the understanding of urban form and dynamics, focusing on cities as complex, emergent systems. His work spans several decades, during which he has applied methods such as CA and ABM to model cities, their structures, and spatial dynamics.

As the editor of ***Environment and Planning B: Planning and Design***, Batty has been instrumental in developing the theoretical and practical frameworks for spatial analysis.

Fractals in Urban Analysis

Fractal geometry challenges traditional Euclidean geometry by describing irregular, fragmented, and self-similar patterns found in nature and cities. The concept of fractals, popularized by Benoit Mandelbrot in the 1970s, has been applied to urban studies to explain and model the irregular patterns seen in city layouts, street networks, and land use.

- **Key Characteristics of Fractals**:
    1. **Irregular Form**: Fractals have broken, non-smooth shapes.
    2. **Self-Similarity**: Fractals exhibit similar patterns at different scales.
    3. **Fractal Dimension**: Unlike traditional geometries, fractals have non-integer dimensions (e.g., a street grid may have a fractal dimension between 1 and 2).
- **Applications**:
    - **Cities as Fractals**: Batty and Longley (1994) applied fractal geometry to study the complexity of cities. They suggested that much of urban form can be understood through fractal patterns, where irregularity and scaling are inherent.
    - **Street Networks**: Research by Jon Cooper has applied fractal analysis to study the complexity of street edges and skylines, relating the fractal dimension to the visual variety of urban streetscapes.

12.4 Understanding Urban Morphology

Urban morphology is the study of the form and structure of urban spaces, focusing on the physical layout of cities. Researchers from different disciplines agree that cities can be analyzed through their physical form, which provides insights into historical, socio-economic, and environmental changes over time.

Three fundamental principles define urban morphological analysis:

1. **Fundamental Physical Elements:** Urban form is composed of three key elements:
    - **Buildings and Open Spaces:** Structures, including residential, commercial, and industrial buildings, along with their associated open spaces such as courtyards, plazas, and green areas.
    - **Plots or Lots:** The division of land into parcels for ownership and development purposes.
    - **Streets and Transportation Networks:** The layout of streets, roads, and other transport infrastructure that connect different parts of the urban area.
2. **Levels of Resolution:** Urban form can be understood at different scales, commonly divided into four levels:
    - **Building/Lot Level:** The smallest unit of urban morphology, consisting of an individual building and its immediate surroundings.
    - **Street/Block Level:** A collection of buildings and plots forming a block, interconnected by streets and pathways.
    - **City Level:** The broader urban fabric, including districts and neighborhoods with different functional zones.
    - **Regional Level:** The city's relationship with its surrounding landscapes, including suburban and rural areas.
3. **Historical Perspective:** Urban form must be examined over time, as cities continuously transform due to socio-economic factors, land-use policies, and technological advancements. The built environment undergoes constant changes, whether through repurposing, redevelopment, or expansion, influencing the evolving nature of the urban landscape (Moudon, 1997).

At its most basic level, a city consists of individual land parcels with buildings and open spaces. These urban cells define the shape, density, and functional potential of urban spaces. The attributes of these elements reflect not only historical periods but also socio-economic conditions at the time of development. Over time, urban cells can be repurposed, transformed, or replaced, influencing the growth and structure of urban environments.

12.5 Flooding and Its Causes

Urban flooding risks, often overlooked by conventional methods, can be profoundly affected by city configurations. (Wang et al., 2023) Flooding occurs when water overflows beyond its normal limits, causing damage to human settlements, infrastructure, and ecosystems. The causes of flooding can be broadly categorized into natural and anthropogenic factors:

12.5.1.1 Natural Causes of Flooding

- **Intense Rainfall:** Prolonged or heavy precipitation can exceed the capacity of natural drainage systems, leading to flash floods and urban inundation.
- **Topography and Land Slope:** Low-lying areas and floodplains are naturally prone to water accumulation, making them vulnerable to flooding.
- **Climate Change:** Rising global temperatures have intensified weather patterns, leading to more frequent and severe flooding events.

12.5.1.2 Human-Induced Causes of Flooding

- **Land Use and Land Cover Change (LULCC):** Rapid urbanization replaces permeable surfaces with impervious materials such as concrete and asphalt, increasing surface runoff and reducing water absorption.
- **Deforestation and Vegetation Loss:** Trees and plants play a crucial role in regulating the water cycle by enhancing infiltration and reducing runoff. Their removal accelerates flooding risks.
- **Drainage System Alterations:** Unplanned urban expansion can lead to inadequate drainage infrastructure, causing water stagnation and urban waterlogging.
- **Encroachment on Water Bodies:** The conversion of wetlands, riverbanks, and natural floodplains into built-up areas restricts water flow and increases flood hazards (Sugianto et al., 2022).

12.6 Impact of Urban Morphology on Flooding

Urban morphology significantly influences flood vulnerability, as the arrangement and density of buildings, roads, and open spaces determine water flow patterns and drainage efficiency. while surface permeability is confirmed the key element influencing flood susceptibility, urban morphology still plays a secondary but non-negligible role in determining inundation patterns and related floodwater depths. (Zhu et al., 2024). Also the distribution of different land cover types proportion of landscape", "number of patches", "perimeter-area ratio" influence the infiltration capacity and runoff during flooding events.

12.6.1.1 Building Configurations and Flood Risks

Urban planning must consider building configurations to mitigate flooding risks. Research suggests that:

- The **Mean Building Volume (MBV)** within a catchment area should be maintained within a specified range to balance urban density and the area's water drainage capacity.

- The **Standard Deviation of Building Volume (SDBV)** should remain below a certain threshold to prevent excessive clustering of high-rise buildings, which can exacerbate localized flooding.
- The geometric characteristics of buildings influence runoff and urban flood levels, making it necessary to consider both horizontal and vertical urban parameters in flood risk management (Bruwier et al., 2020; Wang et al., 2023).

12.6.1.2 Surface Morphology and Drainage

Several urban surface morphology indices influence flooding, including:

- **Road Density (RD):** Roads act as artificial channels for floodwater, influencing drainage efficiency. High road density can either facilitate or obstruct water flow depending on design and connectivity (Rahman et al., 2021).
- **Impervious Rate (IR):** An increased percentage of impermeable surfaces leads to reduced infiltration, accelerating surface runoff.
- **Slope and Elevation (SL & DEM):** The natural gradient of the land affects water accumulation and drainage speed.
- **Subcatchment Area (CA) & Drainage Facilities:** Well-planned drainage systems can mitigate urban flooding by redirecting excess water efficiently.
- **Vegetation and Greening Rate:** Maintaining green spaces and tree coverage enhances absorption capacity and reduces flood severity (Berndtsson et al.).

12.7 Urban Morphology and Flood Volume Reduction

Modifying urban morphology can help reduce local flood volume by up to 7.8% (Zhu et al., 2024). Key insights include:

- **Building Footprint Edge Density:** A higher density increases floodwater volume and depth, worsening flood impacts.
- **Impervious Surface Edge Density:** A higher density decreases floodwater accumulation, indicating that strategic placement of impervious surfaces can aid flood management.
- **Surface Permeability:** Although permeability remains the primary factor influencing flood susceptibility, urban morphology plays a secondary but significant role in flood distribution and depth.

12.8 The Role of Land Use Change in Flooding

LULCC significantly alters the natural drainage system, affecting:

- **Surface Runoff:** Increased impervious surfaces due to urbanization lead to greater runoff, overwhelming drainage networks.
- **Infiltration Capacity:** Reduced permeability limits groundwater recharge, exacerbating flood risks.
- **Evapotranspiration:** Vegetation loss affects humidity levels and precipitation patterns, influencing local hydrology.

Research has shown that land use strongly influences flood risks, especially in urban lowlands and floodplains. The rapid expansion of impervious surfaces contributes to more frequent and severe flooding events, requiring integrated urban planning solutions (Alshammari et al., 2023).

12.9 Urbanization and Flood Vulnerability

Unplanned urban development and the expansion of impervious surfaces significantly impact flooding. Key findings include:

- **Increased Runoff:** High-density developments concentrate water runoff, leading to waterlogging and intensified urban flooding (Shepherd, 2005).
- **Building Density:** Higher building density exacerbates surface sealing, reducing natural water absorption and increasing flood risks (Walsh et al., 2012).
- **Urban Rain Island Effect:** Urbanization alters local climates, intensifying flood events and modifying hydrological conditions (Lee & Brody, 2018).

Urban morphology plays a crucial role in shaping flood risks. Key strategies for mitigating urban flooding include optimizing building configurations, improving drainage infrastructure, maintaining green spaces, and regulating impervious surface expansion. Future urban planning must incorporate both 2D and 3D morphological factors to develop resilient urban landscapes that minimize flood vulnerability (Lin et al., 2021; Lin et al., 2023).

Major variables identified	Significance to flooding	Used in this research
Impervious surface	Blocks infiltration, increases runoff → higher flood risk.	Time series/ trend analysis
Drainge performance(road density + concentration time)	Roads speed up runoff; shorter concentration time = faster, peakier floods.	Comparative analysis. No simulation
Building density	High density reduces open space → more runoff and overloaded drainage.	Comparative analysis
Rainfall (Climate change)	More intense and frequent storms → higher flood volumes.	For peak discharge calculation
Sedimentation	Reduces channel capacity → rivers overflow more easily.	No
Channel geometry	Narrow/shallow or modified channels can't hold excess water → increased flooding.	Fractal analysis
Ecological balance / water cycle	Disruption (e.g., loss of wetlands) weakens natural flood absorption → worsens flood impacts. Extreme rainfall events in short intervals due to	No

Major variables identified	Significance to flooding	Used in this research
	disbalance in the ecosystem.	
Mean building volume	MBV influences how land is used — compact vs sprawled — which directly affects surface runoff and flood potential.	Correlational analysis

13. Data collection

Data collection for this research will involve the gathering of both primary and secondary data to assess the impact of urban morphological changes on flooding in the Kathmandu Valley. The primary data sources will include spatial data such as satellite imagery, remote sensing data, and GIS-based datasets, which will help analyze the changes in land use, infrastructure development, and river morphology over time. Historical flood data will also be collected, including rainfall records, river discharge data, and flood event records, to understand past flood occurrences and patterns. Secondary data sources will consist of urban planning documents, government reports, and previous research studies on flood risk and urban development in the valley. This comprehensive data collection will provide the necessary foundation for analyzing the relationship between urban morphological changes and flood risk, enabling the development of effective flood management strategies.

13.1 Landcover Data

In the data collection phase, **Kathmandu Valley land cover data** was essential for understanding the spatial distribution of urbanization, natural vegetation, water bodies, and other land uses across the region. The land cover data was derived primarily from high-resolution satellite imagery (such as Landsat or Sentinel), which was processed and classified into various categories like urban areas, agricultural land, forests, water bodies, and barren land.

Furthermore, this land cover data was used to **delineate sub-basins**, such as the **Dhobi Khola sub-basin**, by extracting its boundaries from the overall land cover map of Kathmandu Valley. This allowed for a more focused analysis of how land use changes in this specific sub-basin influenced flooding dynamics and river morphology.

The land cover data also provided a basis for examining the **impervious surface area**, which plays a crucial role in influencing surface runoff and flooding risks. By analyzing the proportion of impervious surfaces such as roads, buildings, and pavements, the study was able to assess how urbanization within the valley has altered the natural hydrological processes and increased vulnerability to flooding.

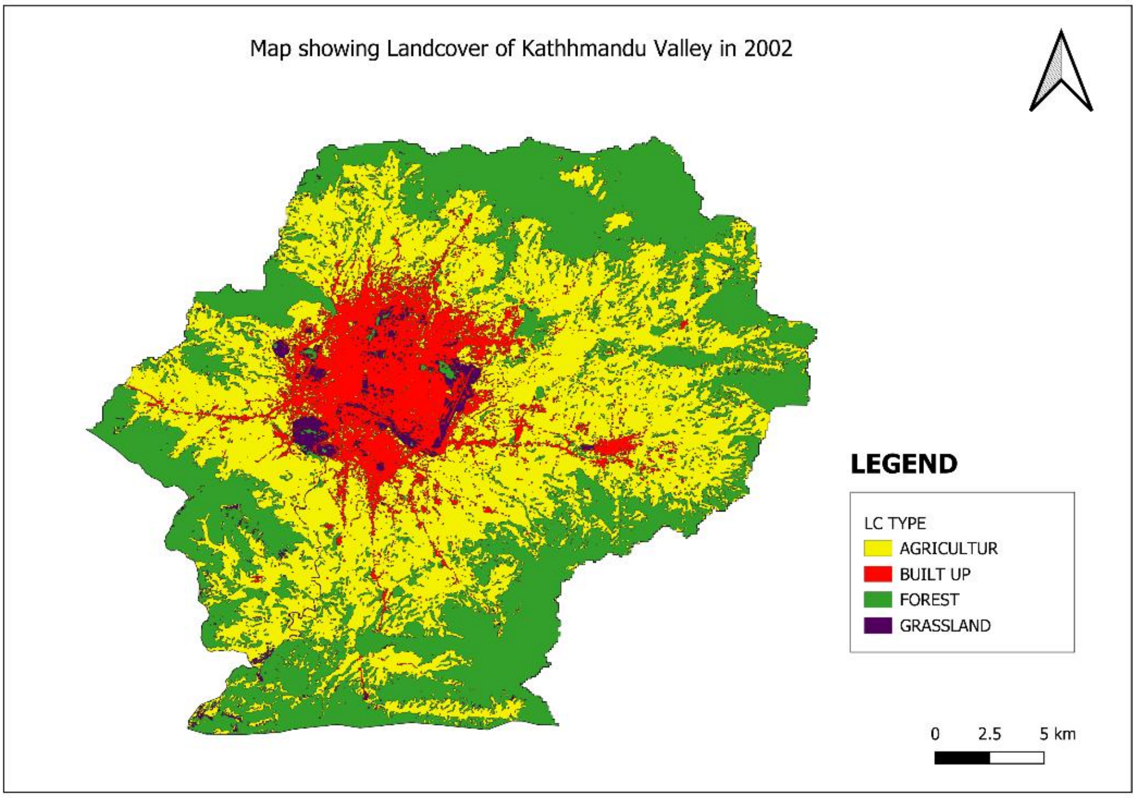


Figure 4 Landcover map of ktm valley in 2002 (Source: ICIMOD)

Table 3 Table showing percentage of different types of landcover in ktm valley in different years (Source: ICIMOD)

2002	**LC TYPE**	**AREA SQ.KM**	**%**
1	BUILT UP	75	11
2	AGRICULTURE	316	47
3	FOREST	262	39
4	GRASSLAND	13	2
2014	**LC TYPE**	**AREA SQ.KM**	**%**
1	BUILT UP	107	16
2	AGRICULTURE	286	43
3	FOREST	264	40
4	GRASSLAND	9	1
2022	**LC TYPE**	**AREA SQ.KM**	**%**
1	BUILT UP	162.93	24
2	AGRICULTURE	239.39	36
3	FOREST	248.12	37
4	GRASSLAND	15.44	2

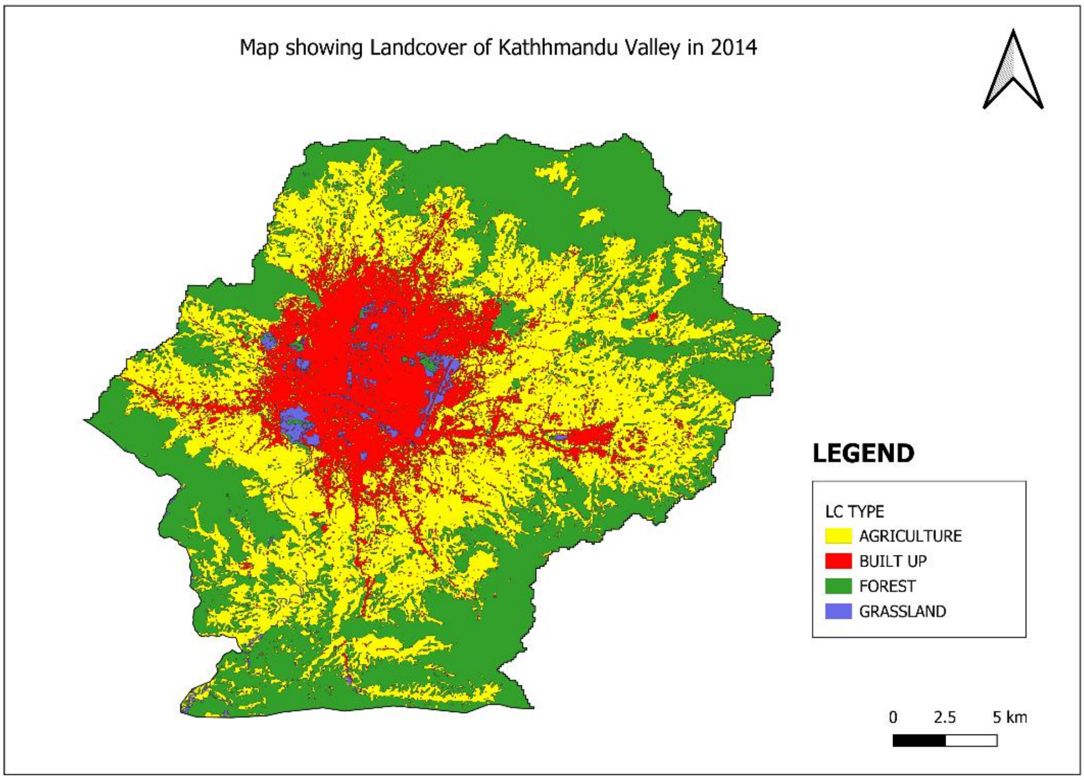


Figure 6 Landcover map of ktm valley in 2014 (Source: ICIMOD)

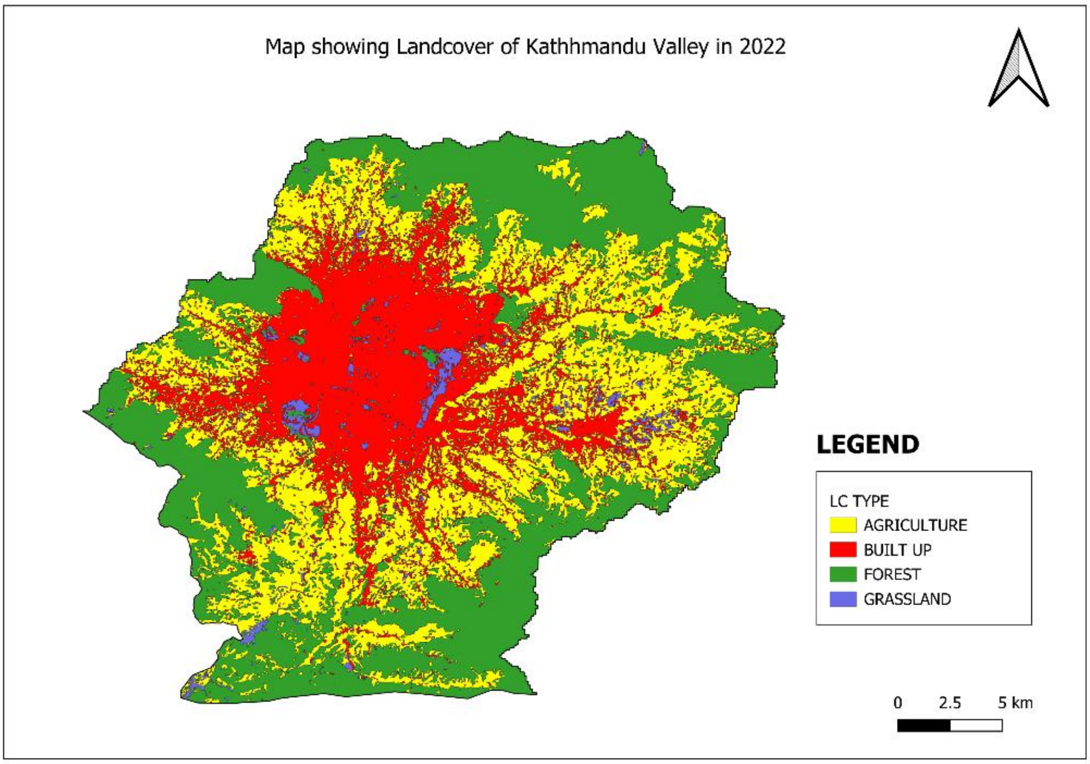


Figure 5 Landcover map of ktm valley in 2022 (Source: ICIMOD)

Dhobi Khola Sub-basin

The Dhobi Khola sub-basin's catchment was delineated and extracted from the overall Kathmandu Valley land cover using Geographic Information System (GIS) techniques and remote sensing data. The first step involved obtaining high-resolution satellite imagery for the Kathmandu Valley, which was classified into various land cover types such as urban areas, vegetation, water bodies, and agricultural land. Using hydrological analysis tools within GIS, the boundaries of the Dhobi Khola sub-basin were defined by analyzing the flow direction and flow accumulation to identify the contributing catchment area.

To delineate the catchment accurately, the Digital Elevation Model (DEM) of the Kathmandu Valley was used to generate watershed boundaries, taking into account the topography and natural drainage patterns. This DEM-based analysis provided the precise spatial extent of the sub-basin. Once the catchment boundary was defined, land cover data specific to the Dhobi Khola sub-basin was extracted, allowing for detailed analysis of land use and morphological changes in the area over time. This method ensured that the study focused on the direct influences of land cover and urbanization within the Dhobi Khola sub-basin, providing insights into how these changes have impacted flood dynamics.

In addition to the land cover data, several other characteristic maps of the Dhobi Khola sub-basin were generated to better understand the hydrological and urban dynamics of the area. These maps included:

1. **Digital Elevation Model (DEM)**: The DEM was used to visualize the topography of the sub-basin, providing critical insights into the elevation, slope, and flow direction within the catchment area. This map helped delineate the watershed boundaries and identified areas prone to water accumulation, which are critical for flood risk analysis.
2. **Slope Map**: Using the DEM, a slope map was created to illustrate the gradient of the terrain. The slope map provided valuable information on water flow patterns, helping to identify areas with high runoff potential that might be more susceptible to flooding, especially during heavy rainfall events.
3. **Drainage Network Map**: The drainage network map was derived from the DEM and field surveys. It highlighted the natural rivers, streams, and constructed drainage systems within the sub-basin. This map helped in understanding the flow paths and the interaction between urban infrastructure and natural drainage.
4. **Road Density and Infrastructure Map**: This map illustrated the distribution and density of roads and other infrastructural elements in the sub-basin. It was used to analyze how infrastructure development affects water runoff, drainage, and flood dynamics, with a particular focus on impervious surfaces that contribute to increased surface runoff.

