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Research Article

Urban Spatial Growth and Geo-Environmental Risk in Pokhara Metropolitan City: A Geospatial Analysis

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Abstract
Urban spatial growth is shaped and directed by geo-environmental and socio-economic factors. Understanding the relationship between geo-environmental risks and urban spatial growth is essential for safe and sustainable urban development. In this context, this study investigates the urban growth in the geo-environmentally fragile area of Pokhara Metropolitan City, Nepal, using Geographic Information System (GIS) and remote sensing tools. Urban spatial growth was determined using aerial photos from 1978, and multisource remote sensing data collected from 1990 to 2020. A geologically fragile zone was traced from the 1998 Geological Map of Pokhara Valley and sinkhole occurrences were documented during field visits. Results indicate that the built-up area has expanded from 1.70 km^2 in 1978 to 8.83 km^2 with a growth rate of 1.87% to 8.74% in 2020. The Ghachok formation indicates a heavy concentration of urban development in this fragile area, increasing hazards like subsidence or sinkholes. This study emphasizes that increased population pressures are causing increased vulnerability in the geo-environmentally fragile Ghachok Formation area which comprises 25,713 built-up structures and over 93,000 populations. The necessity of integrating geo-environmental risk into developmental policies and strategies is emphasized to minimize the consequences on environmental sustainability. This study's results enhance the understanding of the relationship between urban growth and geo-environmental risk areas to help formulate an effective plan of conservation, development, and reduction of hazard risks in vulnerable highly populated zones.

Keywords: *Geo-environmental hazard, geomorphological character, geospatial tools; urban growth, Pokhara.*

Introduction
Urban growth is a complex process that is influenced by various factors such as socioeconomic, geographical, and policy factors (Estoque & Murayama, 2016). The primary drivers of urban growth are demographics and socioeconomic conditions, and factors like income per capita, secondary and tertiary industrial development, and real estate investment, play a key role in this process (Li et al., 2021). On the other hand, topographical, geological, and geomorphological elements influence spatial growth patterns and urban land development. Factors like topography, lithology and soil types, and drainage patterns greatly shape the location and growth of cities (Rimal et al., 2015). While steep slopes and flood-prone areas may restrict urban expansion, flat, fertile terrain often attracts land development. Moreover, geological/geomorphological aspects are vital in determining the availability of resources, development of infrastructure, and land use, particularly for industry and agriculture (Rimal et al., 2018). As cities expand rapidly due to population pressures, development often extends into areas susceptible to natural hazards, and geologically fragile zones (Ghimire & Timalsina, 2020). The relationship between physical geography, geology/geomorphology, and urban growth is of utmost importance for a balance between development and environmental conservation (Fort et al., 2018). In addition, urban land policies at different stages play a crucial role in spatial expansion and urban land development to manage the scale, pace, and direction of urban expansion (Zhou et al., 2022; Zhang & Han, 2024).

The urban geo-environment is concerned with understanding how landforms can limit urban growth, determining the suitability of landforms for urban use, and analyzing the impact of urbanization on both natural and urban morphology (Thornbush, 2015). Understanding the environmental and development consequences of urban spatial growth towards geo-environmentally fragile areas is essential for informed urban planning, and careful land utilization decisions ensuring economic and ecological welfare (Estoque & Murayama, 2016). In many cases, these important considerations are often disregarded resulting in haphazard building construction and urban infrastructure development ignoring susceptibility to geo-environmental hazards, natural disasters, and site suitability. It is hence, emphasized that geomorphological factors must be considered when managing and planning sustainable urban growth (Kanga et al., 2022) particularly geo-environmentally fragile hilly cities Pokhara Valley which is largely formed by gravel deposits from upstream of the Seti River with layers of river terraces (Dixit, 2023). However, though hilly cities present certain geo-environmental challenges, they are valuable due to their natural and cultural significance, as well as their ability to provide space for important economic activities and investments (Kanga et al., 2022).

Several studies have been carried out on the geological and geo-morphological development stages and lithological composition of Pokhara Valley discussing the glacial-fluvial deposits with limited lacustrine

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deposits (Bhandari et al., 2019; Hormann, 1974; Sharma, 1975). However, these studies are confined to the geo-tectonic aspects. On the other hand, a multitude of studies on various aspects of urbanization, and urban expansion in Pokhara (Adhikari, 2000a; Bhattarai & Lal, 2021; Rimal et al., 2015) an integrated and comprehensive analysis of the relationship between geo-environmental risks and urban spatial growth is noticeably absent. To bridge this knowledge gap, this study aims to assess the status of urban growth and expansion in areas prone to geological risks using geospatial techniques, such as remote sensing (RS) and GIS tools. This research focuses on the expansion of urban areas in high-risk zones, particularly in regions like the Pokhara Valley, where fragile geological formations like the Ghachok Formation are prevalent. Urban area in this study refers to the urban municipal area as defined by Local Government Operation Act of 2074 BS (2017) of the Government of Nepal (MoJIPA, 2017). The study employs spatial analysis, field surveys, and spatio-temporal satellite data to assess the geological risk area and provides recommendations to local, regional, and national authorities and organizations to ensure safe and sustainable development.