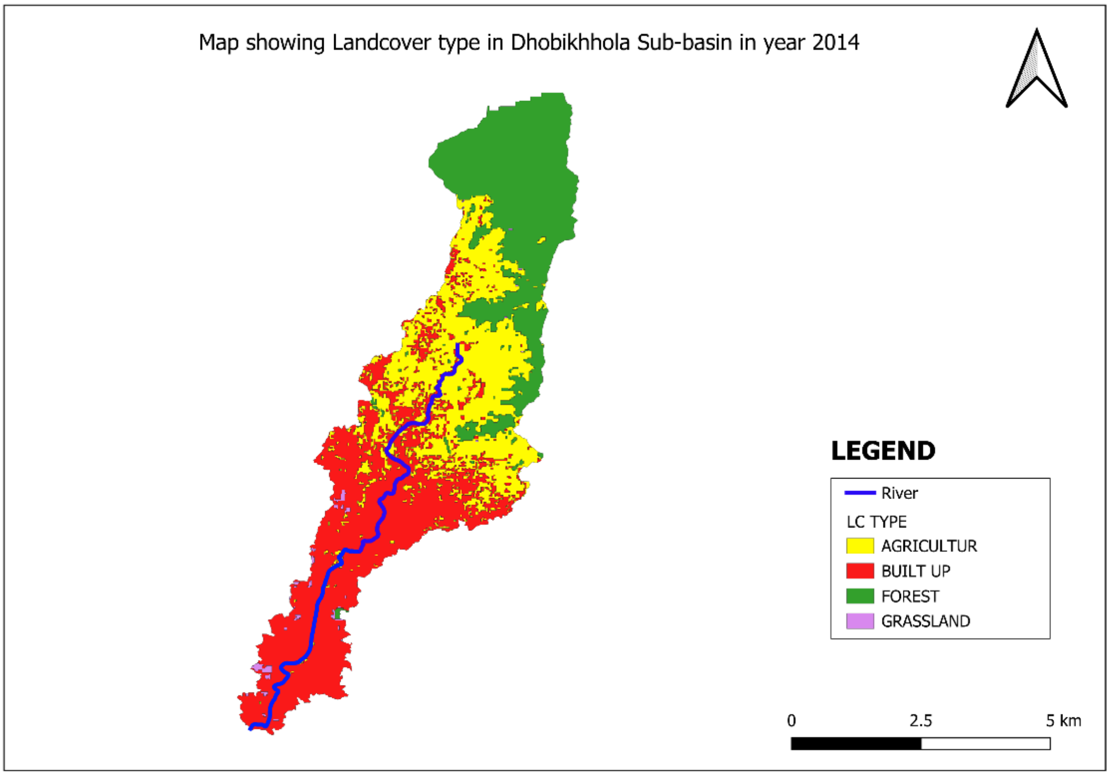


Figure 7 Landcover map of Dhobi khola Subbasin 2002

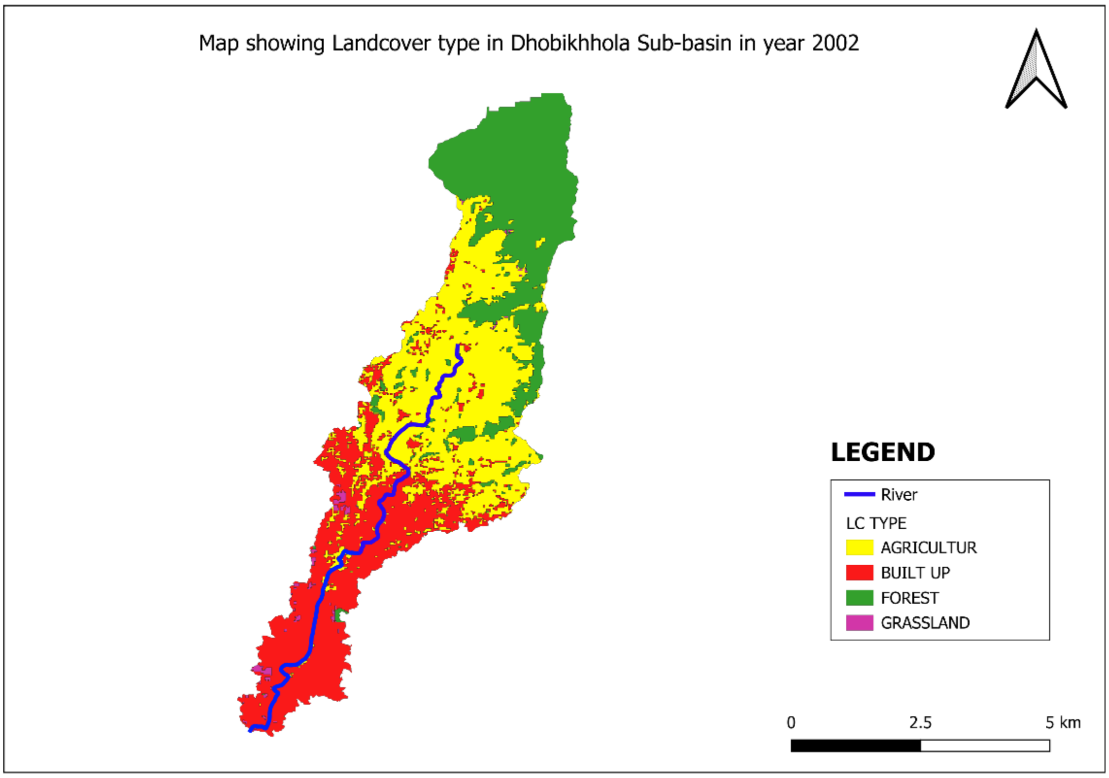


Figure 8 Landcover map of Dhobi khola Subbasin 2014

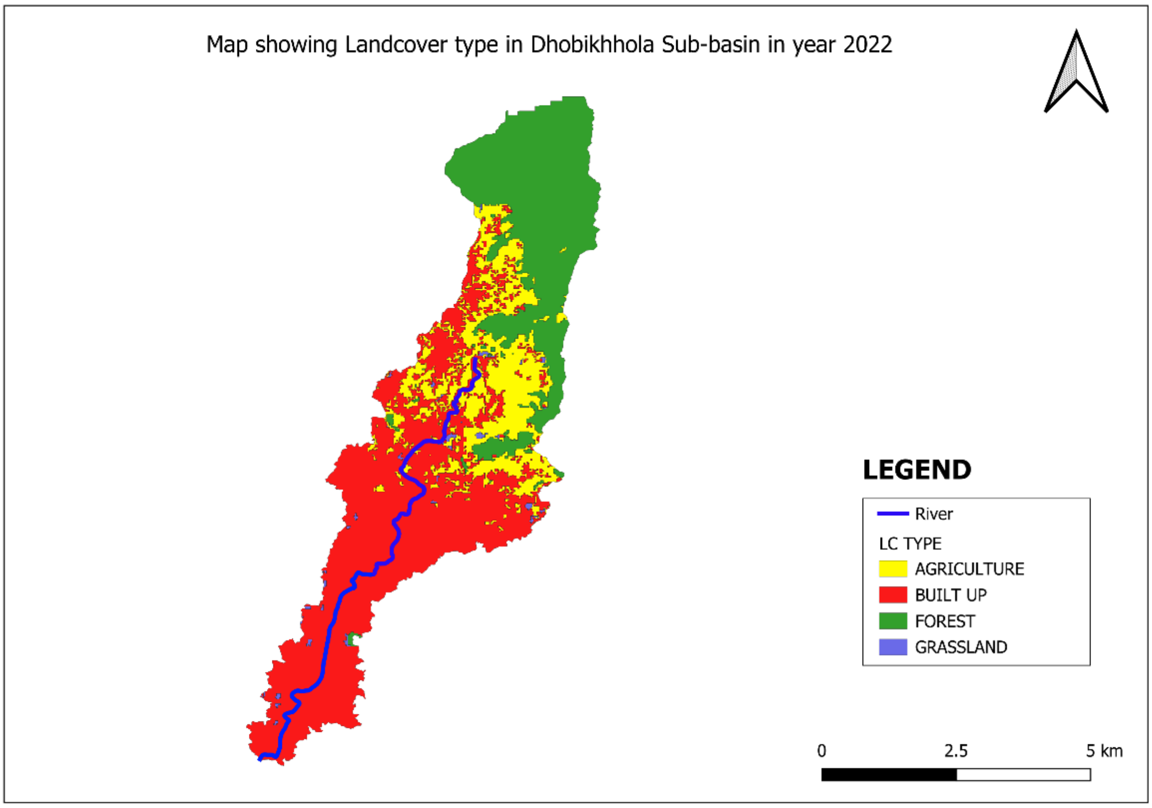


Figure 9 Landcover map of Dhobi khola Subbasin 2022

Table 4 Landcover percentage of Dhobi khola subbasin inside and outside ringroad

2002(DHOBI)			
	LC TYPE	**AREA SQ.KM**	%
1	BUILT UP	10.21	32
2	AGRICULTURE	12.37	38
3	FOREST	9.39	29
4	GRASSLAND	0.29	1
2002(OUT)			
	LC TYPE	**AREA SQ.KM**	**%**
1	BUILT UP	3.81	15
2	AGRICULTURE	9.34	37
3	FOREST	11.75	47
4	GRASSLAND	0.29	1
2014(DHOBI)			
	LC TYPE	**2014**	**%**
1	BUILT UP	12.99	40
2	AGRICULTURE	9.75	30

3	FOREST	9.32	29
4	GRASSLAND	0.19	1
2014(OUT)			
	LC TYPE	**AREA SQ.KM**	**%**
1	BUILT UP	6.15	25
2	AGRICULTURE	9.29	37
3	FOREST	9.48	38
4	GRASSLAND	0.17	1
2022(DHOBI)			
	LC TYPE	**AREA SQ.KM**	**%**
1	BUILT UP	16.52	51
2	AGRICULTURE	6.05	19
3	FOREST	9.45	29
4	GRASSLAND	0.23	1
2022(OUT)			
	LC TYPE	**AREA SQ.KM**	**%**
1	BUILT UP	9.37	38
2	AGRICULTURE	6.05	24
3	FOREST	9.41	38
4	GRASSLAND	0.03	0

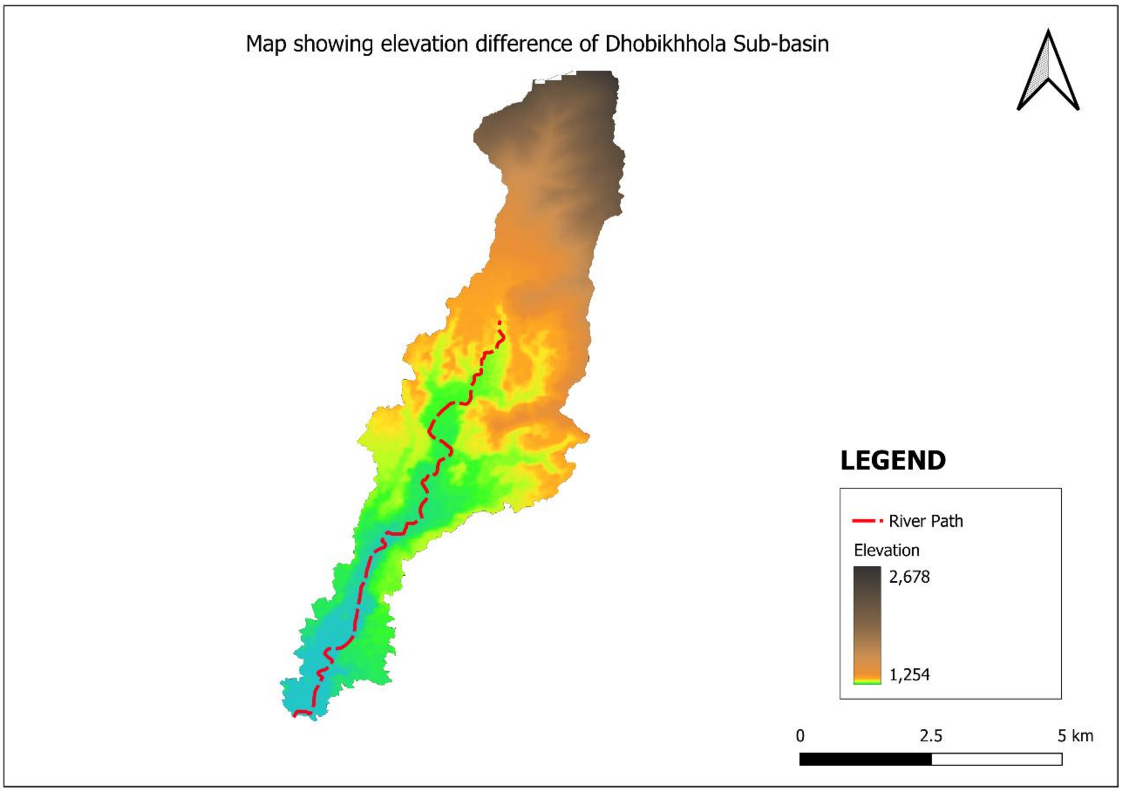


Figure 10 Elevation map of Dhobi khola sub basin

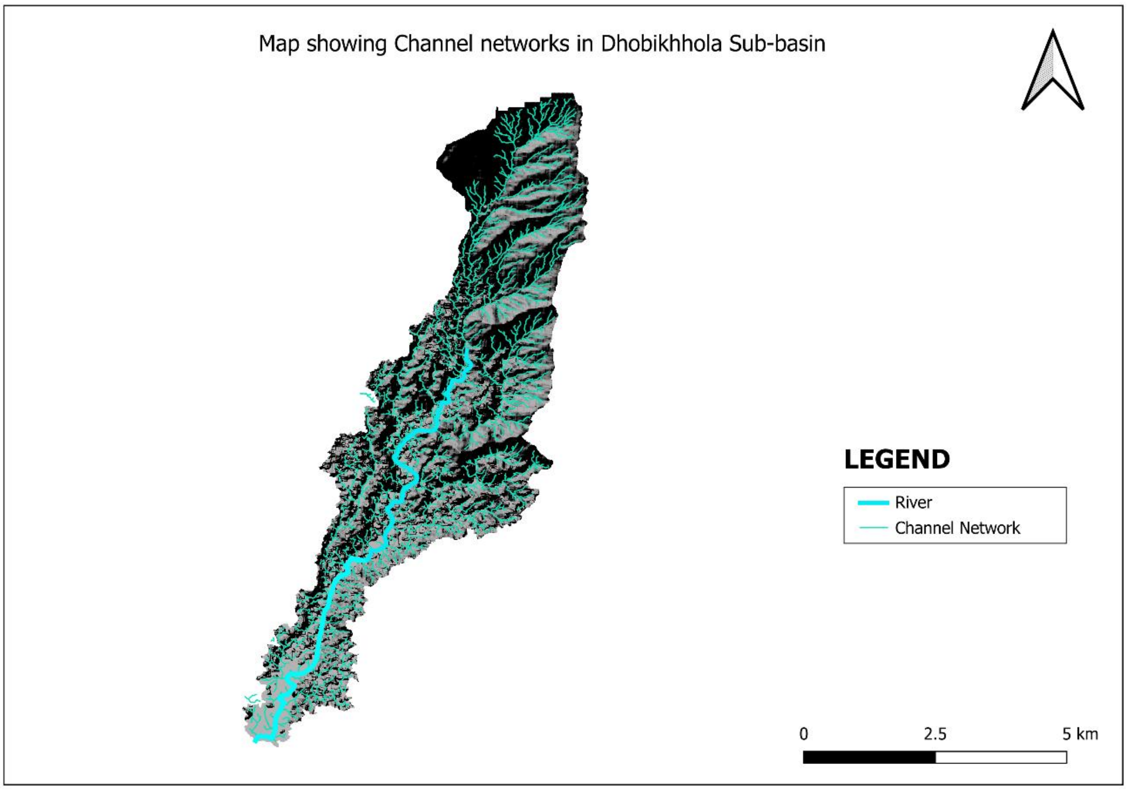
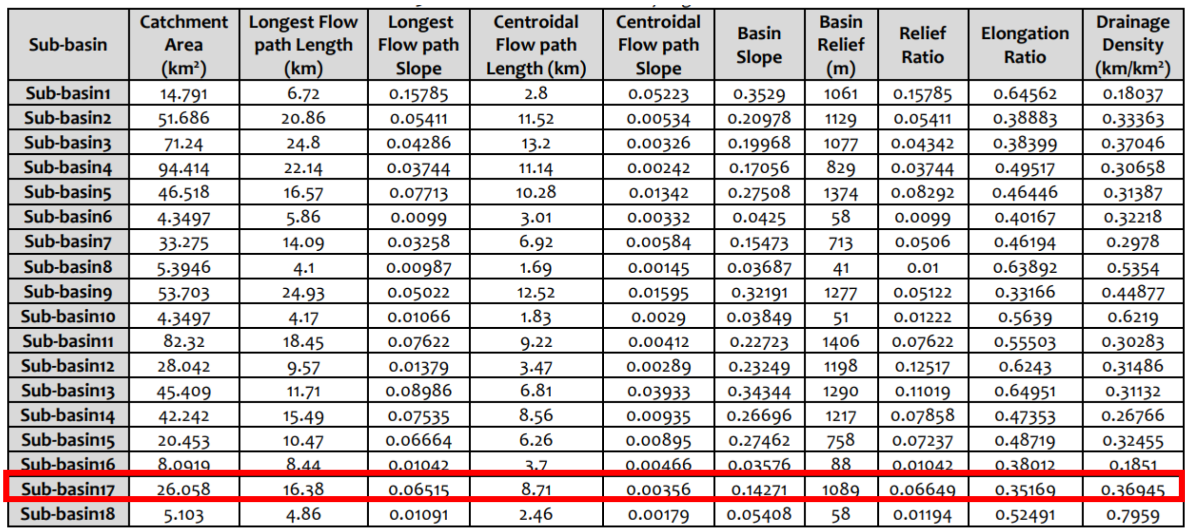


Figure 11 Channel network of Dhobi khola Sub basin

Table 5 Sub basin characteristics of bagmati basin (Source : Hydrological & Flood Modelling Report Supplementary Volume II)



Sub-basin	Catchment Area (km^2)	Longest Flow path Length (km)	Longest Flow path Slope	Centroidal Flow path Length (km)	Centroidal Flow path Slope	Basin Slope	Basin Relief (m)	Relief Ratio	Elongation Ratio	Drainage Density (km/km^2)
Sub-basin1	14.791	6.72	0.15785	2.8	0.05223	0.3529	1061	0.15785	0.64562	0.18037
Sub-basin2	51.686	20.86	0.05411	11.52	0.00534	0.20978	1129	0.05411	0.38883	0.33363
Sub-basin3	71.24	24.8	0.04286	13.2	0.00326	0.19968	1077	0.04342	0.38399	0.37046
Sub-basin4	94.414	22.14	0.03744	11.14	0.00242	0.17056	829	0.03744	0.49517	0.30658
Sub-basin5	46.518	16.57	0.07713	10.28	0.01342	0.27508	1374	0.08292	0.46446	0.31387
Sub-basin6	4.3497	5.86	0.0099	3.01	0.00332	0.0425	58	0.0099	0.40167	0.32218
Sub-basin7	33.275	14.09	0.03258	6.92	0.00584	0.15473	713	0.0506	0.46194	0.2978
Sub-basin8	5.3946	4.1	0.00987	1.69	0.00145	0.03687	41	0.01	0.63892	0.5354
Sub-basing9	53.703	24.93	0.05022	12.52	0.01595	0.32191	1277	0.05122	0.33166	0.44877
Sub-basin10	4.3497	4.17	0.01066	1.83	0.0029	0.03849	51	0.01222	0.5639	0.6219
Sub-basin11	82.32	18.45	0.07622	9.22	0.00412	0.22723	1406	0.07622	0.55503	0.30283
Sub-basin12	28.042	9.57	0.01379	3.47	0.00289	0.23249	1198	0.12517	0.6243	0.31486
Sub-basin13	45.409	11.71	0.08986	6.81	0.03933	0.34344	1290	0.11019	0.64951	0.31132
Sub-basin14	42.242	15.49	0.07535	8.56	0.00935	0.26696	1217	0.07858	0.47353	0.26766
Sub-basin15	20.453	10.47	0.06664	6.26	0.00895	0.27462	758	0.07237	0.48719	0.32455
Sub-basin16	8.0919	8.44	0.01042	3.7	0.00466	0.03576	88	0.01042	0.38012	0.1851
Sub-basin17	26.058	16.38	0.06515	8.71	0.00356	0.14271	1089	0.06649	0.35169	0.36945
Sub-basin18	5.103	4.86	0.01091	2.46	0.00179	0.05408	58	0.01194	0.52491	0.7959

13.2 Rainfall Data:

Rainfall data for the study was obtained from the **Department of Hydrology and Meteorology (DHM)**, which is the authoritative body in Nepal responsible for monitoring and analyzing weather and hydrological parameters. The DHM provides comprehensive historical rainfall data for various locations within the Kathmandu Valley, including key weather stations that record daily and seasonal rainfall measurements.

This rainfall data is crucial for understanding the temporal patterns of precipitation and its impact on flooding dynamics in the region. The dataset includes records of total precipitation, frequency, intensity, and duration of rainfall events, which are essential for assessing the relationship between heavy rainfall events and flood occurrences within the Dhobi Khola sub-basin.The data collected from DHM was used to analyze the correlation between rainfall intensity and flood risks, particularly during monsoon months when precipitation is highest.

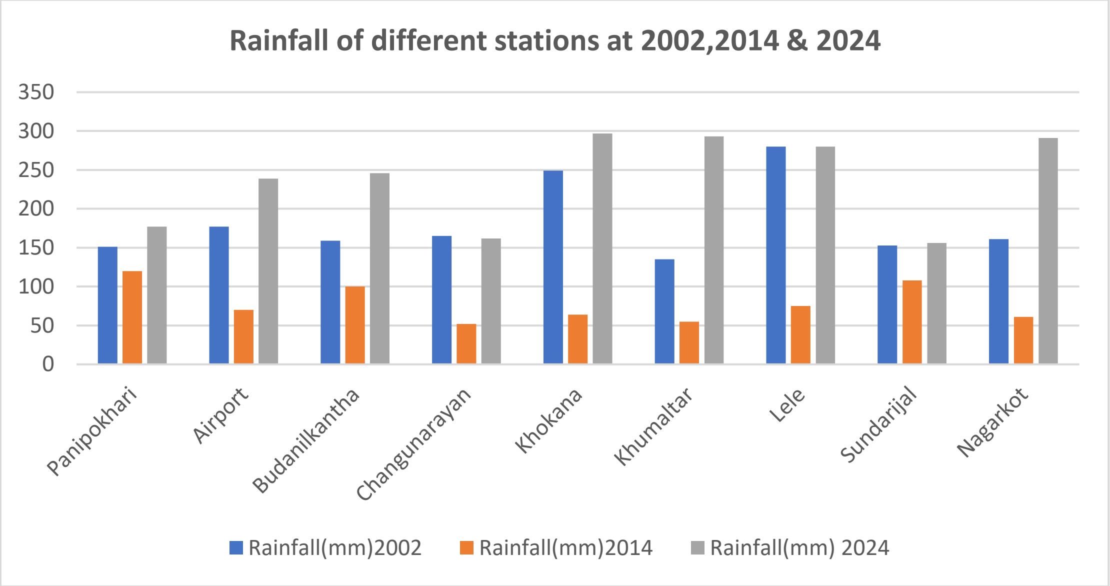


Table 6 Return period calculation for stations near Dhobi khola catchment area

Return Period	5 yr	10 yr	50 yr	100 yr	200 yr	500 yr
Station	**Rainfall(mm)**					
Panipokhari (1039)	120	145	200	223	246	277
Airport AWS(103001)	138	158	220	246	272	300
Budanilkantha(1071)	127	155	216	242	268	302

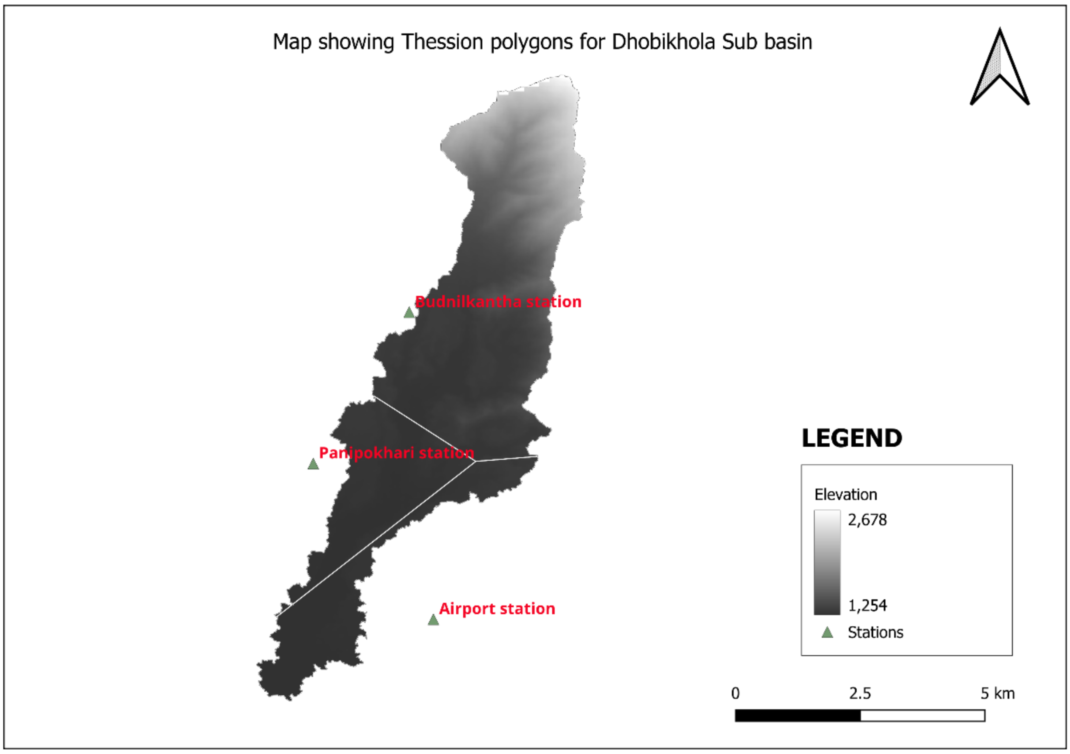


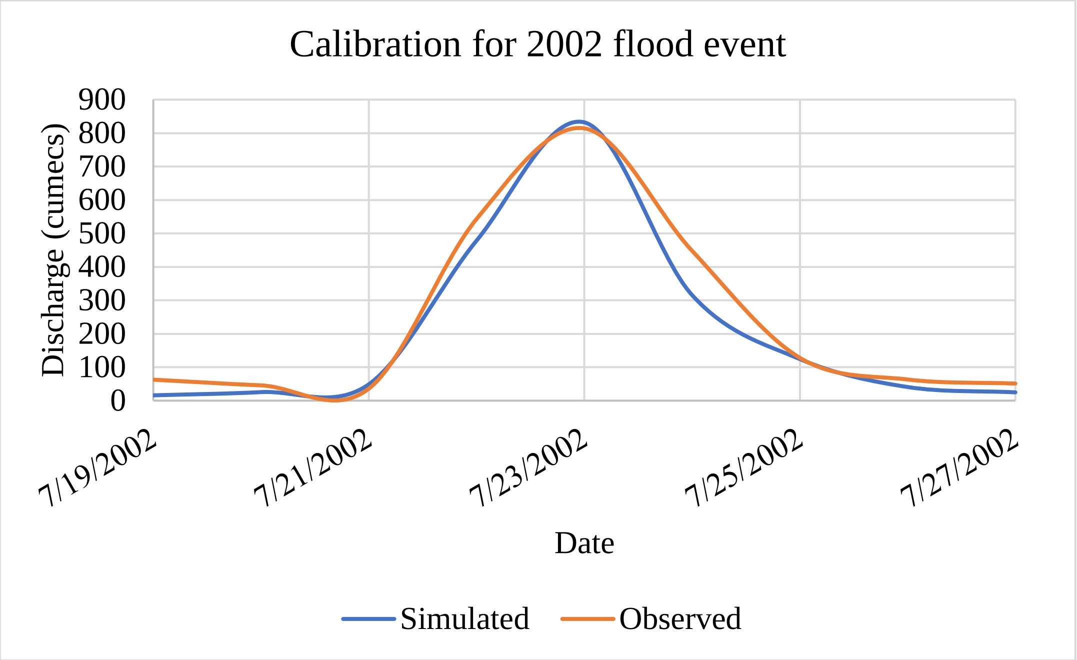
Figure 12 Thiessen polygon for Dhobikhola Sub basin

14. Hydrological Modeling :

This research aims to examine the impact of **urban cover** on **discharge** (Q) over time at two locations, **A (Dhobikhola at thapathali)** and **B (Dhobikhola at chabahil)**, using the **Hydrologic Engineering Center's River Analysis System (HEC-RAS) 2D**. With the increasing urbanization over recent decades, it is crucial to assess how land use changes influence water flow patterns and flood risks in river systems.

The study utilizes high-resolution **ALOS PULSAR 12.5 DEM** data for accurate terrain representation and **ICIMOD land cover data** to model changes in urbanization. The data spans multiple years—2002, 2014, and 2024—allowing for an in-depth analysis of how urban cover has evolved at both locations. Over this period, urban cover has steadily increased, with **Location A** showing an increase from 10.21% in 2002 to 16.52% in 2024, and **Location B** showing a rise from 3.81% in 2002 to 9.37% in 2024. These changes are expected to have significant effects on discharge patterns, water surface elevations, and flood extents.

This research aims to integrate these data sources with HEC-RAS 2D modeling to simulate the impact of land cover changes on river flow and assess potential flood risks for future urban development scenarios.



Calibration Steps:

1. Firstly the model setup was done.

   (Geometric, terrain, boundary condition , and mesh creation)
2. Precipitation data input
   1. Used thessian for distribution over an area
   2. Used station are Sundarijal , Budhanikantha , Panipokhari, Sankhu , Kathmandu airport, Nagarkot, Lele , Khokona, Chhangunarayan,)
3. Initial model simulation
   1. Find out the stage (at khokana gauge point)
4. Comparing the stage data and discharge with the measured data.
   1. Stage of khokana (measure data)
   2. Known measured Discharge with the help of rating curve
5. Then adjusting key parameters
   1. Mannings coefficient
   2. Infiltration parametes (%impervious)
   3. Boundary condition (d/s condition)
   4. Necessary terrain change and modification
6. Performance evaluation
   1. Nash number
7. Validation
   1. Remaining future events used for validation

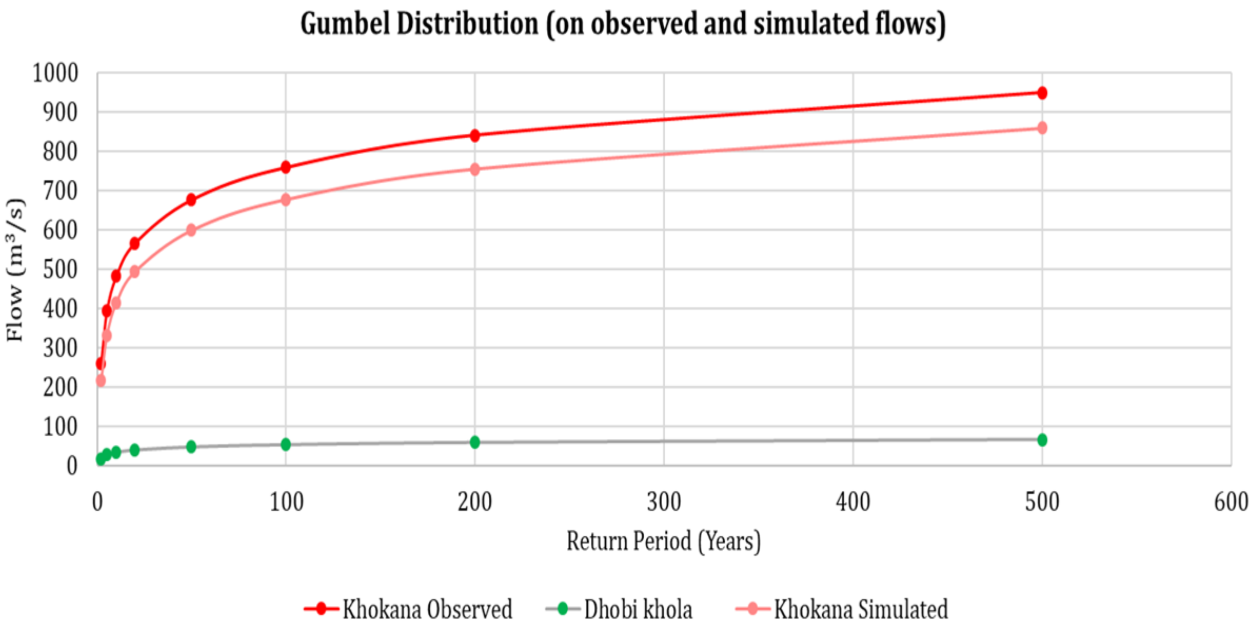


Table 7 Gumbel Distribution (on observed and simulated flows)

Percent (%) exceedance	**Return Period (Years)**	**Khokana Observed**	**Transpose to Dhobi at bagmati**	**Transpose to dhobi outside ring road**
50	***2***	259.7	18.179	7.791
20	***5***	393.2	27.524	11.796
10	***10***	481.6	33.712	14.448
5	***20***	566.4	39.648	16.992
2	***50***	676.1	47.327	20.283
1	***100***	758.3	53.081	22.749
0.5	***200***	840.2	58.814	25.206
0.2	***500***	948.3	66.381	28.449

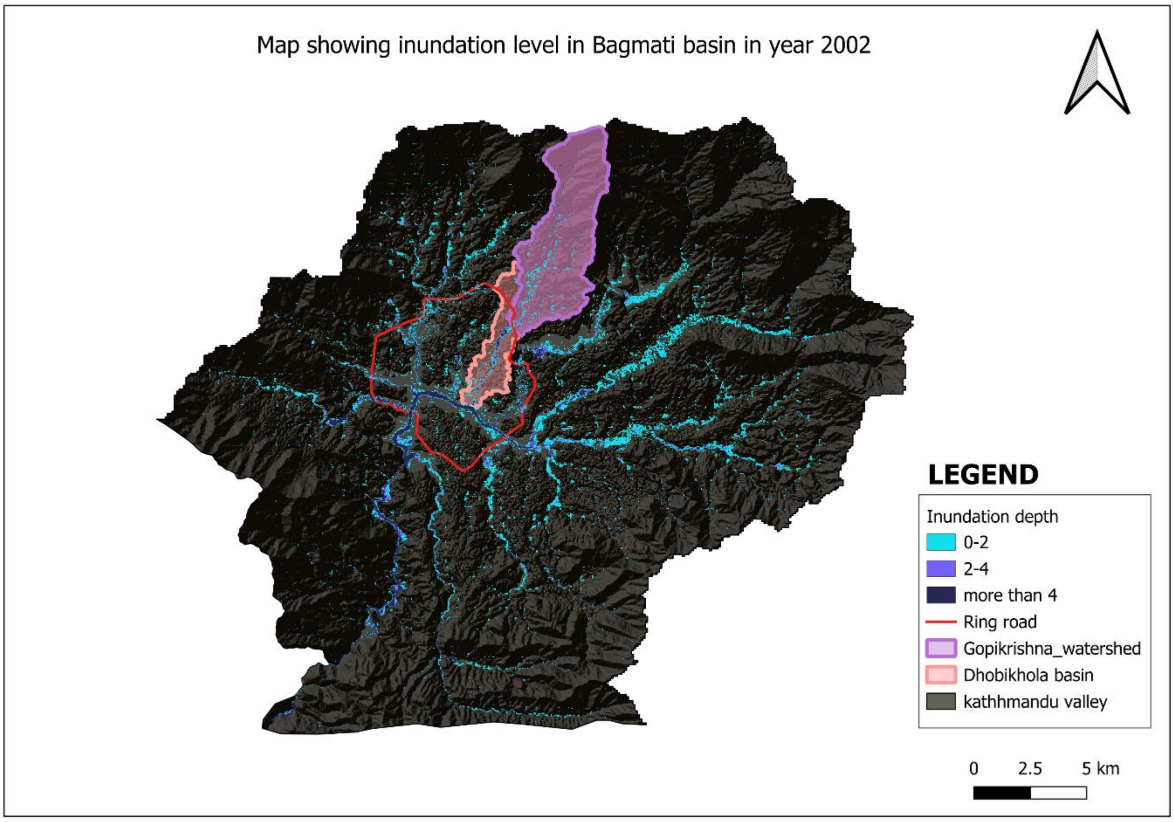


Figure 13 Inundation mapping for 2002 for Bagmati river basin

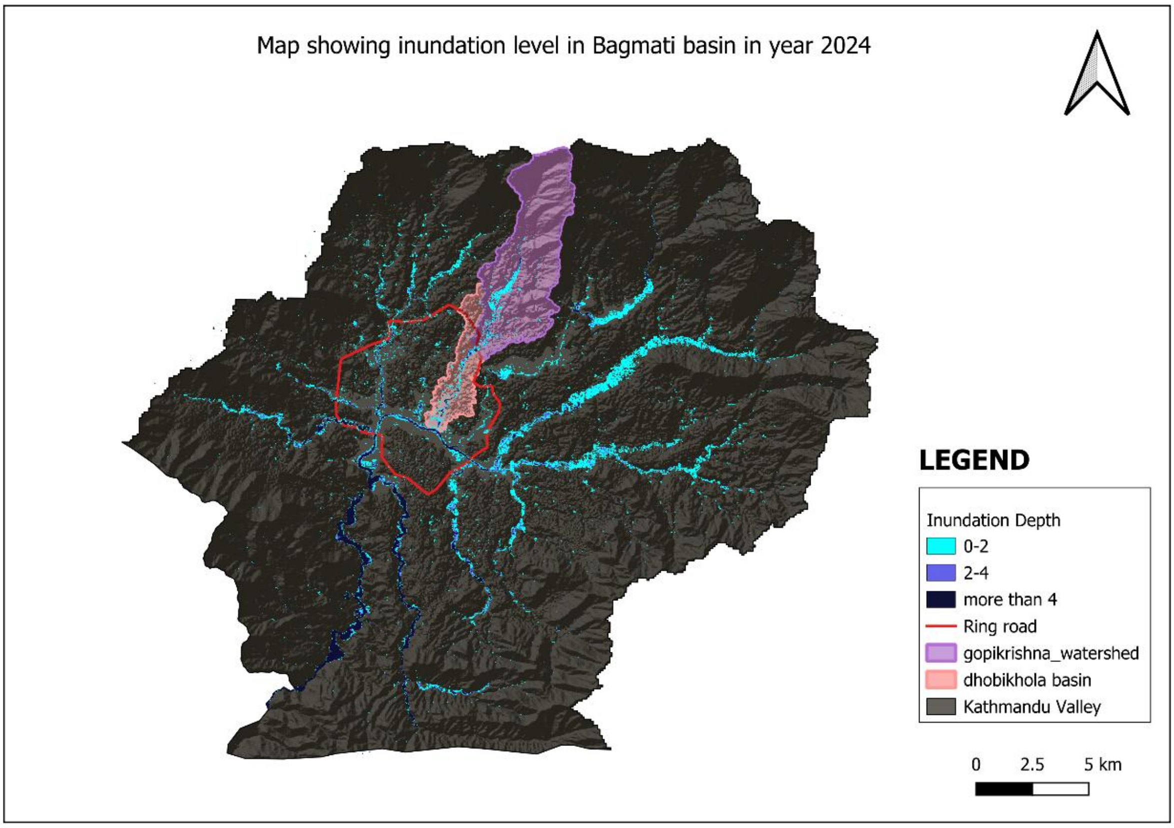


Figure 14 Inundation mapping for 2024 for Bagmati river basin

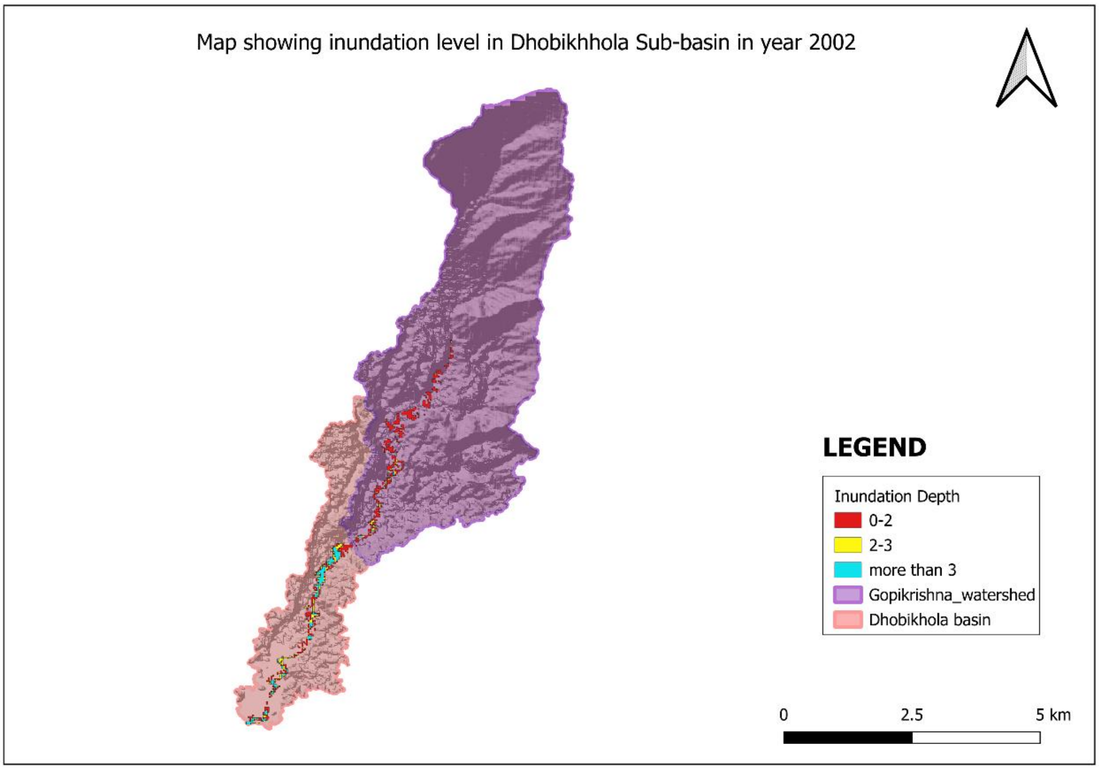


Figure 15 Inundation mapping for 2002 for Dhobi Khola sub basin

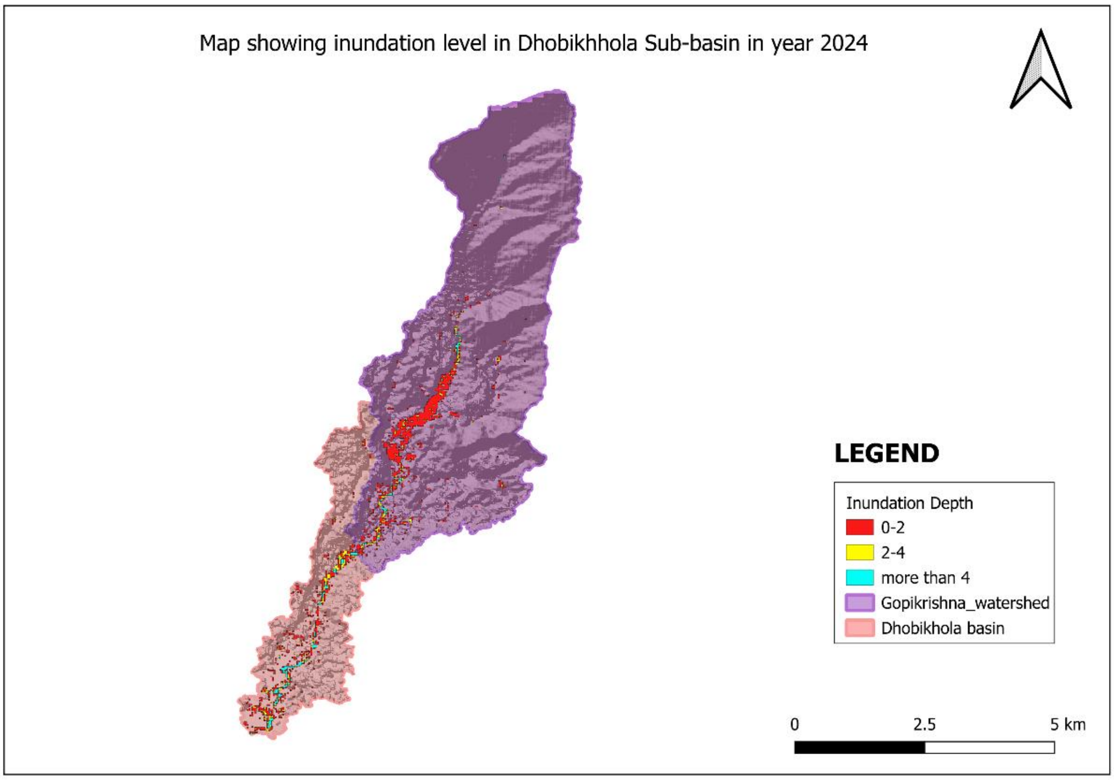


Figure 16 Inundation mapping for 2024 for Dhobi Khola sub basin

15. Morphological Indicators

Based on literature review some key **morphological variables of importance** that should be calculated to assess their effect on flood risk in the Kathmandu Valley, particularly in the Dhobi Khola sub-basin are as follows:

1. **Building Density (BD)**:

Definition: The number of buildings per unit area.

Relevance: High building density can increase impervious surfaces, reduce water infiltration, and worsen surface runoff, contributing to flooding risk.

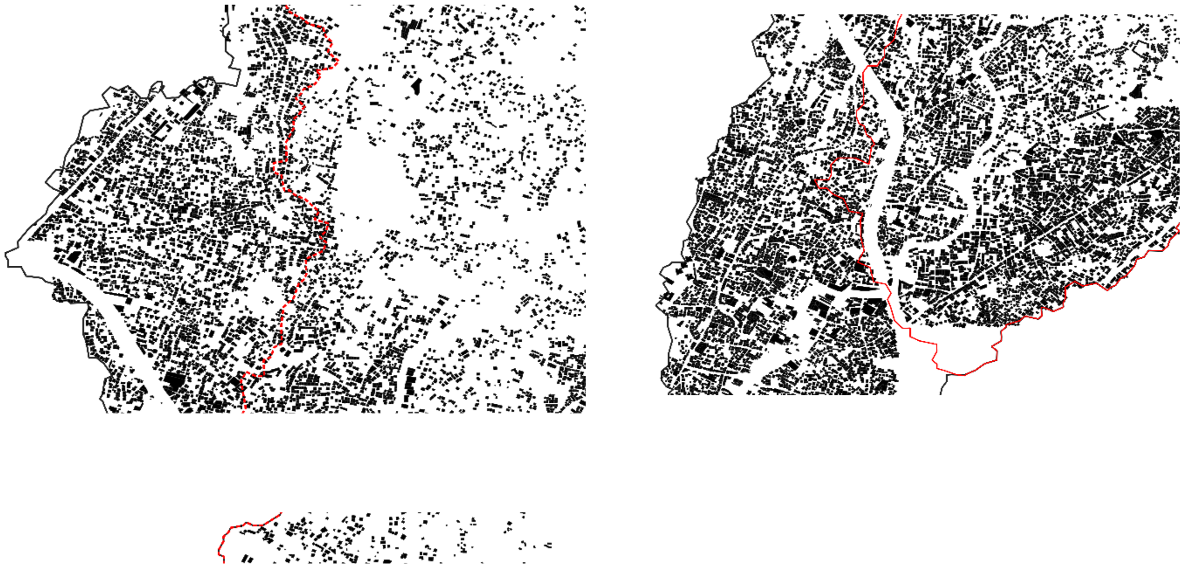
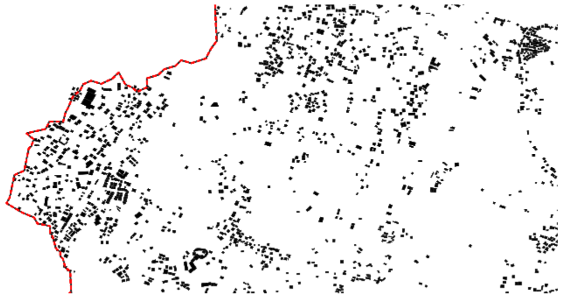


Figure 17 Different building density scenario in the catchment (Source: Open street maps)



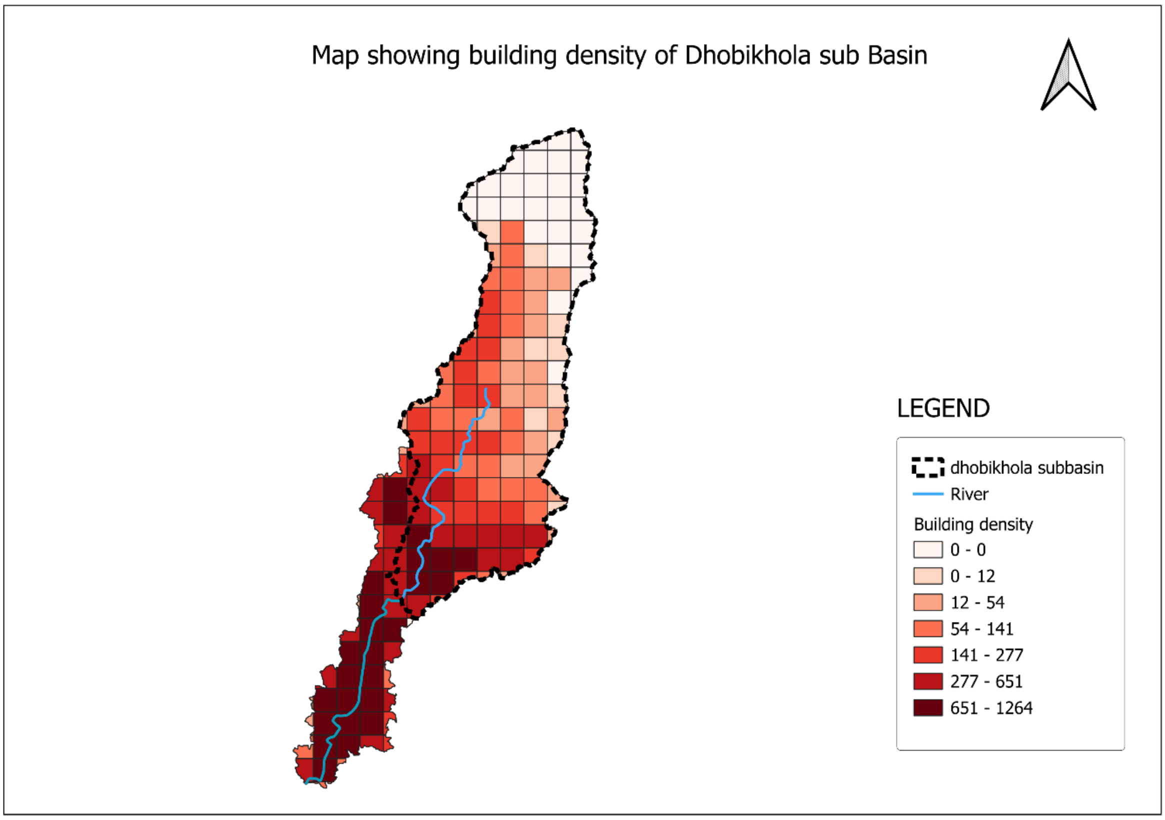
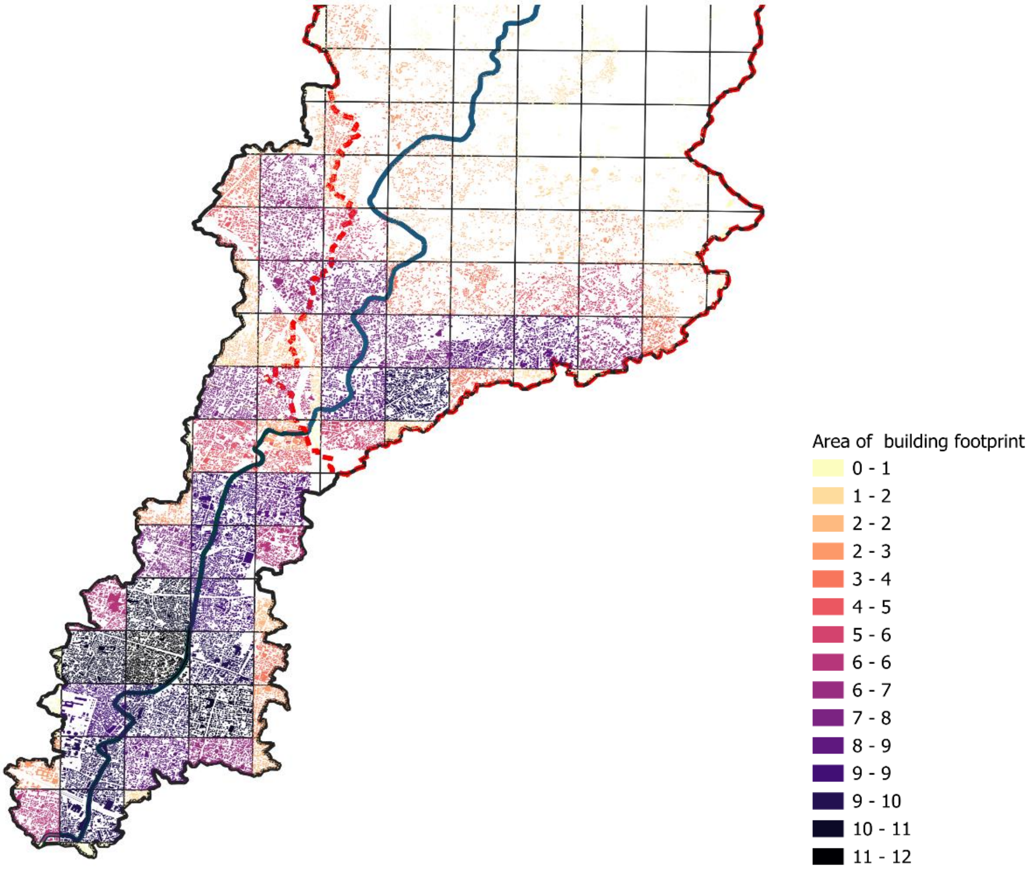


Figure 18 Building Density in a 500 x 500 m grid



2. **Building Volume (BV)**:

Definition: The total volume of buildings in the study area.

Relevance: Larger building volumes can affect runoff patterns and drainage capacity, especially in highly urbanized areas. As per your literature, maintaining the Mean Building Volume (MBV) within a certain range can help balance density and drainage.

3. **Mean Building Volume (MBV) and Standard Deviation of Building Volume (SDBV)**:

Definition: MBV refers to the average volume of buildings in the study area, and SDBV is the variability of building volumes.

Relevance: These indices help assess urban density and the potential for clustering of high-rise buildings, which can lead to localized flooding issues by disrupting water flow and increasing runoff.