Materials and Methods

This study utilizes remote sensing (RS) and geographic information systems (GIS) as tools for analyzing the spatial distribution of geological fragile characteristics (Abebe, 2013). Satellite images and aerial photos provide valuable information about the historical background of changing occurrences and urban growth over various time periods (Xu & Gao, 2021). The study utilizes aerial photos from 1978, as well as multisource and multi-temporal satellite images from 1990 to 2020. Additionally, a digital elevation model (DEM), ancillary data, and fieldwork are utilized to supplement the analysis. The focus of the study is to examine the impact of geological and geomorphological conditions on the urban expansion of Pokhara, as well as to conduct a forty-two-year historical study of urban expansion.

Study Area

Pokhara Valley, one of the geo-environmentally fragile regions in the hill region of Nepal is selected as a study area (Fig. 1). Geographically, Pokhara Valley is situated in the midland between the towering Higher Himalayan Annapurna Massif to the north and the Lesser Himalaya to the south (Fort, 2010). One notable feature of this area is its extremely steep slopes, with a rapid elevation gain of over 8,000 meters in just a 20-kilometer stretch from 500 meters north of the city. The Seti River, flowing through a narrow bedrock valley from the Annapurna range, has a significant impact on the city of Pokhara. The upstream catchment region of the Pokhara Valley covers approximately 270 square kilometers and is home to prominent peaks such as Machhapuchhare (6,993m), Annapurna III (7,555m), and Annapurna IV (7,525m) (Stolle et al., 2017).

Before the 1960s, the land in this area was mainly used for pastoral and agricultural purposes. However, with the successful elimination of malaria, the city has undergone rapid urbanization, leading to significant immigration. This urban growth is well-documented in the region's history (Adhikari, 2000b). Pokhara Metropolitan City, situated between 83° 47'- 84° 09' East and 28°04' - 28°20' North, is the largest city in terms of area, covering 464.24 square kilometers. Over the last fifty years, Pokhara city has experienced substantial growth in both population and area. In 1971, it had a population of 20,611 across 18 wards, covering 27.38 km² of the flat terrain of the Pokhara area. By 2021, it expanded into a Metropolitan City with 33 wards, a population of 513,504, and an area of 464.24 km² (CBS, 2012; NSO, 2021) .

Sources of Data

This study used both primary and secondary data sources (Table 1). During the field observation in 2023, expert consultations and informal interviews with various stakeholders were conducted. Additionally, supplementary data were gathered from publicly accessible sources, including the Central Bureau of Statistics (CBS, 2012) and other government agencies, to evaluate population growth and the urban expansion process.

Table 1. List of primary and ancillary data sources

Data Type	Acquisition Year	Resolution	Sources
Landsat TM	1990-April 16	30 m	USGS (https://earthexplorer.usgs.gov/)
Landsat ETM+	2000-March 26	30 m	USGS (https://earthexplorer.usgs.gov/)
Landsat TM	2010-February 18	30 m	USGS (https://earthexplorer.usgs.gov/)
Sentinel -2	2020-Nov-12	15 m	Copernicus Open Access Hub (https://scihub.copernicus.eu/)
SRTM–DEM data		30 m	USGS (https://earthexplorer.usgs.gov/)
Aerial photo	1978	1 m	Survey Department, Nepal
Geological map	1998		Department of Mines and Geology, Nepal
Google earth image	Accessed 2020-12		Google Earth Pro
Population data	1991, 2001, 2011, 2021		CBS, Kathmandu
Local level boundary	2017		Survey Department, Nepal
Field survey & KII	2023		Pokhara Metropolitan City area