Calculating Mean building volume based on assumption of the existing landuse map of 2008,

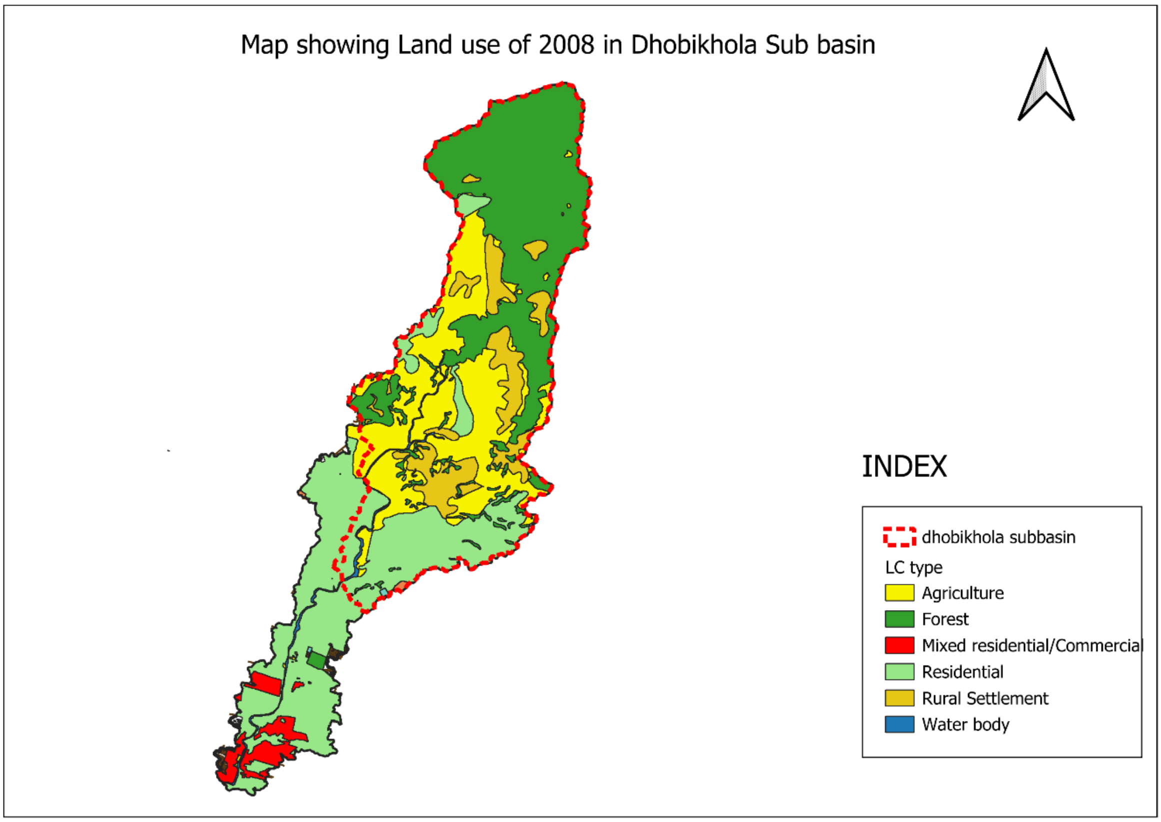


Figure 19 Land use map of 2008 of subbasin

Mean building volume outside ringroad,

Assuming, 15% commercial zone with 4.5 FAR, 25% dense mixed residential zone with FAR 4 and 60% residential subzone with far 3.5 and floor height of m

MBV = (0.15*2.47*7*3+0.25*2.47*5*3+0.6*2.47*3*3)*10^6/ 23,087 = (30.38*10^6) / 23,087 = 1315.89 m^3

MBV / m^2 = 30.38/ 24.93 = 1.21

Mean building volume inside ringroad,

MBV = $(0.15*2.32*7*3+0.25*2.32*5*3+0.6*2.32*3*3)*10^6/ 21,091 = (28.53*10^6) / 21,091 = 1352.99\ m^3$

MBV / m^2 = 28.53/ 8 = 3.5

- **Permissible MBV value depends on the existing drainage infrastructure, zoning regulations, ,flood mitigation strategies and the context.**

Inference of High-Density Settlements Near Rivers on Urban Flooding

The **proximity of dense settlements to a river** has a significant impact on urban flooding, affecting **peak discharge, floodplain capacity, and drainage efficiency**. Here’s a structured breakdown of its implications:

Empirical relationship of MBV to discharge,

Q = C (MBV) * I * A

MBV value can be used to adjust the **runoff coefficient C**

- **Urban areas** might have higher C values **(0.7 to 0.9)** due to impervious surfaces like roads and buildings.
- **Green areas** might have lower C values **(0.1 to 0.3)** since more rainfall infiltrates the ground.

Higher Peak Discharge Due to Increased Runoff

- **High-density settlements** have a higher percentage of **impervious surfaces** (concrete, roads, roofs), reducing infiltration.
- More surface runoff **directly enters the river**, **increasing flood peaks by 30–150%** in extreme rainfall events.
- **Example:** In the **Pearl River Delta (China),** urban expansion near rivers led to a **50% increase in peak discharge** over two decades.

Loss of Natural Floodplains & Storage Capacity

- **Dense urbanization encroaches on floodplains**, reducing their ability to absorb excess water.
- **Water that would have spread across floodplains now directly enters the river**, causing **higher and faster flood peaks**.
- **Example:** In Jakarta, **floodplain encroachment** has reduced storage capacity, increasing flood intensity.

Faster Flood Response (Reduced Time to Peak)

- In a **natural river system**, rainwater takes time to travel through the landscape before reaching the river.

- **Urbanization shortens this travel time**, meaning rainfall is converted to runoff **faster**, leading to **flash floods**.
- **Example:** Mumbai's Mithi River flooding worsened due to rapid urbanization, causing **floodwaters to peak within hours instead of days**.

Drainage Overload & Backflow Issues

- **Storm drains in dense areas near rivers** quickly fill up during extreme rainfall, failing to drain excess water.
- **If the river level rises above the drainage outlets**, water **backs up into streets**, worsening urban flooding.
- **Example:** Bangkok faces regular **backflow flooding** when river levels rise above city drains, leaving streets submerged.

4. **Road Density (RD)**:

Definition: The total length of roads per unit area.

Relevance: Roads act as artificial channels for water flow, affecting drainage efficiency. High road density, especially without proper drainage systems, can exacerbate urban flooding.

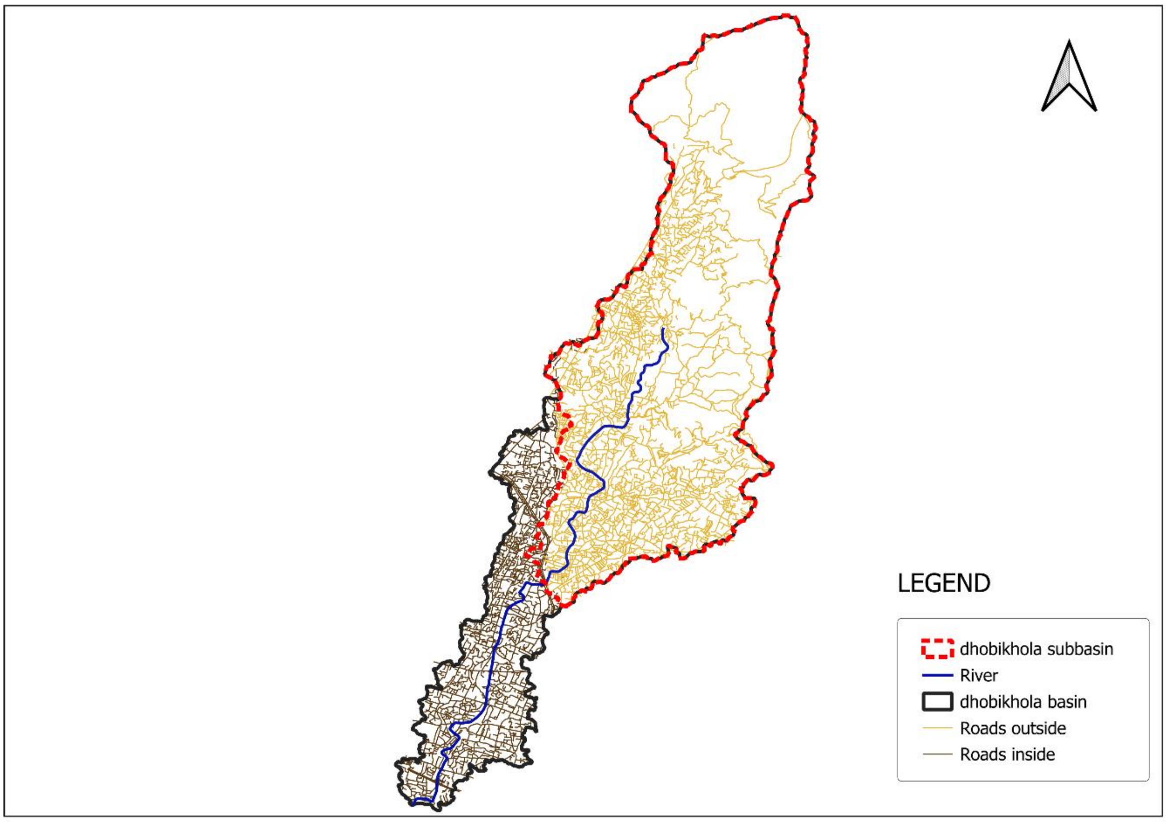


Figure 20 Road map inside and outside ringroad in Kathmandu valley (Source: OSM)

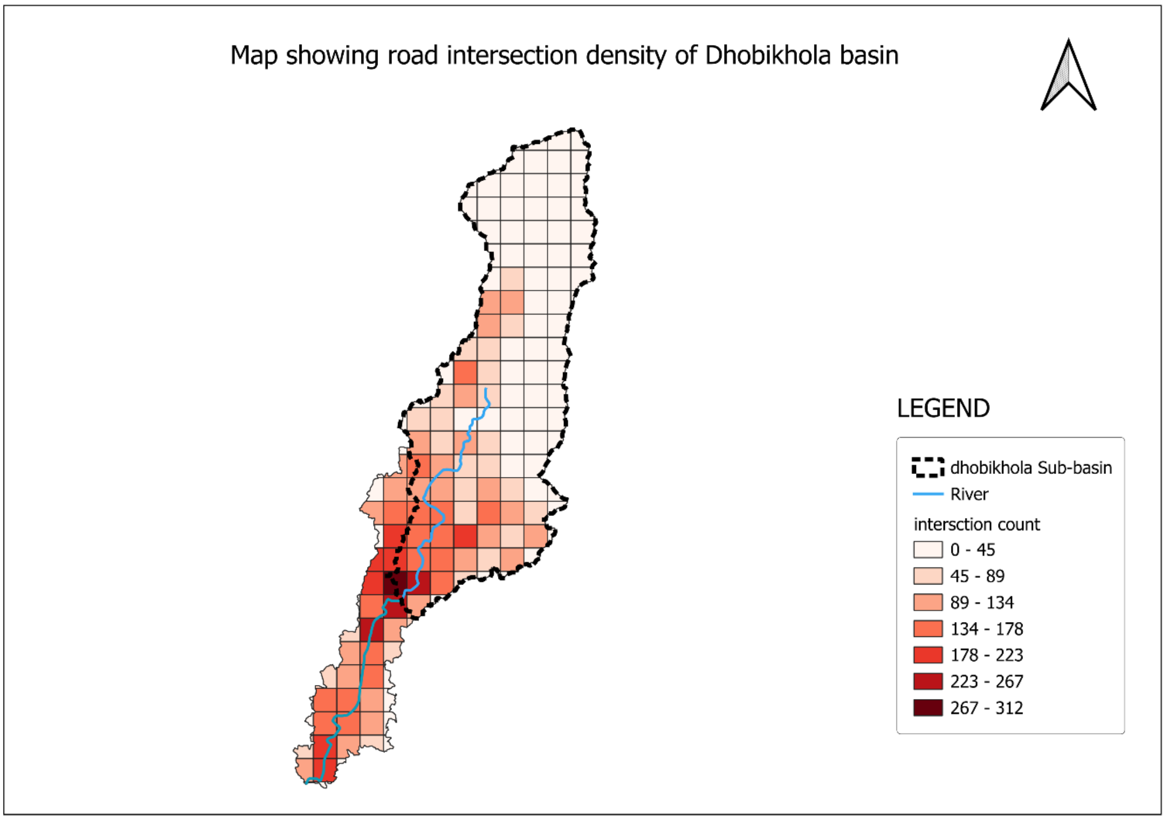


Figure 21 Road Intersection density map in Dhobikhola basin in a 500 x 500 m grid

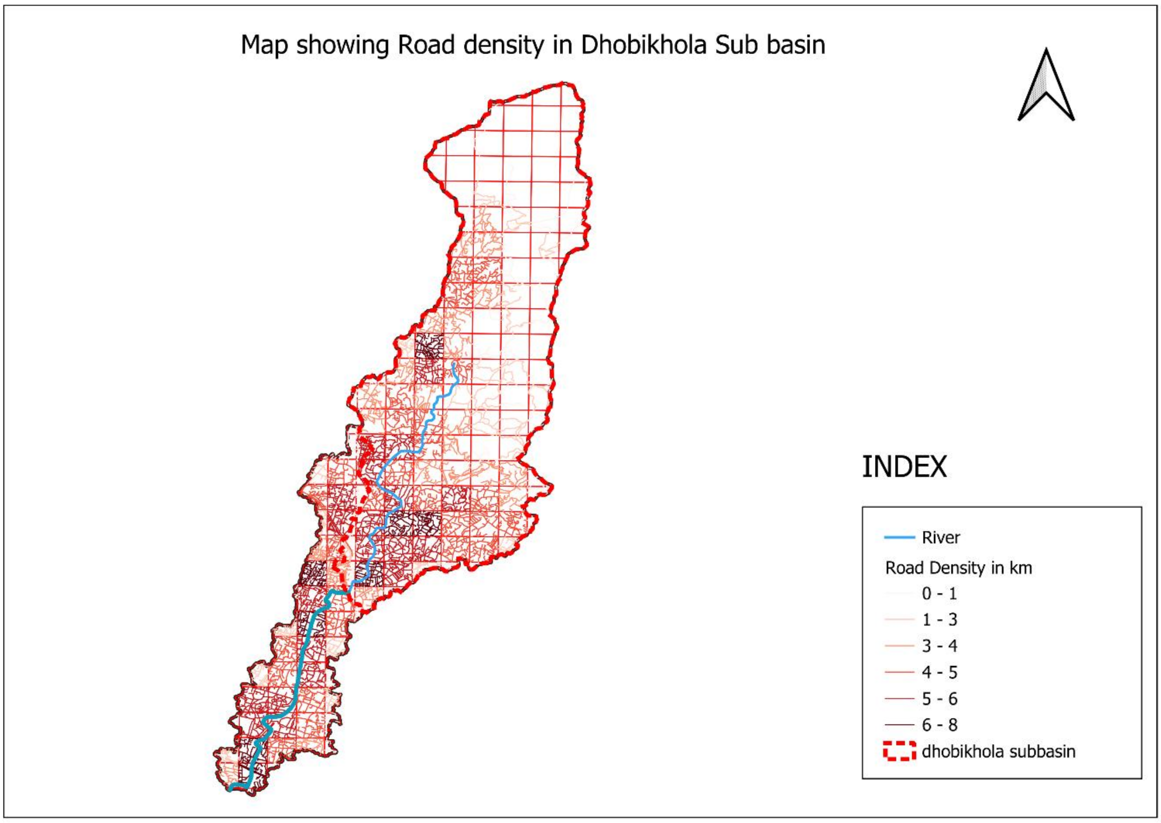


Figure 22 Road density map in Dhobikhola basin in a 500 x 500 m grid

Figure 23 Figure and ground map of Anamnagar section

CONCENTRATION TIME :

Concentration time is the time it takes for runoff to travel from the most distant point in a catchment (or watershed) to the outlet.

Kerby-Hathaway Formula (suitable for overland flow and surface urban runoff):

$$T_c = \frac{K \cdot (L^{0.467})}{(S^{0.235} \cdot N^{0.467})}$$

Where,

Tc = time of concentration (minutes)

L= length of flow path (feet or meters)

S= slope (m/m)

N = roughness coefficient (higher for vegetated, lower for paved)

K = unit conversion constant (depends on units used)

Road Density VS Concentration time:

Higher road density = shorter concentration time

Relative comparison of grid with different road density,

For road density 5.5,

$$D_n = \frac{5.5-0.5}{8-0.5} = 0.6$$

$$T_r = 1 - 0.6 = \mathbf{0.4T}$$

For road density 7.5,

$$D_n = \frac{7.5-0.5}{8-0.5} = 0.9$$

$$T_r = 1 - 0.9 = \mathbf{0.1T}$$

Landscape Statistics (LS):

Definition: The distribution and proportion of different land use types, including built-up areas, agricultural land, forests, and other natural or modified landscapes, in a given region.

Higher road density = shorter concentration time

Relevance: Landscape statistics provide insight into how different land use types impact the natural water cycle and flood risks.

Some relevant landscape statistics variables having high correlation to flooding was calculated for year 2002 and 2002 to study trend of land cover evolution:

Patch Cohesion

- **Significance**: Patch cohesion measures how connected or compact a particular land cover type is. A higher cohesion means that the patches of the same land cover are less fragmented and are more spatially connected.
- **Relation to Flooding and Discharge**: Higher patch cohesion in natural areas (like forests or wetlands) can improve water absorption and reduce surface runoff, thereby potentially decreasing the risk of flooding. Fragmented or less cohesive patches (e.g., urban areas) contribute to higher runoff, which increases the likelihood of flooding and can raise discharge levels in the river.

Edge Density

- **Significance**: Edge density refers to the amount of boundary or edge between different land cover types (e.g., urban areas and forests). A higher edge density means there are more transitions between different types of land cover in a given area.
- **Relation to Flooding and Discharge**: Higher edge density, typically found in urbanized or fragmented landscapes, tends to increase impervious surfaces (like roads and buildings), leading to greater runoff and faster discharge to the river. This can result in higher flood risks and more rapid changes in river discharge during rainfall events.

Patch Density

- **Significance**: Patch density indicates the number of discrete patches (or areas) of a particular land cover type per unit of area. A higher patch density means more small, isolated patches of land cover.
- **Relation to Flooding and Discharge**: Higher patch density, especially in urbanized areas, generally leads to more fragmented land cover with less natural flow regulation. This can result in increased runoff and reduced natural infiltration, contributing to higher river discharge and a greater risk of flooding.

Landscape Proportion

- **Significance**: Landscape proportion measures the relative abundance of a particular land cover type in the landscape. It reflects how much of the landscape is dominated by a specific land cover (e.g., forest, water, or urban).
- **Relation to Flooding and Discharge**: A larger proportion of impervious surfaces (like urban areas) in the landscape leads to higher surface runoff and faster discharge into the river, increasing flood risks. Conversely, a higher proportion of natural land covers (like wetlands or forests) can enhance water retention and infiltration, reducing runoff and mitigating flooding risks.

Patch Cohesion Index

- **Significance**: The patch cohesion index combines the spatial arrangement and connectivity of patches of a specific land cover. It provides a more refined measure of how well different patches of a land cover type are clustered together.
- **Relation to Flooding and Discharge**: A higher patch cohesion index for natural land covers can help reduce runoff, as continuous, connected areas (e.g., wetlands or forests) better absorb water. Lower cohesion, especially in urbanized areas, can exacerbate flooding by promoting runoff and faster discharge into the river.

Summary of the Relation to Flooding and River Discharge:

- **Higher urbanization (more edges, higher patch density, and lower cohesion)** tends to increase **impervious surfaces**, leading to **higher runoff**, **faster river discharge**, and increased **flood risks**.
- **Natural landscapes** (e.g., forests, wetlands, cohesive patches) tend to reduce **runoff** by improving **water infiltration**, which can lower **discharge levels** and reduce **flooding risks**.

Table 8 Landscape Statistics of landcover map of 2022

2022					
LC Class	**Landscape proportion**	**edge density**	**Patch density**	**Overall core area**	**Patch Choesion index**
built up	0.179	0.03	5.21	388600	9.899
Agri	0.065	0.031	7.97	75600	9.827
Forest	0.102	0.009	2.165	255575	9.872

Table 9 Landscape Statistics of landcover map of 2002

2002					
LC Class	**Landscape proportion**	**edge density**	**Patch density**	**Overall core area**	**Patch Choesion index**
Built up	0.11	0.027	0.0001	207250	9.874
Agri	0.133	0.032	0.0001	245300	9.881
Forest	0.101	0.0134	5.905	239850	9.868

Fractal Dimension:

Definition: Fractal dimension quantifies the complexity and irregularity of urban shapes, particularly the boundaries and patterns of built-up areas.

Relevance: Higher fractal dimension indicates more fragmented urban forms, which can hinder drainage efficiency and increase flooding risk due to reduced water absorption and increased surface runoff.

Fractal Dimension calculation of river path:

Box Counting Method:

The box counting method is a technique used to calculate the fractal dimension of a geometric shape by covering the shape with boxes of varying sizes and counting the number of boxes required to cover the shape

This method is often used to quantify the complexity of urban forms, including the spatial distribution of buildings, roads, and green spaces. By examining how the number of boxes changes with size, the fractal dimension is derived, which helps assess how irregular urban patterns influence factors like water flow and flooding risks. A higher fractal dimension often indicates more complex, fragmented urban development, contributing to increased flood susceptibility.

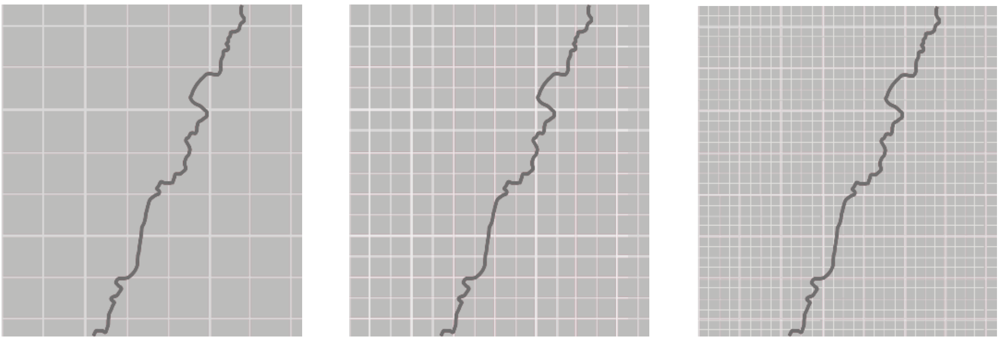


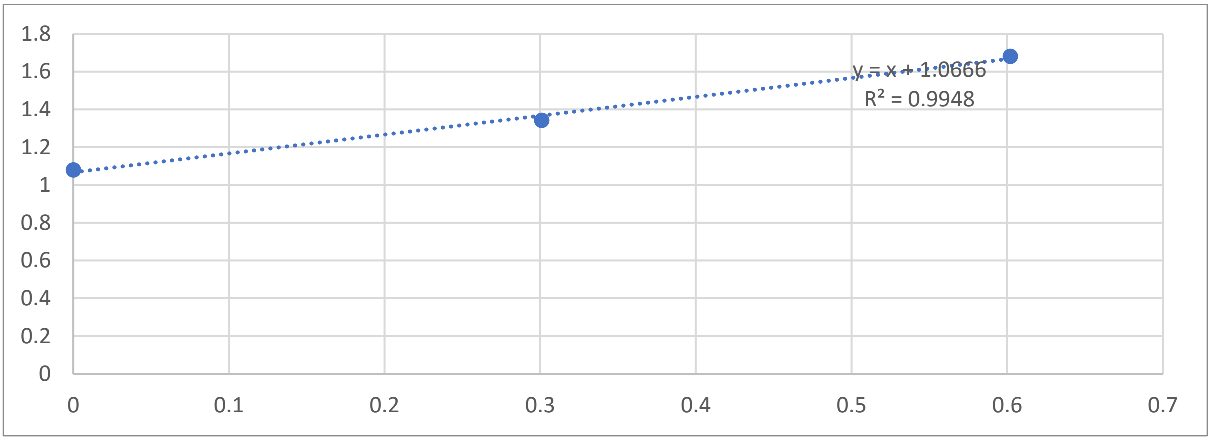
Table 10 Calculating Log(s) and Log(n) for year 2024

Scaled down factor(S)	0	2	4
Log(S)	0	0.301029996	0.602059991
Number of Boxes(N)	12	22	48
Log(N)	1.079181246	1.342422681	1.681241237

Procedure:

1. **Box Sizes and Count:** For each box size **S**, count the number of boxes **N** needed to cover the shape.
2. **Logarithmic Transformation:** Take the natural logarithm (log) of both **S** and **N**.
3. **Plot:** Plot **log(N)** on the y-axis and **log(S)** on the x-axis.
4. **Linear Relationship:** The resulting plot should display a linear relationship.
5. **Slope Calculation:** The slope of the line is calculated by determining the change in **log(N)** over the change in **log(S)**. Mathematically, this can be expressed as:

   Slope = $\Delta\log(S) / \Delta\log(N)$



Relevance: The slope of the line in the log-log plot represents the fractal dimension of the urban morphology, helping to quantify the complexity of spatial structures. A higher slope indicates a more complex, irregular urban form, which can be associated with a higher risk of flooding due to obstructed water flow and increased surface runoff.

Figure 24 Satellite image of Kathmandu valley from 1967 (Source: Corona Satellite USGS website)

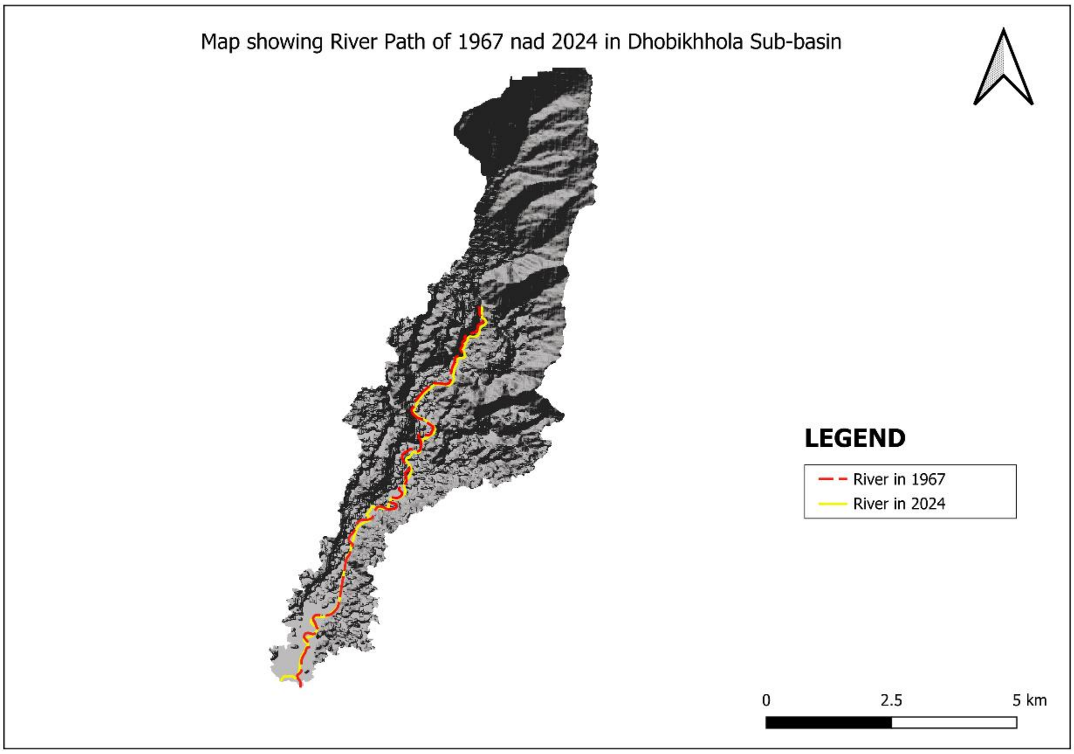


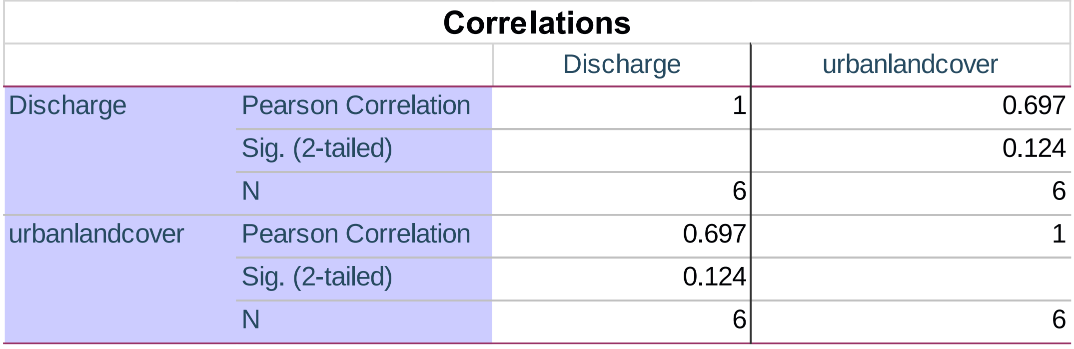
Figure 25 Overlay of river path of 1967 and 2024

16. Data Analysis & Findings

16.1 Correlational Analysis:

To quantify the relationship between urban morphological changes and flooding variables, a correlation approach is applied. The correlation analysis seeks to understand how urbanization and changes in land use influence the frequency and intensity of flooding within the Dhobi Khola sub-basin.

1. **Variables for Correlation**: Several variables are considered in the correlation analysis, including:
    - **Land Use Change**: The proportion of impervious surfaces (such as roads and buildings) and green spaces within the sub-basin.
    - **Drainage Density**: The extent and connectivity of drainage infrastructure, which influences the sub-basin's ability to handle stormwater.
    - **Rainfall Data**: Precipitation patterns, including the intensity and frequency of rainfall events.
    - **Flood Occurrence**: Frequency and magnitude of historical flood events.
2. **Statistical Analysis**: Statistical tools, such as Pearson's correlation coefficient or Spearman's rank correlation, are applied to assess the strength and direction of the relationship between these variables. Regression analysis may also be used to model the extent to which changes in urban morphology contribute to variations in flood occurrence and intensity.



Correlations

		Discharge	urbanlandcover
Discharge	Pearson Correlation	1	0.697
	Sig. (2-tailed)		0.124
	N	6	6
urbanlandcover	Pearson Correlation	0.697	1
	Sig. (2-tailed)	0.124	
	N	6	6

<u>Discharge VS Urban land cover</u>

The correlation coefficient of **0.697** indicates a **moderate positive correlation** between **Discharge (Q)** and **Urban Land Cover**. This means that as urban land cover increases, discharge also tends to increase, albeit moderately. A higher urbanization rate may contribute to increased runoff due to the increase in impervious surfaces like buildings and roads, leading to higher discharge.

Correlations

		Discharge	FD
Discharge	Pearson	1	-0.567
	Sig. (2-tailed)		0.241
	N	6	6
FD	Pearson	-0.567	1
	Sig. (2-tailed)	0.241	
	N	6	6

Discharge VS Fractal dimension

The **correlation coefficient** of **-0.567** indicates a **moderate negative correlation** between **Discharge** and **Fractal Dimension (FD)**. This means that as discharge increases, fractal dimension tends to decrease, or vice versa.

Correlations

		Forestlandcover	Rainall
Forestlandcover	Pearson Correlation	1	.930**
	Sig. (2-tailed)		0.007
	N	6	6
Rainall	Pearson Correlation	.930**	1
	Sig. (2-tailed)	0.007	
	N	6	6

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

Rainfall VS Forest cover

The Pearson correlation coefficient is **0.930**. This means there is a very strong positive relationship between forestland cover and rainfall in the dataset. In other words, as the amount of forest cover increases, rainfall tends to increase as well, and vice versa.

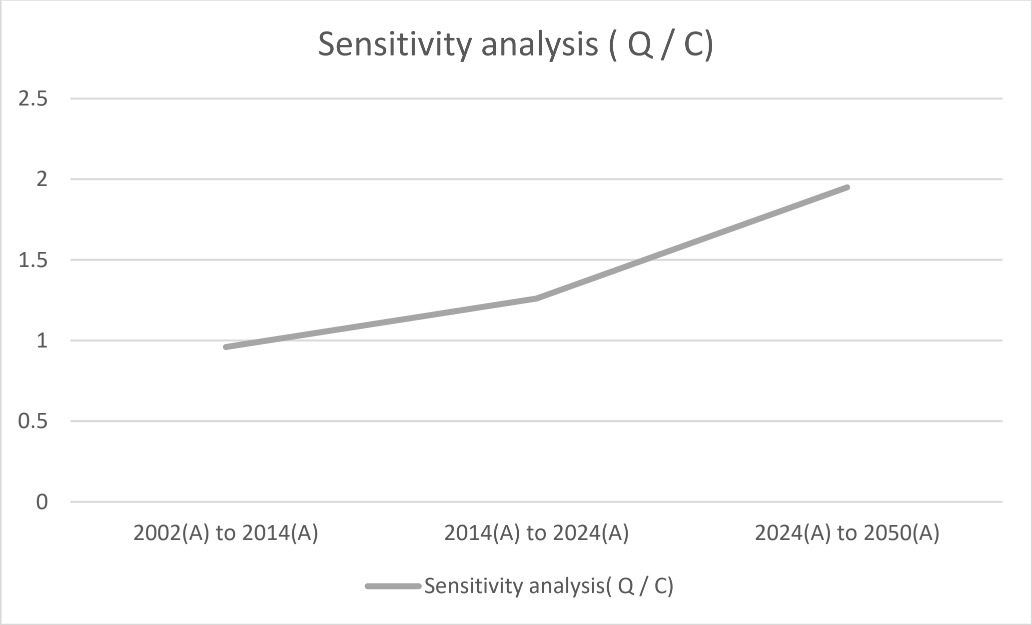
16.2 Sensitivity analysis:

Table 11 Sensitivity analysis between dange in discharge and weighted coefficient

For rainfall of 250mm			
Period	**% change in discharge**	**% change in weighted coefficient**	**Sensitivity analysis(Q / C)**
2002(A) to 2014(A)	13.10%	13.77%	0.96
2014(A) to 2024(A)	9.70%	7.77%	1.26
2024(A) to 2050(A)	38%	19.46%	1.95
2002(B) to 2014(B)	10.97%	22.50%	0.49
2014(B) to 2024(B)	15.61%	15.14%	1.03
2014(B) to 2050(B)	51.85%	30%	1.72

Keeping I = 250 mm in all scenario, and assuming built up area reaches 70 % of total catchment in year 2050,

$$Q = C * \underset{\substack{\uparrow \\ \text{constant}}}{I} * A$$



Higher Q/C Ratio → High Sensitivity:

- If the Q/C value is **large**, it indicates that **small changes in the weighted coefficient (C) result in significant changes in discharge (Q).**
- This could mean that the water system is highly reactive to external factors such as rainfall variations, deforestation, or urbanization.
- Implication: **Greater risk of flooding, water shortages, or ecosystem disruptions** depending on whether discharge increases or decreases.

16.3 Morphological analysis

16.3.1 Fractal analysis of river path

The decrease in Fractal Dimension of River Path by 0.2 from 1967 to 2024 signifies the following discussions.

- **Less Complex River Path**: A decrease in the fractal dimension of the river path suggests that the river's course has become less irregular or more simplified. Fractal dimension is often used to quantify the complexity of natural shapes like rivers, so a decrease would indicate a reduction in the meandering or sinuosity of the river.
- **Human Intervention or Alterations**: Such a decrease could be the result of human modifications to the river, such as straightening or channelizing, which is common in urbanized areas to control flood risks or for infrastructure development. This

simplification of the river path would make it less complex, thus reducing its fractal dimension.

16.3.2 Building density and road density analysis

The analysis of road intersection density and building density in the Dhobikhola sub-basin highlights distinct urbanization patterns that influence flood risks in different ways. While building density is highest in the southern part of the basin, the central part exhibits the highest road intersection density. This discrepancy suggests varying forms of urban development, each with unique hydrological implications.

Roads, being largely impervious, prevent water infiltration and increase surface runoff. If stormwater drainage infrastructure is inadequate, this can result in localized flooding, particularly in low-lying areas. he reduced number of road intersections in this area suggests a different urban layout, possibly characterized by larger buildings or high-rise residential zones with fewer road networks.

Flooding Challenges in Different Urban Forms

The mismatch between road and building density patterns suggests that flooding risks may manifest differently across the sub-basin:

- **Central Region (High Road Intersection Density):**
    - Extensive paved surfaces increase **surface runoff**.
    - A dense road network may obstruct natural drainage paths, leading to **waterlogging**.
    - Poor stormwater management in these areas could exacerbate flood severity.
- **Southern Region (High Building Density):**
    - A high concentration of buildings reduces **permeable surfaces**, increasing direct runoff.
    - Larger building footprints may **alter natural drainage**, contributing to flash floods in extreme rainfall events.
    - Insufficient road networks might mean fewer drainage channels, potentially slowing floodwater evacuation.

Implications for Flood Risk Management

Given these findings, flood mitigation strategies should be tailored to the specific urban characteristics of each region:

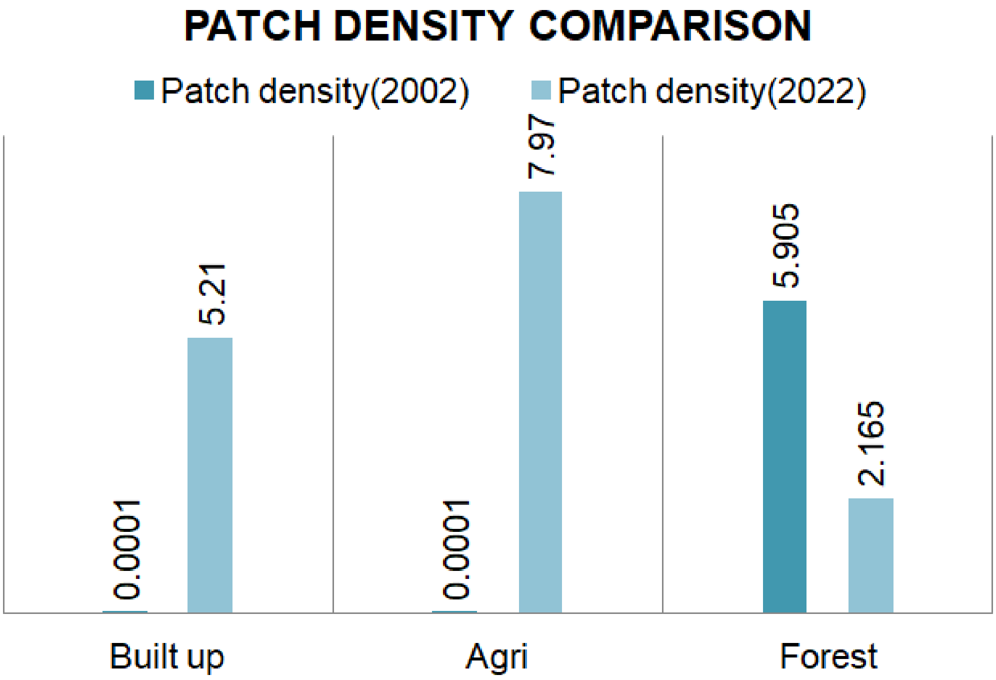
- **For high road intersection density areas (Central Region):**
    - Enhancing stormwater drainage systems along road networks to efficiently channel excess runoff.
    - Incorporating **green infrastructure**, such as bioswales and rain gardens, to improve infiltration.
    - Implementing flood-sensitive road design, such as permeable pavements and urban water retention areas.
- **For high building density areas (Southern Region):**
    - Enforcing **permeable surface regulations** in construction policies to minimize runoff.

  - Encouraging **rainwater harvesting** and **green roofs** to reduce direct stormwater flow.
  - Ensuring urban planning incorporates flood-resilient layouts with open spaces for water absorption.

16.3.3 Landscape statistics analysis:

Built-Up Areas:

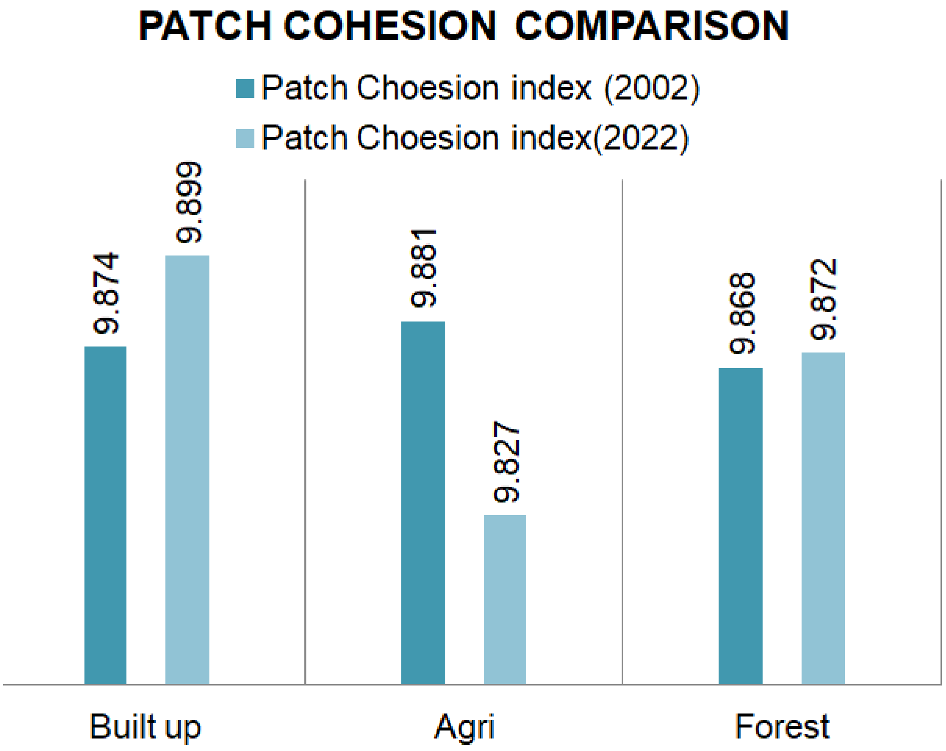
- **Proportion:** Built-up areas have increased significantly from **11% in 2002** to **17.9% in 2022**, indicating urban expansion and urbanization growth. This increase in built-up areas leads to reduced natural land cover, contributing to greater surface runoff and flood risks.
- **Edge Density & Patch Density:** The **edge density** and **patch density** for built-up areas show a slight increase, from **0.027** to **0.03** for edge density and **0.0001** to **0.03** for patch density. The slight rise in patch density suggests a more fragmented urban landscape. More fragmented urban areas tend to reduce water absorption and increase runoff, exacerbating flooding risks.
- **Core Area:** The **core area** for built-up areas has significantly expanded from **207,250 m²** in 2002 to **388,600 m²** in 2022, reflecting the spread of urban development and larger impervious surfaces.
- **Patch Cohesion:** The **patch cohesion index** has slightly increased from **9.874** to **9.899**, indicating that although the built-up areas are expanding, they are becoming more cohesive and interconnected. This reinforces the idea of urban sprawl, which reduces the effectiveness of natural flood mitigation.



Agricultural Areas:

- **Proportion:** Agricultural land has decreased from **13.3% in 2002** to **6.5% in 2022**, indicating a loss of agricultural areas, likely due to urban expansion and land use changes. This reduction in agricultural land limits the ability to absorb rainfall and manage runoff, increasing the flood risks.

- **Edge Density & Patch Density:** The **edge density** has slightly decreased from **0.032** to **0.031**, and the **patch density** has increased significantly from **0.0001** to **0.079**. This suggests that agricultural land has become more fragmented, reducing its capacity to control runoff effectively. The high fragmentation limits the ability of the land to act as a flood buffer, making it less effective at mitigating flooding.
- **Core Area:** The **core area** has dramatically decreased from **245,300 m²** in 2002 to **75,600 m²** in 2022, further reflecting the loss of contiguous agricultural land. Smaller core areas result in reduced water absorption and greater runoff, contributing to more intense flooding.
- **Patch Cohesion:** The **patch cohesion index** has slightly decreased from **9.881** to **9.827**, indicating that agricultural land has become more fragmented, which diminishes its flood control capacity.



Forest Areas:

- **Proportion:** The proportion of forest land has remained relatively stable, increasing slightly from **10.1% in 2002** to **10.2% in 2022**, which suggests that forest cover has been preserved despite urbanization and agricultural land conversion.
- **Edge Density & Patch Density:** The **edge density** has decreased from **0.0134** to **0.009**, which indicates that forests have become more continuous and less fragmented, a positive sign for flood mitigation as continuous forest areas are better at absorbing water and controlling runoff.
- **Core Area:** The **core area** has increased slightly from **239,850 m²** in 2002 to **255,575 m²** in 2022, indicating that forests are expanding in certain areas, which is beneficial for flood control. Larger core areas allow for better water retention and slower runoff, thus reducing flood risks.

- **Patch Cohesion:** The **patch cohesion index** has remained almost unchanged, slightly increasing from **9.868** to **9.872**, which reflects the continued cohesion of forest patches and their effectiveness in mitigating flooding.

17. Discussion:

Urbanization in the Dhobi Khola catchment is progressing rapidly, with the built-up area already at approximately 50% and projected to reach 70–80% in the near future. This trend is inevitable given population growth and urban expansion pressures. However, past planning practices have largely overlooked morphological factors such as urban form, slope, and hydrological connectivity, which has significantly increased the flood vulnerability of the area. The sensitivity analysis conducted in this study reveals that the catchment is becoming increasingly sensitive to extreme rainfall events. This implies that, without intervention, the frequency and severity of future flooding will likely rise. Urban expansion, if not managed properly, will further amplify the risks through increased impervious surfaces and reduced natural infiltration.

The landscape analysis comparing 2002 and 2022 statistics demonstrates the profound impact of urbanization. There has been a sharp decline in agricultural land—from 13.3% to 6.5%—and a corresponding increase in built-up area, patch density, and core urban zones. These changes have led to reduced permeability, higher surface runoff, and an elevated risk of urban flooding. The fragmentation of agricultural land, in particular, has weakened the landscape’s ability to absorb and regulate water, while only minor improvements in forest cover offer limited ecological compensation.

Further, the study identifies that upper catchment development poses an additional risk due to steeper slopes and shorter concentration times, which accelerate runoff. Therefore, land-use interventions in these areas must be approached with caution. Slope, flow path length, and concentration time were all found to be significant in shaping runoff behavior. Additionally, the research shows that **mean building volume (MBV)** has a notable influence on peak discharge. Areas with smaller but denser structures create more impervious spread, whereas more compact vertical development with higher MBV tends to preserve permeable surfaces and reduce sprawl. Coupled with consistent road density, encouraging such forms of development can help maintain concentration time and accommodate more people without exacerbating flood risks.

This study advocates for integrating morphological indicators—such as building density, slope, and MBV—into catchment-specific planning policies. It highlights the potential for proactive strategies, such as compact development, permeable design, and ecological restoration, to mitigate flood risks while supporting sustainable urban growth.

18. Conclusion

The research emphasizes the urgent need to address flooding through both preventive and mitigation strategies, particularly in the context of rapidly urbanizing catchments like Dhobi Khola. With the built-up area expected to rise sharply in the coming years, failure to incorporate morphological factors into planning will lead to increasingly severe flooding impacts.

Key findings show that:

- Urban growth has drastically reduced permeable surfaces and fragmented agricultural land, leading to increased surface runoff.
- The catchment is becoming more sensitive to extreme rainfall, underscoring the need for forward-looking planning.
- Morphological variables—especially slope, concentration time, road density, and mean building volume—significantly influence flood behavior.
- High-density, vertical development can reduce sprawl, improve runoff behavior, and support better flood management if combined with consistent road infrastructure and green interventions.

Therefore, a **catchment-specific, morphology-informed planning approach** is essential. Developing new zoning laws, encouraging compact urban forms, and maintaining ecological buffers can significantly improve resilience. The findings call for local governments and planners to adopt data-driven, context-aware strategies that align urban growth with hydrological sustainability.

19. Recommendations

- Integration of Morphological Indicators into Existing Byelaws

Update land use and zoning regulations to include morphological factors such as **building density**, **mean building volume**, **slope**, and **road density** as criteria for development control.

Define **permissible building volume** and density thresholds at the **ward or catchment level**, informed by hydrological sensitivity and land cover.

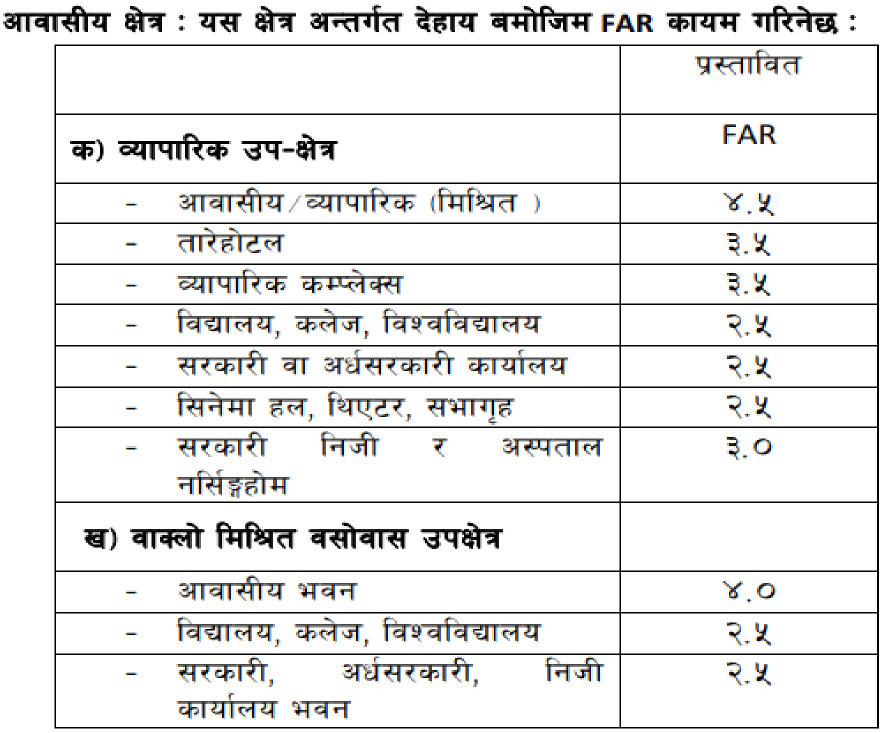
Introduce **flexible zoning** that allows vertical growth (higher mean building volume) while **restricting horizontal sprawl** to preserve open and permeable spaces.

Some Documents reviewed,

Dhobikhola Corridor and Kapan-Budhanilkantha Flood Control Project, 2024
Kathmandu building bye laws, 2075
Budanilkantha building bye laws
National urban policy, 2081
Kathmandu Ecological corridor and urban renewal project preparation report

Some insights into current plans and policies and how we can integrate morphological variables in current building bye laws,

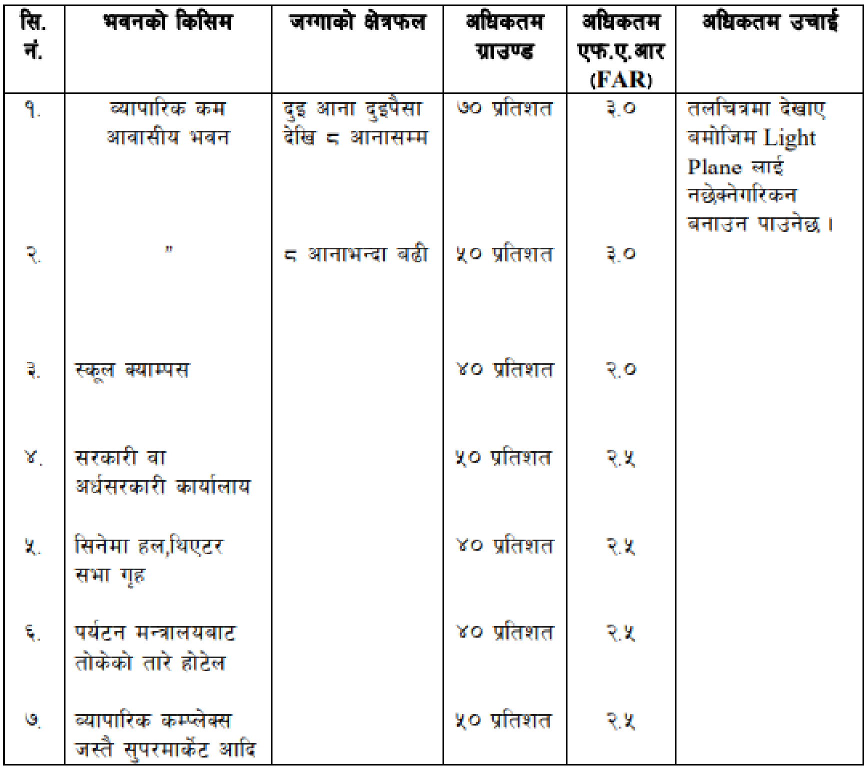
The current scope of the Dhobikhola and Kapan–Budanilkantha Flood Control Project primarily emphasizes flood mitigation. However, future projects should also incorporate runoff control measures and factors such as concentration time to enhance their effectiveness. Since the Dhobi Khola flows through both Kathmandu and Budanilkantha municipalities, the respective by-laws should integrate morphological considerations to better understand urban evolution and its influence on flooding dynamics. Similarly, other sub-catchments of the Bagmati River within Kathmandu could benefit from tailored, catchment-specific frameworks. These frameworks can be layered onto existing municipal by-laws to provide more localized and adaptive planning tools. While such integration will require further in-depth research, adopting a holistic approach is essential—especially in the Kathmandu Valley, where rivers are numerous and intricately connected with the urban fabric.