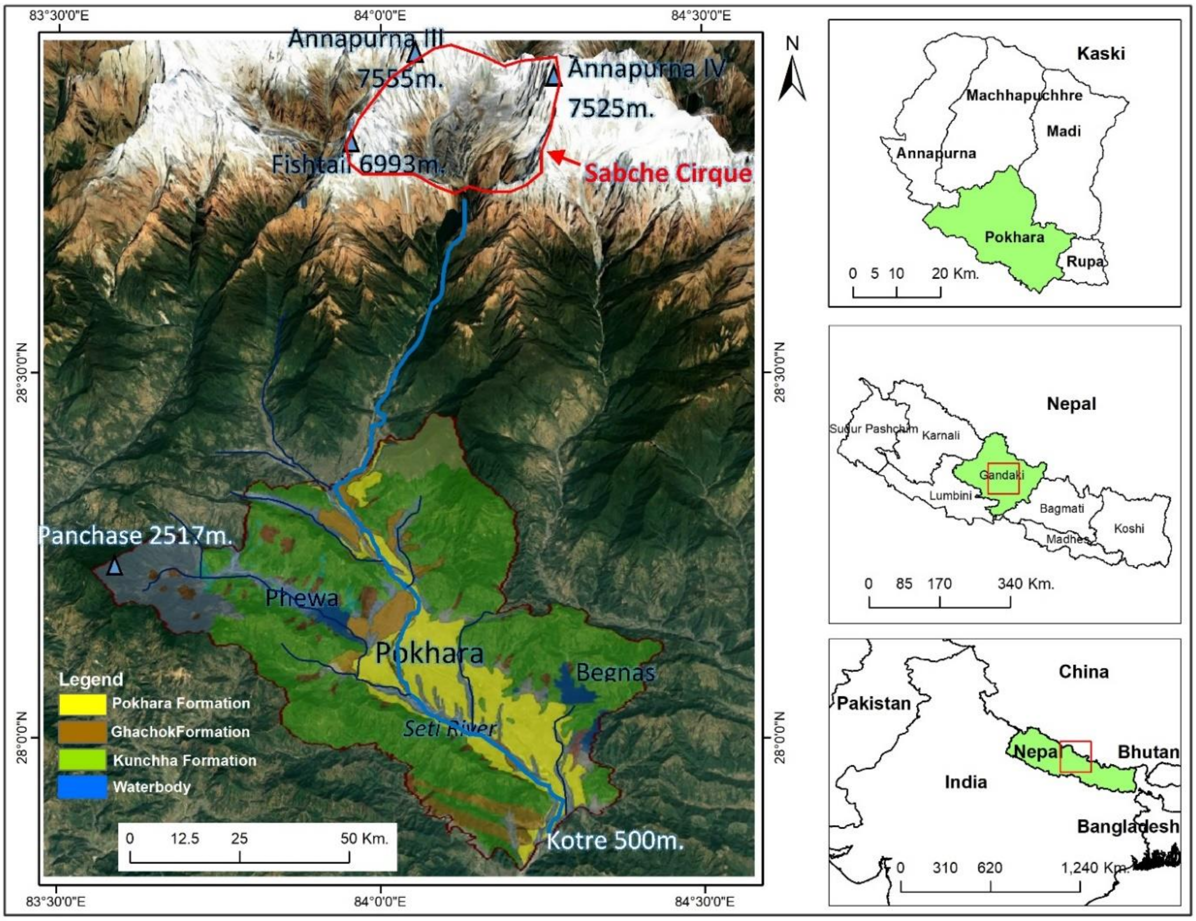

Figure 1. Study area; Pokhara Metropolitan City and backgrounds topography

Image Processing and Geospatial Data Extraction

The study involved verifying the geometric accuracy of Landsat TM and ETM, as well as Sentinel-2 images, using ENVI 5.3 software for image formation. The process included analyzing visual depiction, texture, and associations, and extracting information from satellite images, field visits, aerial photographs, and urban sector documents to identify built-up areas. Three categories of urban land use (Bhatti & Tripathi, 2014) were identified: built-up areas (areas with buildings structures, and infrastructure), non-built-up areas (open spaces, parks, or barren land), and water bodies (rivers, lakes, and ponds). To maintain consistency in spatial resolution, the Landsat image (30 m) was resampled using the nearest neighbor resampling method to match the resolution of Sentinel (15 m). Ground truths were verified using Google Earth imagery. Training samples representing the identified classes were created as ground control points (GCP), and the maximum likelihood algorithm (Poudel & Rawat, 2023) was used to calculate mean, variance, and covariance statistics. A total of 20 samples for each sub-class of built-up and non-built-up categories were selected randomly following the standard image classification procedure.

Field Survey & Key Informant Interviews

Field surveys and Key Informant Interviews (KII) were conducted to identify and classify urban built-up and non-built-up areas and verify built-up growth. A total of ten KII were consulted which included three elderly, two municipal staff, two geographers, two urban planners, and one geologist. Their knowledge and information provided insights into urban growth and historical changes, ensuring precise classification and analysis.

Accuracy Assessment

An accuracy assessment for the year 2020 was conducted to validate the classification of urban built-up and non-built-up areas with 350 ground truth verification points in May 2024. Ground-truth data were compared to classified maps using error matrices to derive metrics including overall, producer, and user accuracy.