आवासीय क्षेत्र : यस क्षेत्र अन्तर्गत देहाय बमोजिम FAR कायम गरिनेछ :

	प्रस्तावित
क) व्यापारिक उप-क्षेत्र	FAR
- आवासीय/व्यापारिक (मिश्रित)	४.५
- तारेहोटल	३.५
- व्यापारिक कम्प्लेक्स	३.५
- विद्यालय, कलेज, विश्वविद्यालय	२.५
- सरकारी वा अर्धसरकारी कार्यालय	२.५
- सिनेमा हल, थिएटर, सभागृह	२.५
- सरकारी निजी र अस्पताल नर्सिङ्गहोम	३.०
ख) वाक्लो मिश्रित वसोवास उपक्षेत्र	
- आवासीय भवन	४.०
- विद्यालय, कलेज, विश्वविद्यालय	२.५
- सरकारी, अर्धसरकारी, निजी कार्यालय भवन	२.५

Figure 26 Building bye laws for Kathmandu municipality in commercial subzone, 2080 B.S

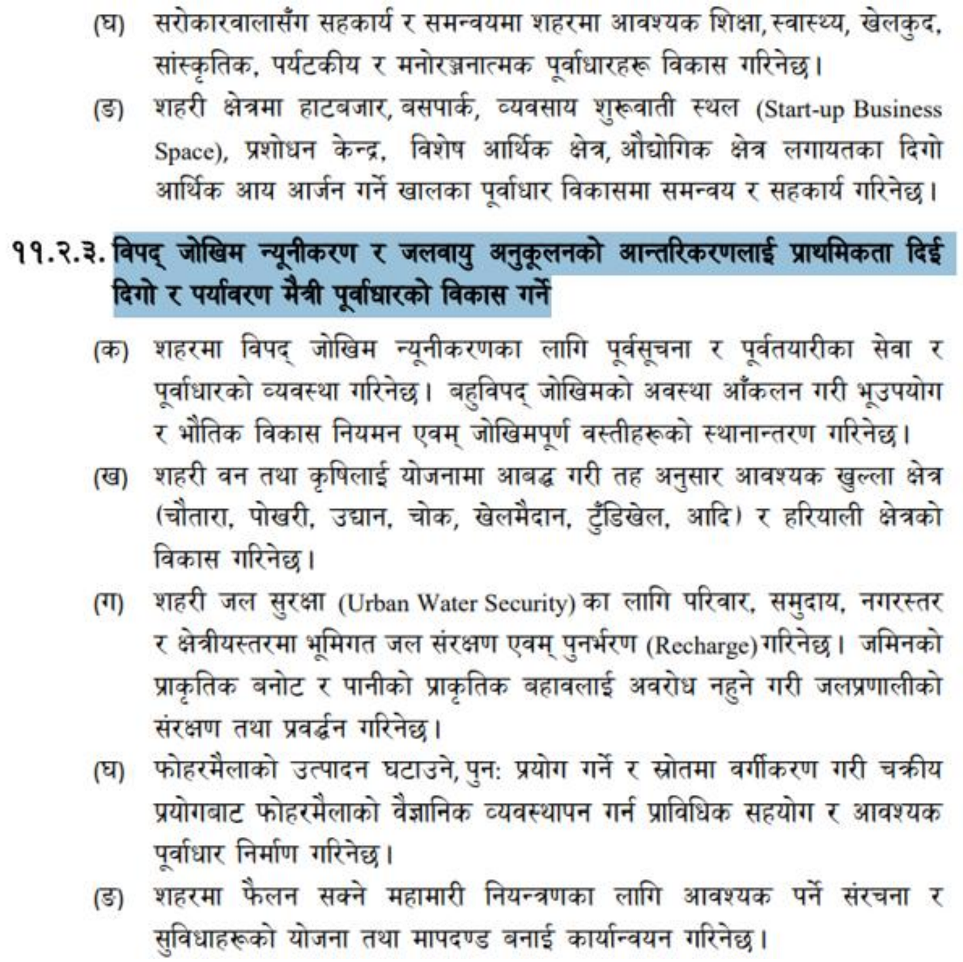


सि. नं.	भवनको किसिम	जग्गाको क्षेत्रफल	अधिकतम ग्राउण्ड	अधिकतम एफ.ए.आर (FAR)	अधिकतम उचाई
१.	व्यापारिक कम आवासीय भवन	दुइ आना दुइपैसा देखि ८ आनासम्म	७० प्रतिशत	३.०	तलचित्रमा देखाए बमोजिम Light Plane लाई नछेक्नेगरिकन बनाउन पाउनेछ।
२.	"	८ आनाभन्दा बढी	५० प्रतिशत	३.०	
३.	स्कूल क्याम्पस		४० प्रतिशत	२.०	
४.	सरकारी वा अर्धसरकारी कार्यालय		५० प्रतिशत	२.५	
५.	सिनेमा हल,थिएटर सभा गृह		४० प्रतिशत	२.५	
६.	पर्यटन मन्त्रालयबाट तोकेको तारे होटेल		४० प्रतिशत	२.५	
७.	व्यापारिक कम्प्लेक्स जस्तै सुपरमार्केट आदि		५० प्रतिशत	२.५	

Figure 27 Building bye laws for Kathmandu municipality in commercial subzone, 2064 B.S

The Floor Area Ratio (FAR) has seen little change over the past 15 years, and the lack of proper land use zoning and its implementation has been a major contributor to unplanned urban sprawl in the Kathmandu Valley. This has led to a significant rise in both road and building density. To address this, future amendments to the by-laws should focus on identifying high-density zones where vertical development is encouraged. This approach can help accommodate growing population needs while minimizing the expansion of built-up areas and preserving open and permeable spaces.

The nation urban policy has also addressed some issues relating to the morphological factors of a more holistic approach and taking into account climate change and disaster risk reduction. It is also mentioned that the policy going to be very flexible to adapt to changes in the future. Hence incorporating these morphological factors can play a key role in achieving the vision and goals of the newly implemented plan and policies.



(घ) सरोकारवालासँग सहकार्य र समन्वयमा शहरमा आवश्यक शिक्षा, स्वास्थ्य, खेलकुद, सांस्कृतिक, पर्यटकीय र मनोरञ्जनात्मक पूर्वाधारहरू विकास गरिनेछ।

(ङ) शहरी क्षेत्रमा हाटबजार, बसपार्क, व्यवसाय शुरूवाती स्थल (Start-up Business Space), प्रशोधन केन्द्र, विशेष आर्थिक क्षेत्र, औद्योगिक क्षेत्र लगायतका दिगो आर्थिक आय आर्जन गर्ने खालका पूर्वाधार विकासमा समन्वय र सहकार्य गरिनेछ।

११.२.३. विपद् जोखिम न्यूनीकरण र जलवायु अनुकूलनको आन्तरिकरणलाई प्राथमिकता दिई दिगो र पर्यावरण मैत्री पूर्वाधारको विकास गर्ने

(क) शहरमा विपद् जोखिम न्यूनीकरणका लागि पूर्वसूचना र पूर्वतयारीका सेवा र पूर्वाधारको व्यवस्था गरिनेछ। बहुविपद् जोखिमको अवस्था आँकलन गरी भूउपयोग र भौतिक विकास नियमन एवम् जोखिमपूर्ण वस्तीहरूको स्थानान्तरण गरिनेछ।

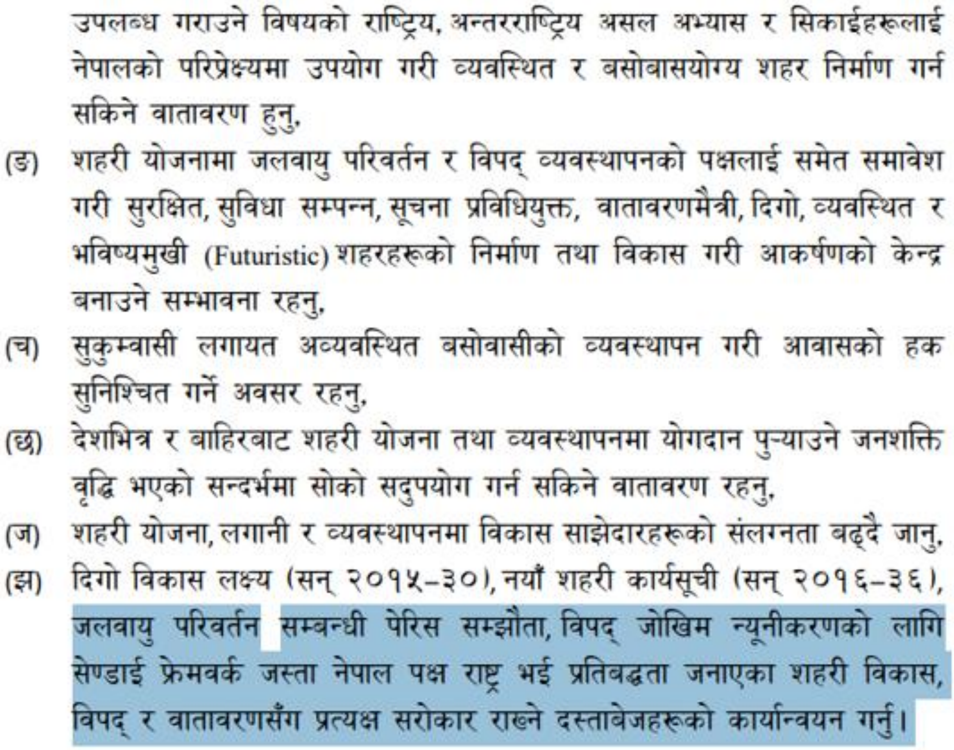
(ख) शहरी वन तथा कृषिलाई योजनामा आबद्ध गरी तह अनुसार आवश्यक खुल्ला क्षेत्र (चौतारा, पोखरी, उद्यान, चोक, खेलमैदान, टुँडिखेल, आदि) र हरियाली क्षेत्रको विकास गरिनेछ।

(ग) शहरी जल सुरक्षा (Urban Water Security) का लागि परिवार, समुदाय, नगरस्तर र क्षेत्रीयस्तरमा भूमिगत जल संरक्षण एवम् पुनर्भरण (Recharge) गरिनेछ। जमिनको प्राकृतिक बनोट र पानीको प्राकृतिक बहावलाई अवरोध नहुने गरी जलप्रणालीको संरक्षण तथा प्रवर्द्धन गरिनेछ।

(घ) फोहरमैलाको उत्पादन घटाउने, पुन: प्रयोग गर्ने र स्रोतमा वर्गीकरण गरी चक्रीय प्रयोगबाट फोहरमैलाको वैज्ञानिक व्यवस्थापन गर्न प्राविधिक सहयोग र आवश्यक पूर्वाधार निर्माण गरिनेछ।

(ङ) शहरमा फैलन सक्ने महामारी नियन्त्रणका लागि आवश्यक पर्ने संरचना र सुविधाहरूको योजना तथा मापदण्ड बनाई कार्यान्वयन गरिनेछ।

Figure 28 National Urban policy , 2081



उपलब्ध गराउने विषयको राष्ट्रिय, अन्तरराष्ट्रिय असल अभ्यास र सिकाईहरूलाई नेपालको परिप्रेक्ष्यमा उपयोग गरी व्यवस्थित र बसोबासयोग्य शहर निर्माण गर्न सकिने वातावरण हुनु,

(ङ) शहरी योजनामा जलवायु परिवर्तन र विपद् व्यवस्थापनको पक्षलाई समेत समावेश गरी सुरक्षित, सुविधा सम्पन्न, सूचना प्रविधियुक्त, वातावरणमैत्री, दिगो, व्यवस्थित र भविष्यमुखी (Futuristic) शहरहरूको निर्माण तथा विकास गरी आकर्षणको केन्द्र बनाउने सम्भावना रहनु,

(च) सुकुम्वासी लगायत अव्यवस्थित बसोवासीको व्यवस्थापन गरी आवासको हक सुनिश्चित गर्ने अवसर रहनु,

(छ) देशभित्र र बाहिरबाट शहरी योजना तथा व्यवस्थापनमा योगदान पुऱ्याउने जनशक्ति वृद्धि भएको सन्दर्भमा सोको सदुपयोग गर्न सकिने वातावरण रहनु,

(ज) शहरी योजना, लगानी र व्यवस्थापनमा विकास साझेदारहरूको संलग्नता बढ्दै जानु,

(झ) दिगो विकास लक्ष्य (सन् २०१५–३०), नयाँ शहरी कार्यसूची (सन् २०१६–३६), जलवायु परिवर्तन सम्बन्धी पेरिस सम्झौता, विपद् जोखिम न्यूनीकरणको लागि सेण्डाई फ्रेमवर्क जस्ता नेपाल पक्ष राष्ट्र भई प्रतिबद्धता जनाएका शहरी विकास, विपद् र वातावरणसँग प्रत्यक्ष सरोकार राख्ने दस्तावेजहरूको कार्यान्वयन गर्नु।

Figure 29 Sendai Framework

- Catchment-Specific Planning Guidelines

Promote **catchment-based urban planning** by linking urban development strategies with localized flood sensitivity and drainage capacity.

Make it mandatory for large-scale developments to submit **catchment impact assessments** (similar to EIA), focusing on runoff behavior and surface permeability.

The current Bye laws takes into account FAR, Building height and setbacks The current Bye laws takes into account FAR, Building height and setbacks with very less correlation to land use planning, density of buildings and roads and its impact on the overall ecosystem.

For future research, We can **statistically correlate MBV and Q** using regression a more complex multivariable model, given we have the building volume data of the catchment area,

$Q = A * MBV + B * \text{Built Density} + C * \text{Rainfall} + D$

For example,

In areas with >40% slope or within 500m of Dhobi Khola riverbank:

- *Maximum building height: 12m*
- *Minimum permeable surface: 30% of plot*
- *Rainwater harvesting system mandatory*

- Green Infrastructure and ecological corridors :

Integrate **green roofs, bioswales, rain gardens, and permeable pavements** into the building code as incentivized options for flood mitigation.

Mandate **permeable surface ratio** within plot-level development, especially in flood-prone zones.

Prioritize **urban green corridors** and **riparian buffers** in master plans to support infiltration and water retention.

Figure 30 Temporary Flood walls

Figure 31 Natural Embankments

Figure 32 Grass Crete

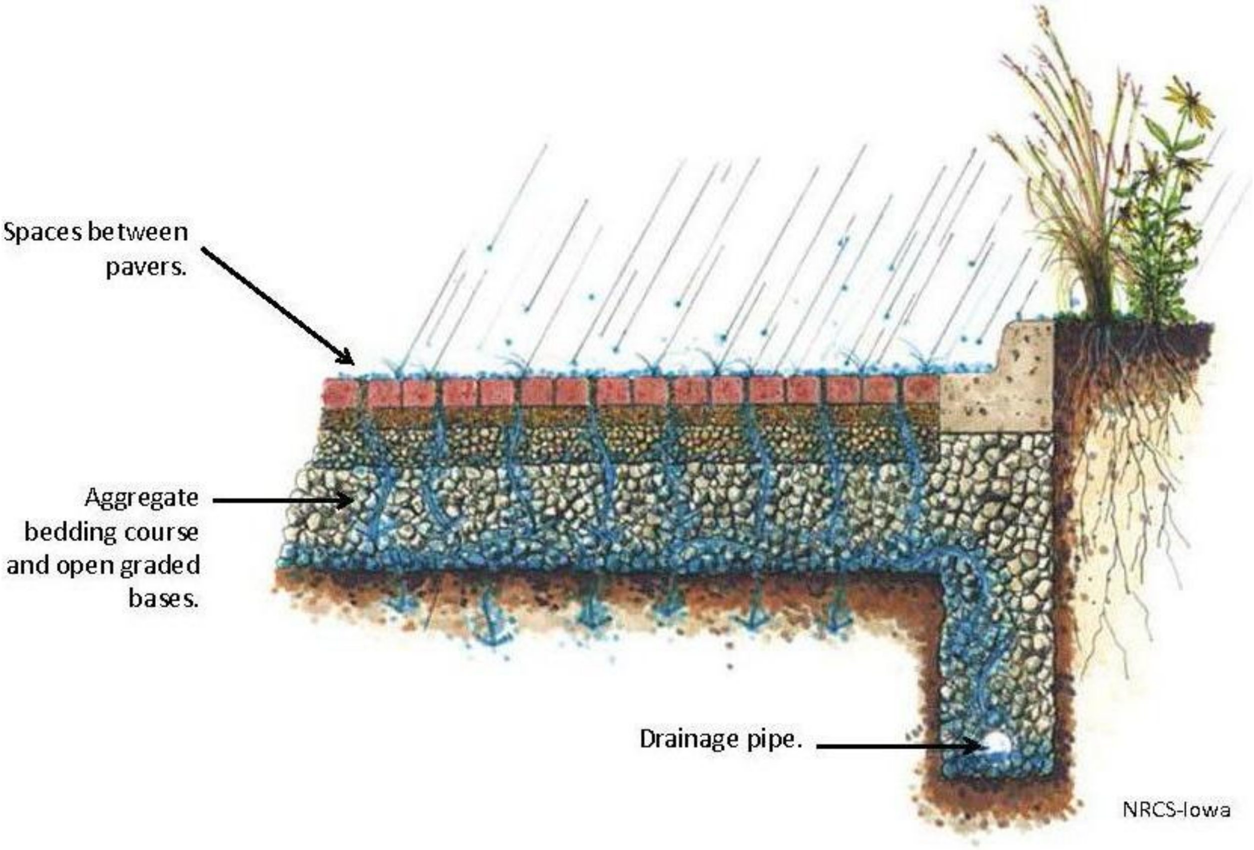


Figure 33 Sectional detail of Permeable surface

Figure 34 Pervious pipes

- Implementation of Separate Stormwater and Sewerage Systems

Implement dual drainage systems in new developments to prevent overflow and reduce flood risk. Retrofit high-risk areas with green infrastructure like soak pits and bioswales. Update building codes and raise public awareness to support implementation despite challenges like cost and poor infrastructure mapping.

- Rainwater Harvesting (RWH) Policy Enforcement

Make **rainwater harvesting systems mandatory** for new buildings (e.g., >100 sqm plot area), especially in high-density zones.

Provide **incentives/subsidies** for retrofitting RWH in existing buildings through tax rebates or utility bill discounts.

Encourage community-level RWH in public infrastructure like schools, parks, and hospitals.

- Addressing Implementation Challenges in Nepal

Institutional coordination between municipalities, DUDBC, and DWIDP is crucial to align urban policies with water and disaster management strategies.

Limited technical capacity and budget at the local level can be mitigated through capacity-building programs and partnerships with academic institutions and NGOs.

Monitoring and enforcement are often weak—introduce a digital building permit system tied to compliance with hydrological and green infrastructure codes.

Co-coordinating with Federal, Provincial and Local level authorities needs to be addressed.

- Public Awareness and Cultural Perceptions

There is often a **preconception in Nepal** that "bigger and more concrete" buildings symbolize progress, while green infrastructure is seen as non-essential or aesthetic.

Address this mindset through **public education campaigns**, community workshops, and demonstration projects that showcase the **benefits of green infrastructure**, not just for floods, but for cooling, air quality, and water conservation.

Engage **local communities** in planning and maintaining green infrastructure to foster a sense of ownership and long-term sustainability.

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Annex

THIESSEN POLYGON :

Precipitation for Kathmandu valley at 2002 event 23/7/2002:

$P_t = 0.11*151+0.07*177+0.09*159+0.14*165+0.21*249+0.07*135+0.15*280+153*0.07+0.08*161=$ **193.92mm**

Precipitation for Kathmandu valley at 2024 event 27/9/2024:

$P_t = 0.11*177+0.07*239+0.09*246+0.14*162+0.21*297+0.07*293+0.15*364+156*0.07+0.08*291=$ **231.74mm**

Precipitation for Kathmandu valley for 2014:

$P_t = 0.11*120+0.07*70+0.09*100+0.14*52+0.21*64+0.07*55+0.15*75+0.07*108+0.08*61=$ **75.36mm**

Precipitation for Dhobikhola at 2002 event 23/7/2002:

$P_t = 159*0.64+177*0.17+151*0.20=162$mm

Precipitation for Dhobikhola at 2024 event 27/9/2024:

$P_t = 246*0.64+239*0.17+177*0.19=231.7$mm

Precipitation for Dhobikhola Outside ringroad at 2002 event 23/7/2002:

$P_t = 159*0.81+177*0.06+151*0.12=157$mm

Precipitation for Dhobikhola Outside ringroad at 2024 event 27/9/2024:

$P_t = 246*0.81+239*0.06+177*0.13=236.61$mm

DISCHARGE CALCULATION :

For 2002 at point A,

From flow rate equation,

$Q = C*I*A = (0.217+0.087+0.058)*A*I = 0.3625*32.5*162*1000/24*3600 =$ **21.91 m^3/sec**

From Catchment area method,

$813/Q_2 = (634*193)/(32.25*162) =$ **34.91 m^3/sec**

For 2002 at point B,

From flow rate equation,

$Q = C*I*A = (0.7*0.15+0.3*0.37+0.15*0.47)*A*I = 0.286*24.98*157*1000/24*3600 = 13.05\ m^3$/sec

From Catchment area method,

$813/Q_2 = (634*193)/(24.93*157) =$ **26.91 m^3/sec**

For 2014 at point A,

From flow rate equation,

$Q = C*I*A = (0.7*0.4+0.3*0.3+0.15*0.29)*A*I = 0.413*32.5*83*1000/24*3600 =$ **12.79 m^3/sec**

From Catchment area method,

$125/Q_2 = (634*75)/(32.25*83) = 7.03$ **m^3/sec**

For 2014 at point B,

From flow rate equation,

$Q = C*I*A = (0.7*0.25+0.3*0.37+0.15*0.38)*A*I = 0.343*24.98*74*1000/24*3600 =$ **7.3 m3/sec**

From Catchment area method,

$125/Q_2 = (634*75)/(24.93*74) = 4.85$ **m^3/sec**

For 2024 at point A,

From flow rate equation,

Q = C*I*A = (0.7*0.51+0.3*0.19+0.15*0.29)*A*I = 0.457*32.5*233*1000/24*3600 = **39 m^3/sec**

For 2024 at point B,

From flow rate equation,

Q = C*I*A = (0.7*0.38+0.3*0.24+0.15*0.38)*A*I = 0.395*24.98*242*1000/24*3600 = **27 m3/sec**

For 2050 at point A,

From flow rate equation,

Q = C*I*A = (0.7*0.7+0.3*0.25+0.15*0.05)*A*I = 0.5675*32.5*250*1000/24*3600 = **54m^3/sec**

For 2050 at point B,

From flow rate equation,

Q = C*I*A = (0.7*0.7+0.3*0.25+0.15*0.05)*A*I = 0.5675*24.98*250*1000/24*3600 = **41m3/sec**

Mean building volume outside ringroad,

Assuming, 15% commercial zone with 4.5 FAR, 25% dense mixed residential zone with FAR 4 and 60% residential subzone with far 3.5 and floor height of m

MBV = (0.15*2.47*7*3+0.25*2.47*5*3+0.6*2.47*3*3)*10^6/ 23,087 = (30.38*10^6) / 23,087 = 1315.89 m^3

MBV / m^2 = 30.38/ 24.93 = 1.21

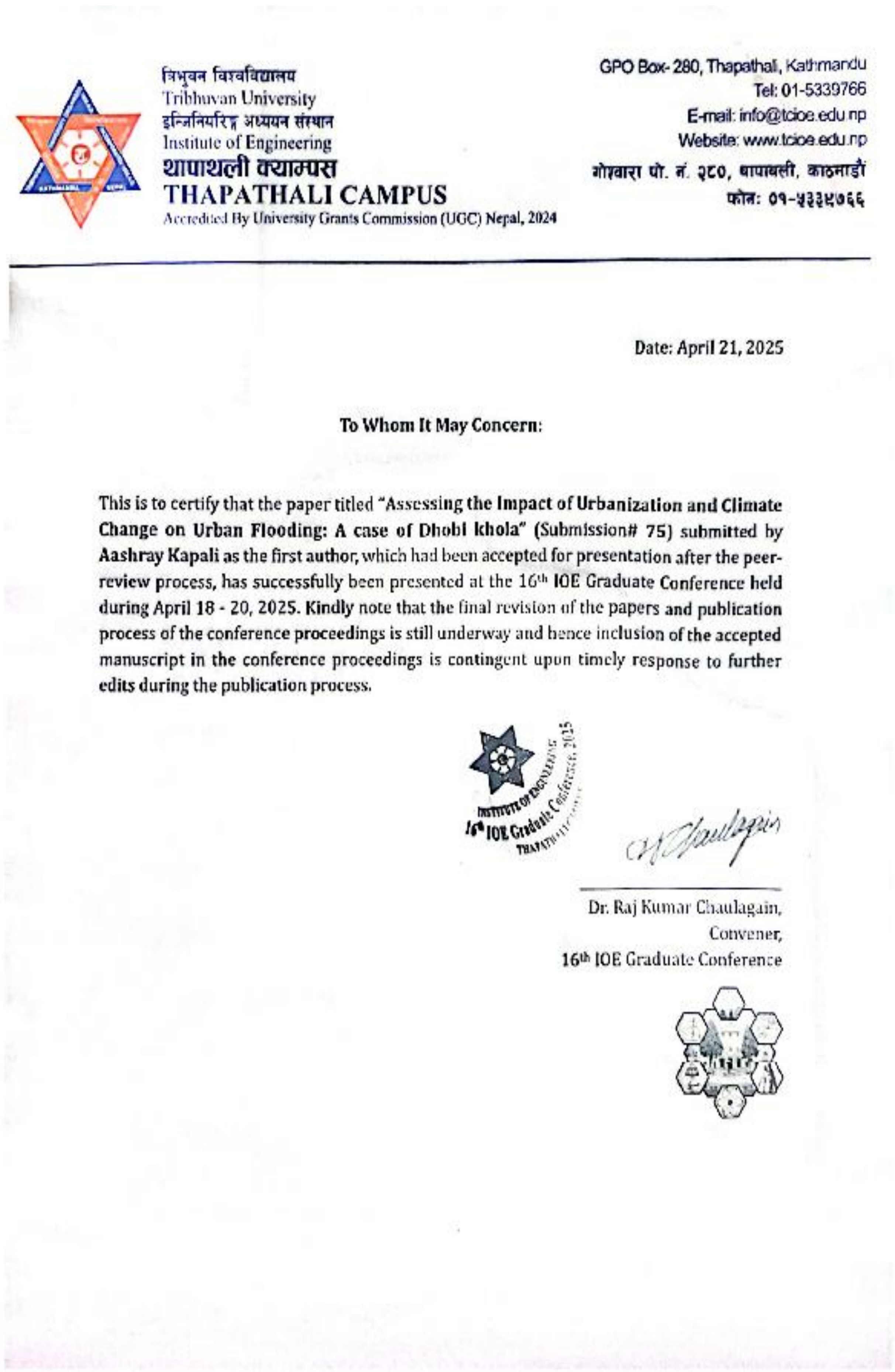
Mean building volume inside ringroad,

MBV = (0.15*2.32*7*3+0.25*2.32*5*3+0.6*2.32*3*3)*10^6/ 21,091 = (28.53*10^6) / 21,091 = 1352.99 m^3

MBV / m^2 = 28.53/ 8 = 3.5

Jury	Comments	How addressed	Page.No
Kishore kumar Jha	• No. of variables in the study variables in study • Why do we need mean building volume and not just building volume is enough?	• After literature review, peak discharge is correlated mainly to imperviousness of catchment, built density and climate change. These are key variables for this study. Total building volume only tells you how much has been built — it doesn't tell you how it's distributed. Mean building volume gives insight into the type of development: • Low mean volume = many small buildings (e.g., sprawled settlements, slums, low-rise areas) • High mean volume = fewer, larger or taller buildings (e.g., compact, vertical development) This distinction is crucial, because sprawled areas tend to have more impervious surface, while vertical growth can preserve open spaces.	30 48
Navaraj pyakurel	• Need for research not very clear • What aspects of climate change does research address. In recommendations	• Existing vision for development does not address morphological factors in context to flooding. Addressing morphological variables while planning can improve many aspects of urban development. • Peak rainfall for calculation of peak discharge during extreme events. Recommendations; • The grid based approach used for building density and road density analysis can be combined with the	12 39 63

Jury	Comments	How addressed	Page.No
	- How to green existing infrastructure a challenge. - Connect with existing bye laws and zoning. - Kathmandu soil has good infiltration capacity. Study current project for rain water harvesting and ground water recharge. - Challenge dry season too much water monsoon flooding. Currently dam under construction in upstream. Review ongoing projects and plans for dhohbikhola. - How can findings of this research be connected to the bye laws	existing land use plan and future development can address building density and volume with a detailed catchment specific research to reduce flooding impacts. - The current river set back policy and research from the bagmati action plan can be integrated with the research with morphological study for a more realistic and sustainable outcome. - Encouraging rainwater harvesting, and using permeable materials will significantly lessen peak discharge during extreme events. Also the dhobi khola catchment in the upstream areas has potential areas for new urban development. Hence having separate storm water drainage and sewerage system can be encourage for newer development. Plus high density developments and minimizing built areas to restore the ecological balance of the basin with make future development. - Current land use planning does not address the building density of the urban areas but just the height restrictions setbacks. Should focus more on zoning and land use typology addressing flooding and other factors.	64 68



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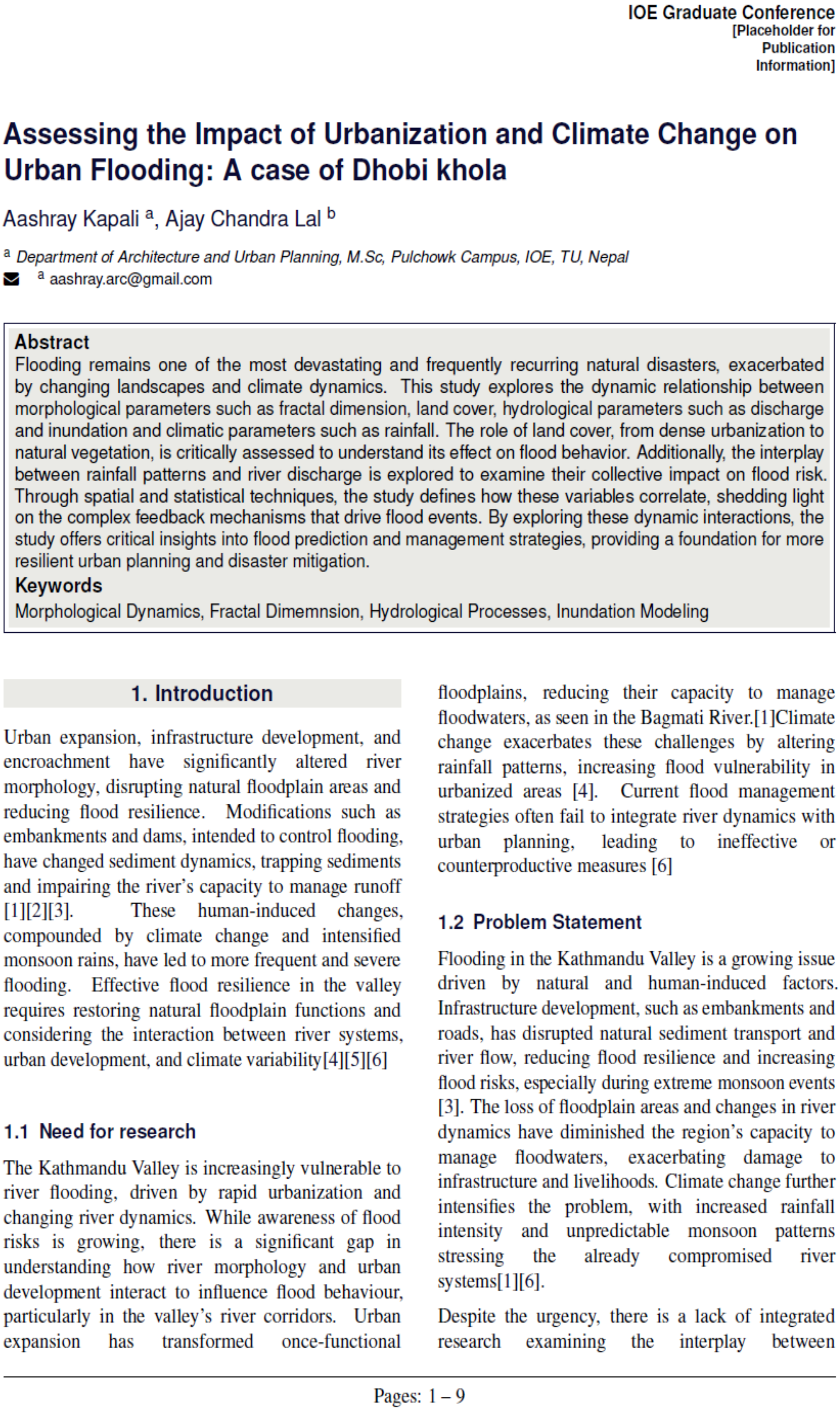
Date: April 21, 2025

To Whom It May Concern:

This is to certify that the paper titled "Assessing **the Impact of Urbanization and Climate Change on Urban Flooding: A case of Dhobi khola"** (Submission# 75) submitted by **Aashray Kapali** as the first author, which had been accepted for presentation after the peer-review process, has successfully been presented at the 16th **IOE Graduate Conference held during April 18 - 20, 2025.** Kindly note that the final revision of the papers and publication process of the conference proceedings is still underway and hence inclusion of the accepted manuscript in the conference proceedings is contingent upon timely response to further edits during the publication process.

Dr. Raj Kumar Chaulagain,
Convener,
16th IOE Graduate Conference



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Assessing the Impact of Urbanization and Climate Change on Urban Flooding: A case of Dhobi khola

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Abstract

Flooding remains one of the most devastating and frequently recurring natural disasters, exacerbated by changing landscapes and climate dynamics. This study explores the dynamic relationship between morphological parameters such as fractal dimension, land cover, hydrological parameters such as discharge and inundation and climatic parameters such as rainfall. The role of land cover, from dense urbanization to natural vegetation, is critically assessed to understand its effect on flood behavior. Additionally, the interplay between rainfall patterns and river discharge is explored to examine their collective impact on flood risk. Through spatial and statistical techniques, the study defines how these variables correlate, shedding light on the complex feedback mechanisms that drive flood events. By exploring these dynamic interactions, the study offers critical insights into flood prediction and management strategies, providing a foundation for more resilient urban planning and disaster mitigation.

Keywords

Morphological Dynamics, Fractal Dimemnsion, Hydrological Processes, Inundation Modeling

1. Introduction

Urban expansion, infrastructure development, and encroachment have significantly altered river morphology, disrupting natural floodplain areas and reducing flood resilience. Modifications such as embankments and dams, intended to control flooding, have changed sediment dynamics, trapping sediments and impairing the river's capacity to manage runoff [1][2][3]. These human-induced changes, compounded by climate change and intensified monsoon rains, have led to more frequent and severe flooding. Effective flood resilience in the valley requires restoring natural floodplain functions and considering the interaction between river systems, urban development, and climate variability[4][5][6]

1.1 Need for research

The Kathmandu Valley is increasingly vulnerable to river flooding, driven by rapid urbanization and changing river dynamics. While awareness of flood risks is growing, there is a significant gap in understanding how river morphology and urban development interact to influence flood behaviour, particularly in the valley's river corridors. Urban expansion has transformed once-functional floodplains, reducing their capacity to manage floodwaters, as seen in the Bagmati River.[1]Climate change exacerbates these challenges by altering rainfall patterns, increasing flood vulnerability in urbanized areas [4]. Current flood management strategies often fail to integrate river dynamics with urban planning, leading to ineffective or counterproductive measures [6]

1.2 Problem Statement

Flooding in the Kathmandu Valley is a growing issue driven by natural and human-induced factors. Infrastructure development, such as embankments and roads, has disrupted natural sediment transport and river flow, reducing flood resilience and increasing flood risks, especially during extreme monsoon events [3]. The loss of floodplain areas and changes in river dynamics have diminished the region's capacity to manage floodwaters, exacerbating damage to infrastructure and livelihoods. Climate change further intensifies the problem, with increased rainfall intensity and unpredictable monsoon patterns stressing the already compromised river systems[1][6].

Despite the urgency, there is a lack of integrated research examining the interplay between urbanization, river morphology, sediment dynamics, and climate change in the Kathmandu Valley. Existing studies often focus on isolated aspects, leaving a gap in understanding how these factors collectively impact flood risk. Dhobi khola, a tributary of bagmati river has experienced significant morphological changes due to urban encroachment and infrastructure development along its banks [1]. The river's capacity to dissipate floodwaters has been compromised, contributing to downstream flooding. However, there is insufficient data on how these changes have impacted the river's overall flood behaviour, particularly in the context of increasing urbanization and climate change.

2. Research Objectives

The primary research question guiding this study is:

- How do changes in a river basin, driven by urbanization and infrastructure development, affect flooding in kathmandu valley ?

- What are the combined effect of climate change and altered river systems on flood patterns ?

3. Literature review

3.1 River Morphology

Rivers shape Earth's surface through erosion and sediment transport, with around 100 x 10^{12} m^3 of precipitation falling annually, two-thirds of which evaporates and the rest flows to the sea. Water forms rills, floods, streams, and rivers, continuously altering landforms. River morphology, a subfield of geomorphology, studies the formation and development of rivers, integrating hydraulic engineering, geology, climatology, and landscape ecology. Understanding river dynamics requires studying channel hydraulics, sediment transport, and geometry from multiple perspectives. Rock hardness influences sediment transport, and rivers are classified by climate and rock type, reflecting changes in climate and landscapes driven by tectonic and climatic forces. [7]

3.1.1 Some problems in river morphology

1. **Human Impact on Rivers**: Since ancient times, humans have altered rivers for water, navigation, power, and irrigation, disturbing the river's stability.

2. **Graded Stream**: A "graded" or "equilibrium" stream, as defined by Mackin (1948), is one where channel dimensions and slope adjust to carry sediment and water without significant erosion or deposition. In the short term, most rivers are in equilibrium, except for unstable rivers like the Koshi, Brahmaputra, and Yellow River.

3. **Disturbances to River Equilibrium**:
   - **Dams**: Reduce sediment transport upstream, causing aggradation in reservoirs and degradation downstream, potentially leading to channel widening.
   - **Navigation**: Modifications for navigation (dams, dredging, channel straightening) disturb river stability.
   - **Irrigation Works**: Barrages and sediment excluders change sediment flow, leading to downstream aggradation.
   - **Mining**: Sand and gravel extraction causes degradation downstream, affecting the river and its tributaries.
   - **Water Transfers**: Large-scale water transfers can disrupt the balance between water and sediment loads.
   - **Flood Control Works**: Embankments and other structures can disturb river equilibrium.
   - **Dredging**: Sediment balance is disrupted, affecting river stability.
   - **Land Use Changes**: Deforestation, urbanization, and construction increase runoff and sediment load, triggering changes in river characteristics.

4. **Urbanization**: Leads to increased runoff, sedimentation, pollution, and encroachment on flood plains, raising flood levels and affecting river stability.

5. **Climate and Hydrologic Changes**: Long-term climate shifts can alter discharge, sediment type, and river morphology, potentially causing rivers to change course or cease to exist.

6. **Tectonic Activity**: Earthquakes and tectonic movements (e.g., subsidence or uplift) can

significantly impact river stability. For example, the 1950 Brahmaputra earthquake caused massive landslides, blocked rivers, and changed river courses.

These factors disrupt the natural equilibrium of rivers and require careful consideration in river management and engineering projects. [8]

3.1.2 General Ranges of n Values

Smooth (e.g., concrete, asphalt): 0.010–0.015 Grasslands (short): 0.030–0.035 Vegetated or forested (dense): 0.040–0.060 Rough, boulder channels: 0.040–0.080 Wetlands or dense, tall vegetation: 0.50–0.75

In summary, Manning's n value helps quantify the influence of surface roughness on water flow, with higher values indicating more resistance and slower flow, and lower values corresponding to smoother, faster flows. It is essential for flood modeling, drainage design, and hydrologic studies. [9]

Flow rate equation

The equation often used in hydrology and hydraulics:

Q=C×I×A where,

- Q = Discharge (flow rate), usually in cubic meters per second (m³/s) or cubic feet per second
- C = Runoff coefficient (dimensionless)
- I = Rainfall intensity, typically in millimeters per hour (mm/h)
- A = Area of the watershed or catchment

Runoff coefficient (C): This coefficient varies depending on the land use or cover of the area. For example: **Urban areas** might have higher C values (e.g., 0.7 to 0.9) due to impervious surfaces like roads and buildings. **Forested areas** might have lower C values (e.g., 0.1 to 0.3) since more rainfall infiltrates the ground.

3.2 Fractals in Urban Analysis

Fractal geometry challenges traditional Euclidean geometry by describing irregular, fragmented, and self-similar patterns found in nature and cities. The concept of fractals, popularized by Benoit Mandelbrot in the 1970s, has been applied to urban studies to explain and model the irregular patterns seen in city layouts, street networks, and land use.

· **Key Characteristics of Fractals**:

Irregular Form: Fractals have broken, non-smooth shapes.

Self-Similarity: Fractals exhibit similar patterns at different scales.

Fractal Dimension: Unlike traditional geometries, fractals have non-integer dimensions (e.g., a street grid may have a fractal dimension between 1 and 2). · **Applications**:

o **Cities as Fractals**: Batty and Longley (1994) applied fractal geometry to study the complexity of cities. They suggested that much of urban form can be understood through fractal patterns, where irregularity and scaling are inherent.

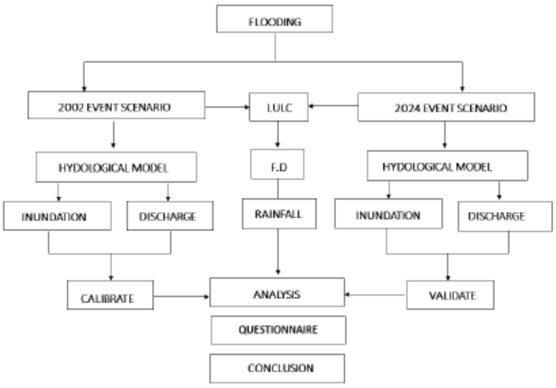
o **Street Networks**: Research by Jon Cooper has applied fractal analysis to study the complexity of street edges and skylines, relating the fractal dimension to the visual variety of urban streetscapes.[10][11]

Fractal Dimension: Fractal dimension is a measure used to describe the complexity or roughness of a fractal or irregular shape. Unlike traditional Euclidean dimensions (1D, 2D, 3D), it quantifies how a shape fills space at different scales. It helps to understand patterns and structures in nature, such as coastlines, mountain ranges, and river networks, where self-similarity and complexity are present at various levels of magnification. The higher the fractal dimension, the more complex the shape.

Box Counting Method: The box counting method is a common technique used to estimate the fractal dimension of a shape. It involves covering the object with a grid of boxes (of a fixed size) and counting how many boxes are needed to cover the shape. The process is repeated with smaller boxes, and a logarithmic relationship between box size and the number of boxes is plotted. The slope of this plot gives the fractal dimension of the object. This method is widely used for irregular objects, such as river networks or coastlines, to quantify their fractal characteristics.[11]

4. Methodology

This research method uses post positivism paradigm with a correlational approach which allows you to test hypotheses and look for causal relationships, but with an understanding that all findings are approximate and subject to revision as new evidence emerges. Both qualitative and quantitative approaches will be followed, for which the quantitative approach was used in the simulation while the qualitative approach will be used in the validation of the results from the simulation in the field.



Year	2002	2014	2024
Point A (at bagmati)	Scenario A	Scenario C	Scenario E
Point B (outside ringroad)	Scenario B	Scenario D	Scenario F

Figure 1: Theoritical framework of research

4.1 Data collection

The literature study was done through research reports, journals. Topographical data that include DEM, survey data, hydro-meteorological data covering daily precipitation and discharge used for this study.

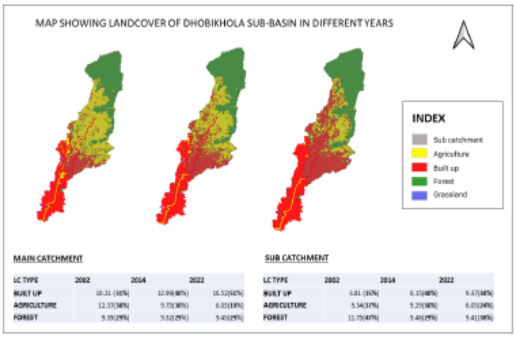


Figure 2: Map showing landover of dhobikhola sub-basin in different years (Source: ICIMOD)

4.2 Watershed Area Ratio Method

In absence of real field discharge data, one of the most common method which is used extensively in several studies for estimating flow in an ungauged catchment is the watershed area ratio method. This method estimates flow for sites where no stream flow are collected by multiplying the measured flow at the nearby stream flow gauging station by the area of ungagued to gaued watersheds.

Qungauged = Qgauged *Aungauged/Agauged where, Q= flow A=watershed area

4.3 Hydraulic modeling

This research aims to examine the impact of **urban cover** on **discharge** (Q) over time at two locations, **A (Dhobikhola at thapathali)** and **B (Dhobikhola at chabahil)**, using the **Hydrologic Engineering Center's River Analysis System (HEC-RAS) 2D version 6.6**. With the increasing urbanization over recent decades, it is crucial to assess how land use changes influence water flow patterns and flood risks in river systems.

The study utilizes high-resolution **ALOS PULSAR 12.5 DEM** data for accurate terrain representation and **ICIMOD land cover data** to model changes in urbanization. The data spans multiple years—2002, 2014, and 2024—allowing for an in-depth analysis of how urban cover has evolved at both locations. Over this period, urban cover has steadily increased, with **Location A** showing an increase from 10.21% in 2002 to 16.52% in 2024, and **Location B** showing a rise from 3.81% in 2002 to 9.37% in 2024. These changes are expected to have significant effects on discharge patterns, water surface elevations, and flood extents.

This research aims to integrate these data sources with HEC-RAS 2D modeling to simulate the impact of land cover changes on river flow and assess potential flood risks for future urban development scenarios.

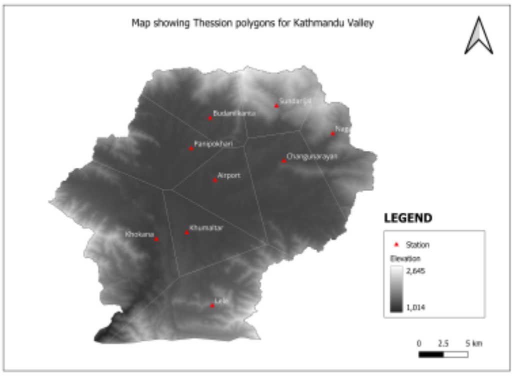
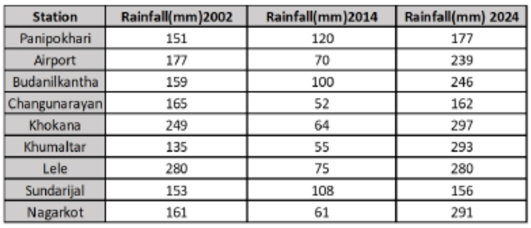


Figure 3: Thessein Polygon for meterological stations in kakthmandu valley



Station	Rainfall(mm)2002	Rainfall(mm)2014	Rainfall(mm) 2024
Panipokhari	151	120	177
Airport	177	70	239
Budanilkantha	159	100	246
Changunarayan	165	52	162
Khokana	249	64	297
Khumaltar	135	55	293
Lele	280	75	280
Sundarijal	153	108	156
Nagarkot	161	61	291

Figure 4: Rainfall of 10 stations in different time period. Source: DHM

The model setup involved creating the geometry, terrain, boundary conditions, and mesh. Precipitation data was input using the Thessen method for distribution across the area, with station data from Sundarijal, Budhanikantha, Sankhu, Kathmandu Airport, Nagarkot, and Lele. Initial simulations were conducted to determine the stage at the Khokana gauge point. The model results were then compared with measured stage and discharge data using a rating curve. Key parameters were adjusted, including the Manning's coefficient, infiltration parameters, boundary conditions, and necessary terrain modifications. The model was validated using remaining future events to ensure accuracy.

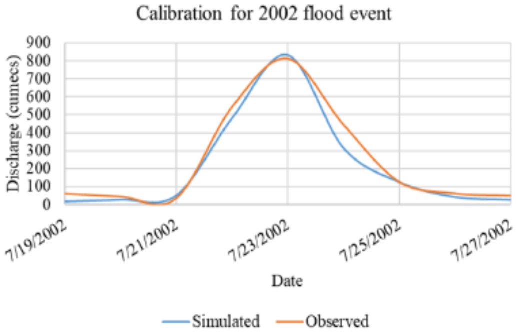


Figure 5: Calibration chart for 2002 event in HEC-RAS 6.6

Fractal Dimension Calculation

Fractal dimension of years 2002, 2014, is calculated

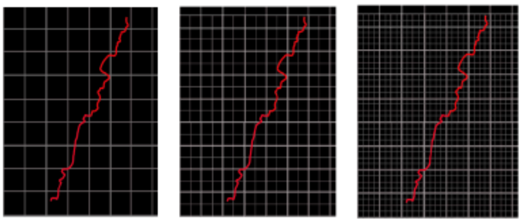
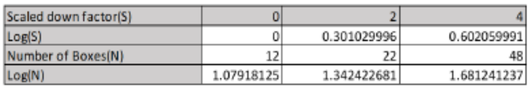


Figure 6: Calculation of fractal dimension of year 2024 using box counting method



Scaled down factor(S)	0	2	4
Log(S)	0	0.301029996	0.602059991
Number of Boxes(N)	12	22	48
Log(N)	1.07918125	1.342422681	1.681241237

Figure 7: Box counting of different scale factor

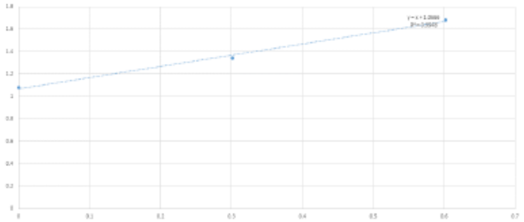


Figure 8: Graph plotting log(S) to log(N) to find fractal dimension

5. Site Context

Why Dhobikhola is Ideal for Study ?

The river basin is characterized by two distinct regions with contrasting urbanization patterns: one area lies inside the Kathmandu Valley's ring road, which has experienced rapid urbanization and infrastructure development, while the other area is outside the ring road, where urbanization is occurring at a slower pace. This provides an excellent opportunity to compare the hydrological responses of different morphological settings within the same river system, allowing for a scenario-based analysis of flood dynamics.

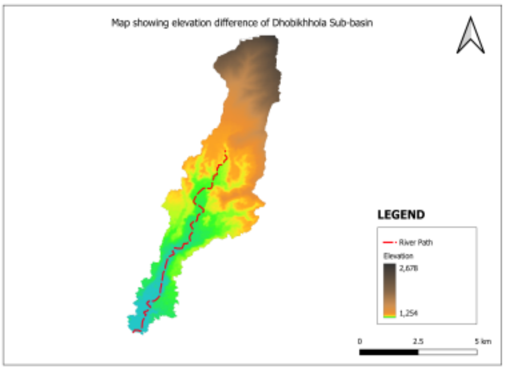


Figure 9: Elevation map of Dhobi Khola sub basin

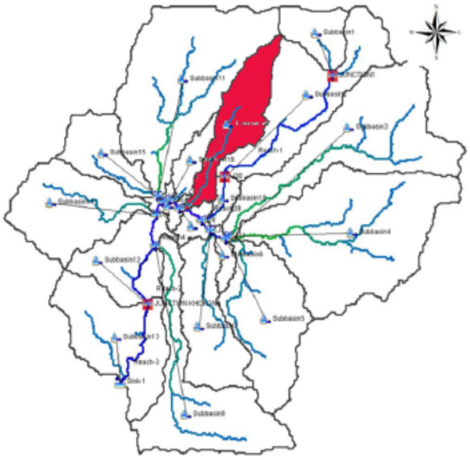
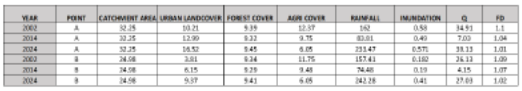


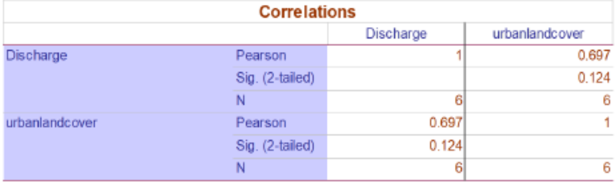
Figure 10: Map showing Dhobi khola Sub basin in ktm valley. Source: BAP Hydrological report Vol - II

6. Findings



YEAR	POINT	CATCHMENT AREA	URBAN LANDCOVER	FOREST COVER	AGRI COVER	RAINFALL	INUNDATION	Q	FD
2002	A	32.25	10.21	9.39	12.37	162	0.58	34.91	1.1
2014	A	32.25	12.99	9.32	9.75	83.01	0.49	7.03	1.04
2024	A	32.25	16.52	9.45	6.05	233.47	0.571	38.13	1.01
2002	B	24.98	3.81	9.34	11.75	157.41	0.182	26.13	1.09
2014	B	24.98	6.15	9.29	9.48	74.48	0.19	4.15	1.07
2024	B	24.98	9.37	9.41	6.05	242.28	0.41	27.03	1.02

Figure 11: Table showing data collected of all 6 scenario

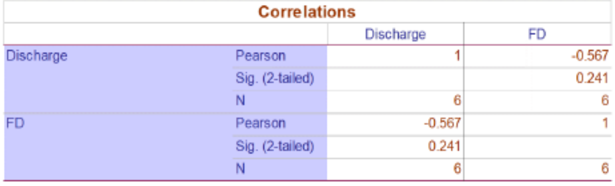


Correlations

		Discharge	urbanlandcover
Discharge	Pearson	1	0.697
	Sig. (2-tailed)		0.124
	N	6	6
urbanlandcover	Pearson	0.697	1
	Sig. (2-tailed)	0.124	
	N	6	6

Figure 12: Discharge VS Urban cover

The correlation coefficient of **0.697** indicates a **moderate positive correlation** between **Discharge (Q)** and **Urban Land Cover**. This means that as urban land cover increases, discharge also tends to increase, albeit moderately. A higher urbanization rate may contribute to increased runoff due to the increase in impervious surfaces like buildings and roads, leading to higher discharge.

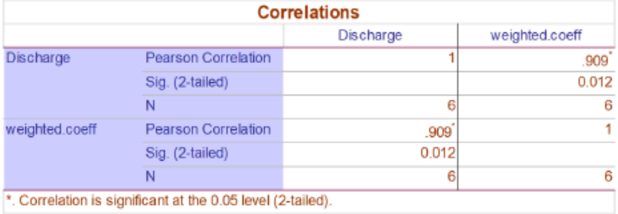


Correlations

		Discharge	FD
Discharge	Pearson	1	-0.567
	Sig. (2-tailed)		0.241
	N	6	6
FD	Pearson	-0.567	1
	Sig. (2-tailed)	0.241	
	N	6	6

Figure 13: Discharge VS FD

The **correlation coefficient** of **-0.567** indicates a **moderate negative correlation** between **Discharge** and **Fractal Dimension (FD)**. This means that as discharge increases, fractal dimension tends to decrease, or vice versa.



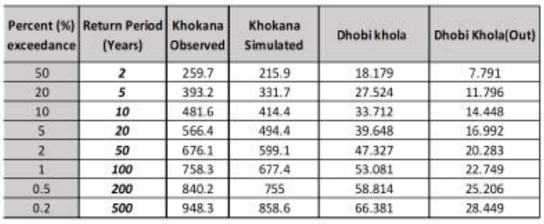
Correlations

		Discharge	weighted.coeff
Discharge	Pearson Correlation	1	.909*
	Sig. (2-tailed)		0.012
	N	6	6
weighted.coeff	Pearson Correlation	.909*	1
	Sig. (2-tailed)	0.012	
	N	6	6

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

Figure 14: Discharge VS Weighted Coefficient

This value indicates a **strong positive correlation** between **Discharge** and **Weighted Coefficient**. In other words, as one variable (Discharge) increases, the other variable (Weighted Coefficient) also tends to increase, and vice versa.



Percent (%) exceedance	Return Period (Years)	Khokana Observed	Khokana Simulated	Dhobi khola	Dhobi Khola(Out)
50	*2*	259.7	215.9	18.179	7.791
20	*5*	393.2	331.7	27.524	11.796
10	*10*	481.6	414.4	33.712	14.448
5	*20*	566.4	494.4	39.648	16.992
2	*50*	676.1	599.1	47.327	20.283
1	*100*	758.3	677.4	53.081	22.749
0.5	*200*	840.2	755	58.814	25.206
0.2	*500*	948.3	858.6	66.381	28.449

Figure 15: Gumbel Distribution of khokona station 550.5

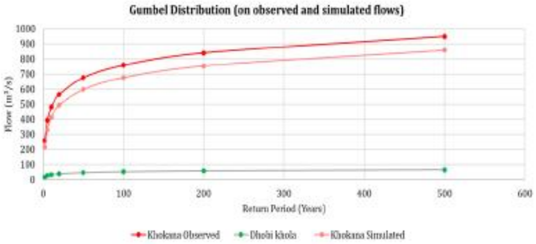
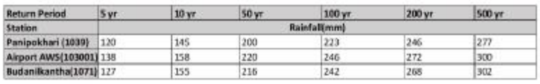


Figure 16: Graph plotting simulated and observed discharge of khokona station 550.5



Return Period	5 yr	10 yr	50 yr	100 yr	200 yr	500 yr
Station				Rainfall(mm)		
Panipokhari (1039)	120	145	200	223	246	277
Airport AWS(103001)	138	158	220	246	272	300
Budanilkantha(1071)	127	155	216	242	268	302

Figure 17: Gumbel desitribution of 3 stations in Dhohbi khola Catchment

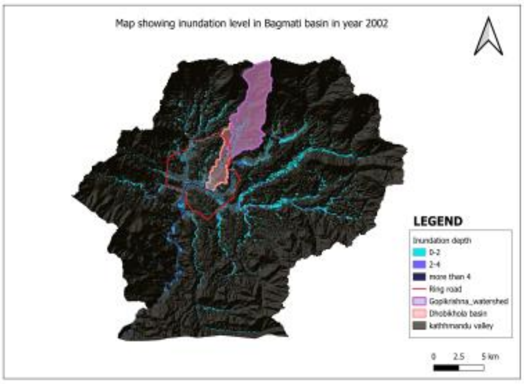


Figure 18: Simulated Innundation map of ktm valley 2002 scenario

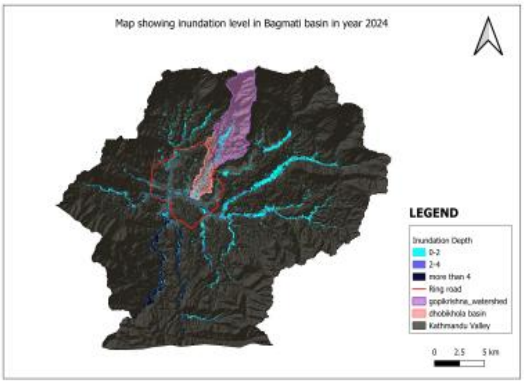


Figure 19: Simulated innundation map of ktm valley 2024 scenario

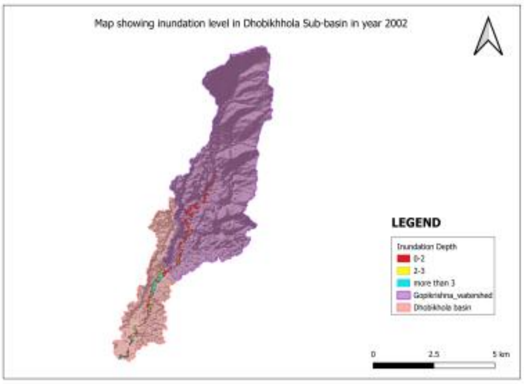


Figure 20: Innundation map of dhobi khola sub basin in 2002

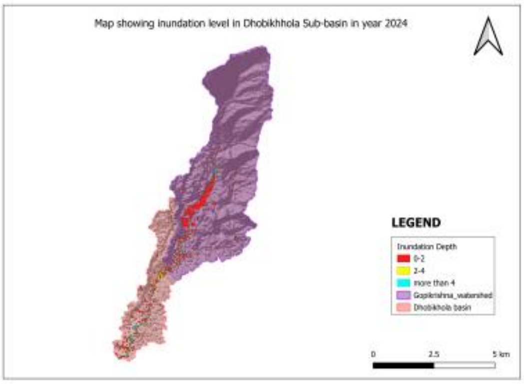


Figure 21: Innundation map of dhobi khola sub basin in 2024

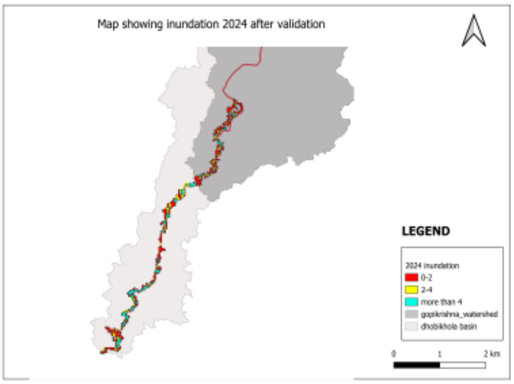


Figure 22: Innundation map of 2024 after validation

Site Inferences

Embankments inside the ring road of Dhobi Khola began construction in 2063, while those outside the ring road started after 2020. River cleaning occurs once every two years to maintain the flow. Inundation has been experienced in certain sections of Dhobi Khola outside the ring road, particularly from the Smile Workshop to the Daffodil School area. The drainage system along the roads is also affected by rising water levels, leading to frequent flooding. Comparisons between the years 2002 and 2024 show increased inundation due to the absence of proper embankments in earlier years. The discharge levels in areas outside the ring road are generally lower, except for the Daffodil area. Additionally, ongoing disputes regarding the 20-meter setback have added to the challenges in managing the river's flow and surrounding land use.

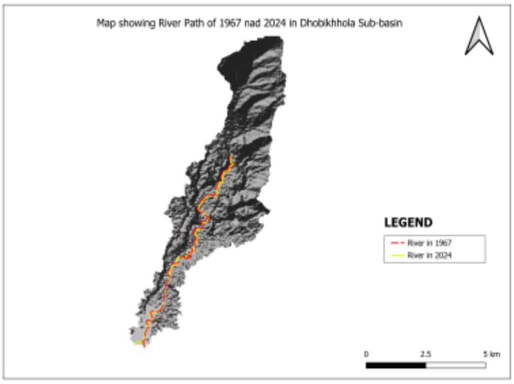
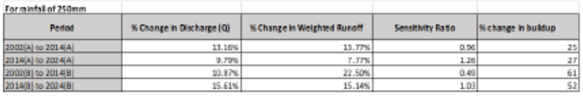


Figure 23: Figure comparing river path from 1967 and 2024



For rainfall of 250mm

Period	% Change in Discharge (Q)	% Change in Weighted Runoff	Sensitivity Ratio	% change in buildup
2002(A) to 2014(A)	13.16%	13.77%	0.96	25
2014(A) to 2024(A)	9.79%	7.77%	1.26	27
2002(B) to 2014(B)	10.97%	22.50%	0.49	61
2014(B) to 2024(B)	15.61%	15.14%	1.03	52

Figure 24: Table for sensitivity analysis keeping rainfall 250mm constant

Discharge Sensitivity to Runoff:

The sensitivity ratio varies across periods, indicating that discharge responds differently to changes in weighted runoff at different times.

From 2002(A) to 2014(A), the sensitivity ratio is relatively low (0.96), suggesting a near-proportional change in discharge to weighted runoff.

The highest sensitivity ratio is observed from 2014(A) to 2024(A) (1.26), indicating that discharge will be more sensitive to changes in runoff in the future.

Conversely, from 2002(B) to 2014(B), the sensitivity ratio is low (0.49), meaning discharge is less responsive to runoff changes in this period.

Impact of Land Use and Other Factors: The periods with higher percentage changes in buildup (61% in 2002(B) to 2014(B), 52% in 2014(B) to 2024(B)) correspond with lower sensitivity ratios, possibly due to changes in land use or catchment management practices.

Buildup and Sensitivity: Periods with significant changes in buildup (25% to 61%) tend to show differing sensitivity ratios, highlighting that other factors, such as land use or infrastructure changes, may be influencing discharge more than just runoff.

· **Temporal Variability:** The varying sensitivity ratios suggest that the relationship between runoff and discharge is not static, with the system becoming more sensitive over time, especially in 2014(A) to 2024(A).

7. Discussion and Conclusion

After validation,it was found that only some part of the section outside ringroad was inundated. During the 2002 flooding higher inundation was observed in downstream as from survey of old residents in the area. the embankment height was just enought for the 2024 event which was more than 100 year return period discharge. Also, the water level reading is higher in upstream at kapan station than at chabahil station which shows that there might have be modifications in cross section which might have caused the inundations in those areas.

Also, after the sensitivity analysis, it is found that the sensitivity of weighted runoff and discharge increases exponentially as the value of weighted runoff coefficient increases.

8. Limitations

· Discharge data of 2024 not published. Staff gauge height only available for validation. Rating curve is also not published for khokona station.

· The area ratio method provides discharge estimates for Dhobikhola which may not represent the actual discharge of the study catchment.

· Due to ongoing disputes of 20m setback validation of 2024 event made challenging.

· Sediment transport has not been studied in this study.

· DEM of different years not available 12.5 x 12.5 m of 2014 was used in the study.

9. Recommendations

From the findings, Based on analysis and literature review, following recommendations are made to the policy makers and concerned authority. The research of Dhobikhola catchment is carried out under major constraints of data availability. For future studies, following recommendations are made:

- Due to unpublished data of discharge measuring gauging station of recent years in the study site, area proportion method was used for discharge calculation which may not represent the true discharge of the study catchment. So, it is recommended that stations data should be processed and published as soon as possible.

- The waterway of Dhobi khola river has been reduced over the years due to many interventions According to Bagmati action plan Supplementary Volume (II) - Hydrological & Flood Modeling Report meters detail width is calculated on both sides of the river in different sections . These type of research findings can help check and upgrade the exisiting setbacks and policies in different sub catchments with pressing flooding issues.

- Further research to with greater number of datasets can be done the increase the significance value of correlation coefficients and derive a mathematical relation between different variables.

Acknowledgments

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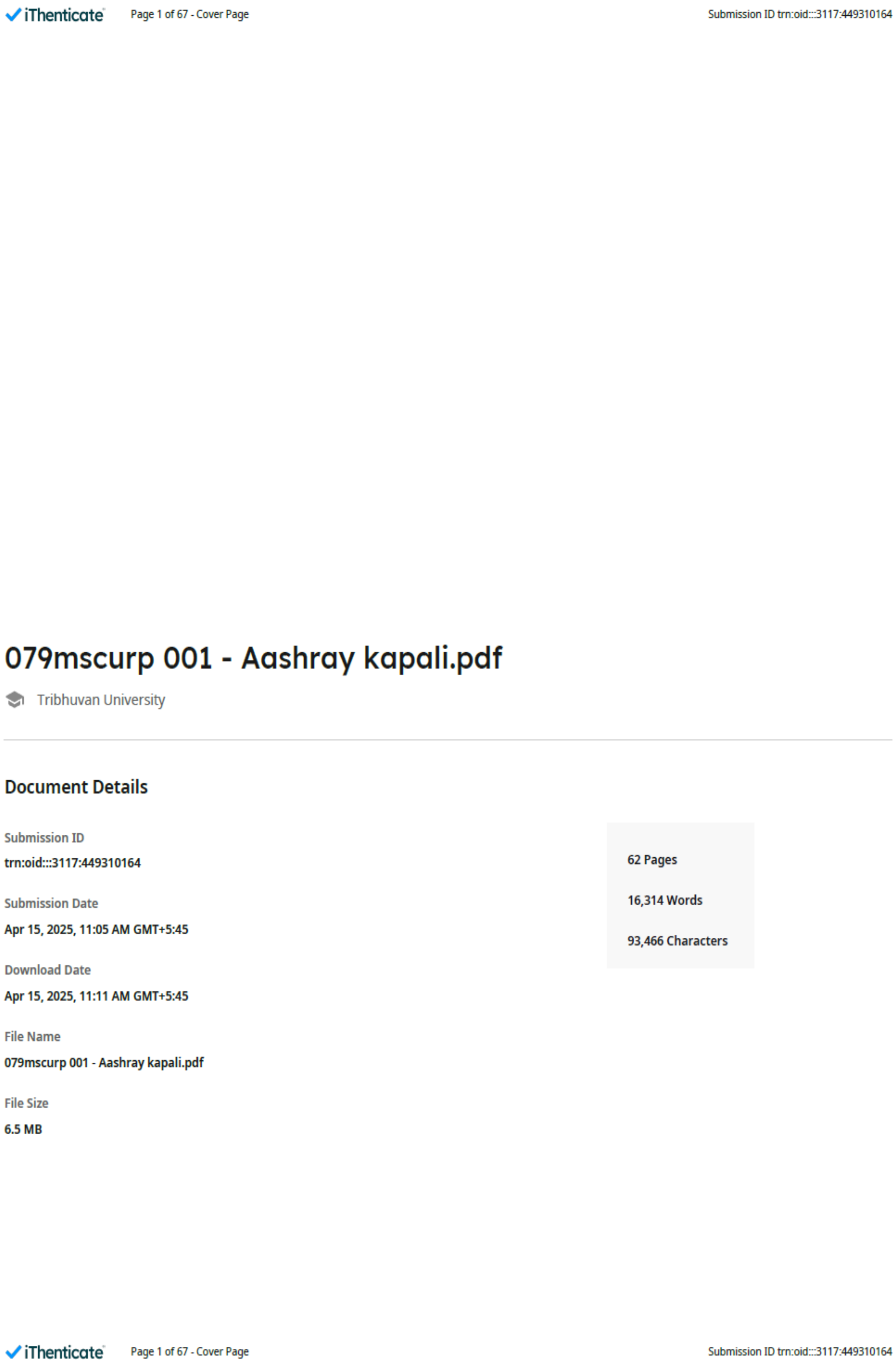

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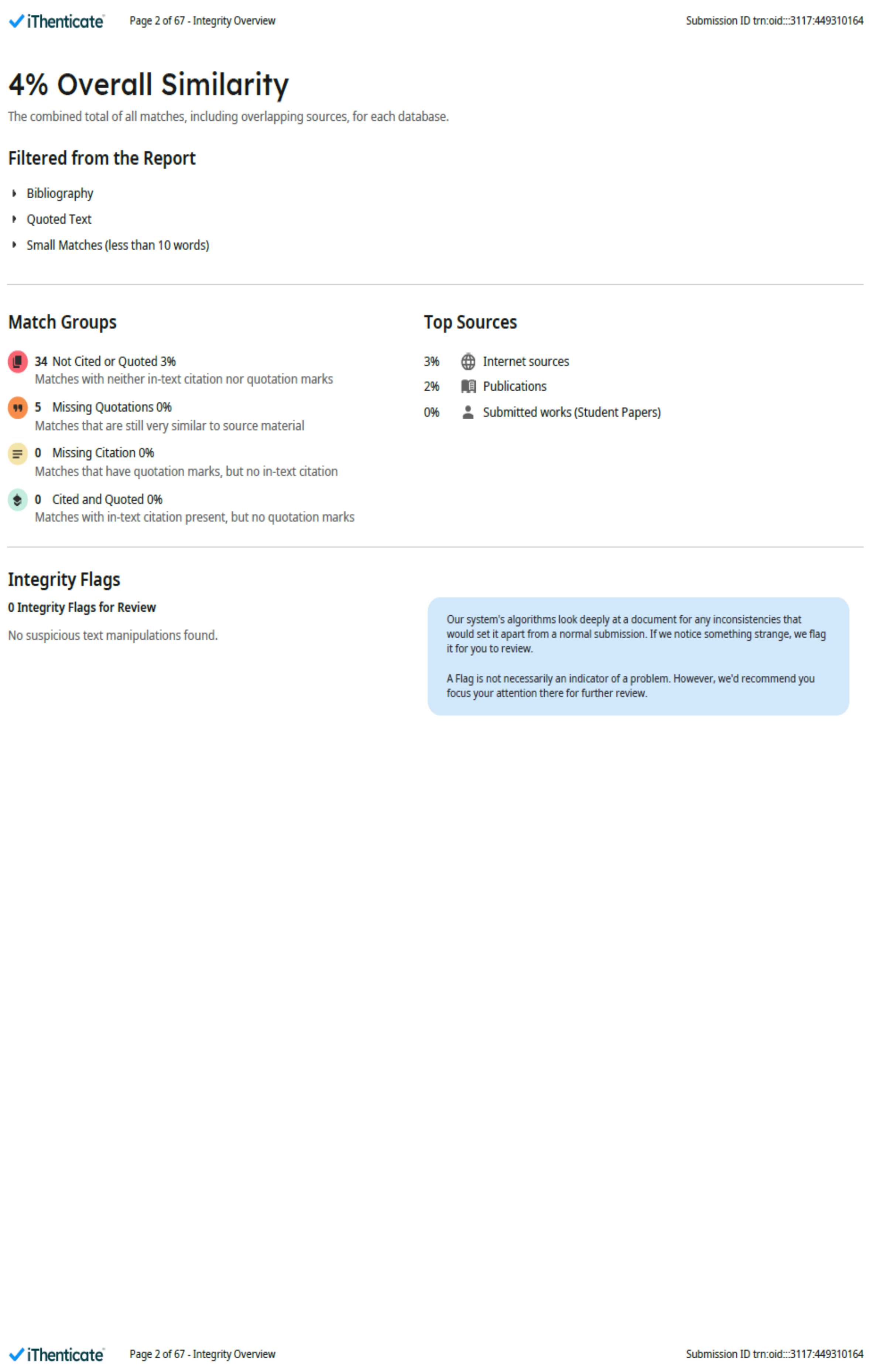

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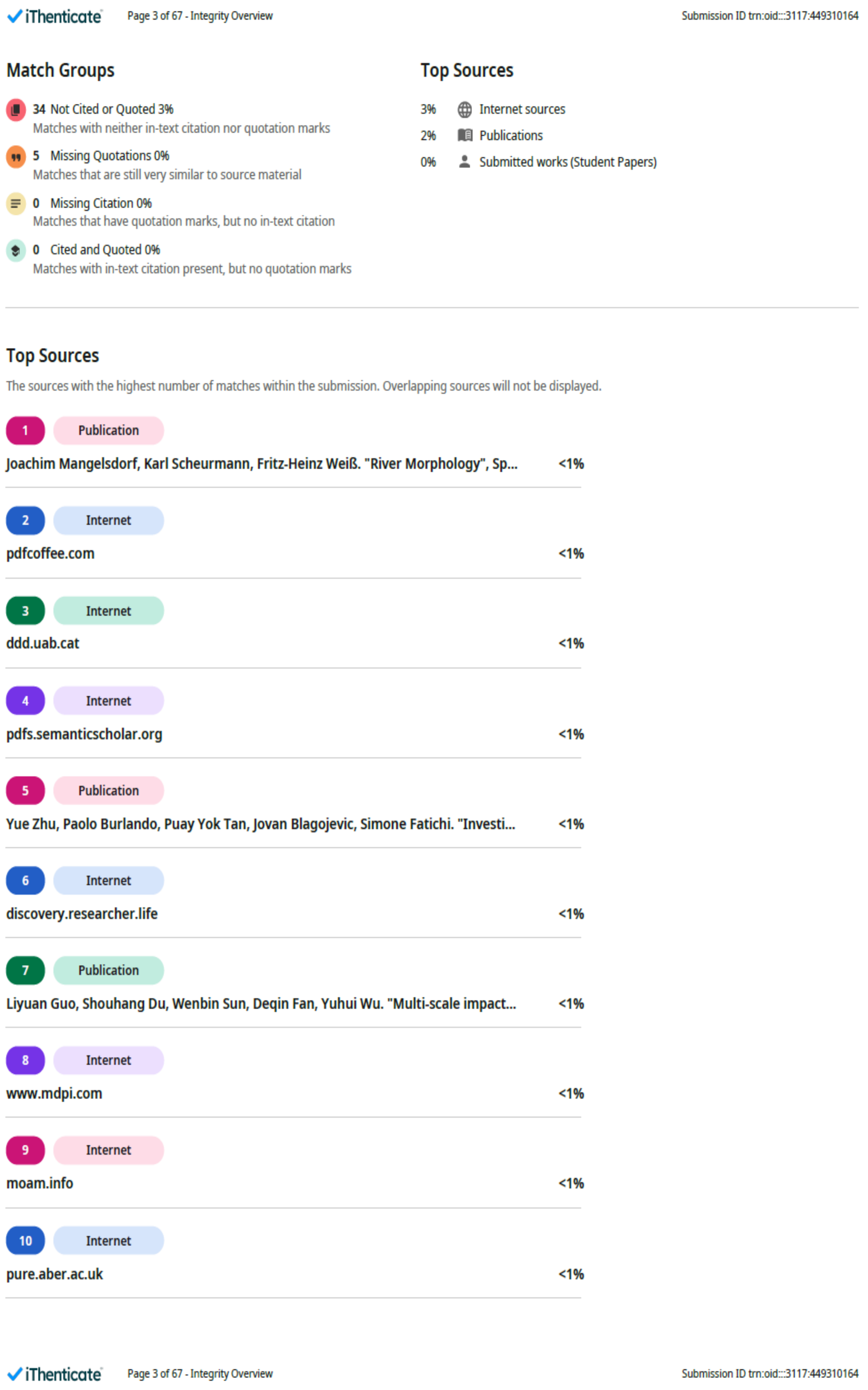

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