Analysis of Urban Expansion through Geological Characteristic

The methodology involved extracting urban expansion maps from aerial photos of 1978 and satellite images for the years 1990, 2000, 2010, and 2020 (Fig. 2). The growth rate indicates the proportion of existing land transformed into built-up land use. The percentage growth controls urban annual growth rates (Mue) from the original built-up land-use zones using the following equation:

$$M_{ue} = \frac{\triangle U_i}{\triangle t \times TLA_i} \times 100\% \quad ...(1) \quad \text{(Liu \textit{et al.}, 2017)}$$

Where Δt is the study period, ΔU_i is the expansion area of urban land use in the study period, and TLA_i is the first urban land use area.

The geological digital vector data map included information about bedrock geology and quaternary deposits. Risk area identification was carried out only for sinkholes. The integration of urban expansion and risk area identification was achieved through overlay analysis. A examination of the relationship between urban expansion and potential risk areas was based on geological factors.

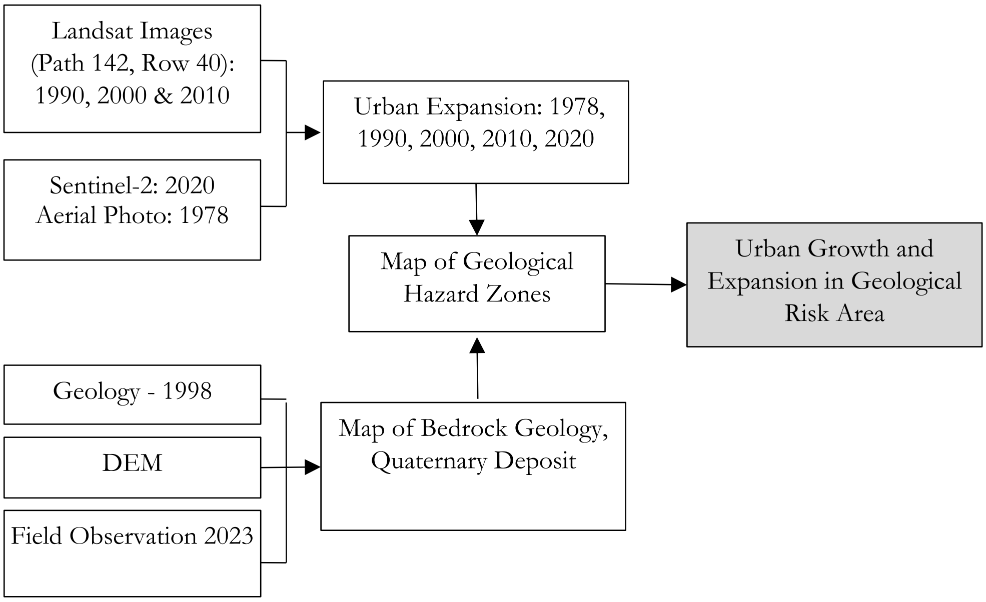

Figure 2. Overview of the research methodology

Results and Discussion

Geomorphological and Geological Characteristics of Pokhara

The Pokhara Valley, located in the Lesser Himalayas, has unique geomorphological characteristics. It is believed that a tectonic depression zone formed in the center of the valley during the late Pleistocene upheaval of the Mahabharat range (Gurung, 1965). The valley floor and river terraces consist of a mixture of stones, boulders, and calcareous cement, which are tightly consolidated, solidified, or loosely stratified. These materials come from various geological formations, including rounded or rolled quartzites, limestone, schist, gneiss, and central crystalline. The lithological composition of the Pokhara Valley area is formed by three distinct tectonic units separated by significant regional faults (Fort et al., 2018). Additionally, the presence of Karst topography (with easily soluble carbonate rocks) is another characteristic landform along the river terraces of the Valley which plays a significant role in shaping the landscape (Kargel et al., 2014).

The sediment on the bed of Pokhara is mainly a result of glacial-fluvial activity over many geological epochs (Koirala, 1998). Calcareous sediments, consisting of incants and matrices, are the main components of these deposits. The area exhibits different geomorphic units, such as Quaternary surface materials in the valley and exposed bedrock on the hillsides surrounding the basin (Fig. 3). The bedrock in this area comprises six geological formations: Benighat slates, Dhading Dolomite, Nourpul Formation, Dandagaon Phyllite, Fagfog Quartzite, and Kunchha Formation. For example, the central and northern parts are dominated by Kunchha Formation, which is a combination of phyllite and quartzite (Koirala, 1998). The mechanical strength of these rocks can range from weak to strong, with weathered and jointed rocks being susceptible to landslides. Fagfog Quartzite, on the other hand, consists of fine-grained, white quartzite intercalated with phyllite and basic rock, and has lower groundwater potential and low permeability.

The sediment deposits on the valley floor in Pokhara, originating from the Annapurna region due to extensive debris flows along the Seti River, play a crucial role in understanding urban expansion in the area. These deposits include various units, such as alluvial terrace deposits, colluvial soil, residual soil, alluvial fans, and lake sediment deposits. The Pokhara Formation is particularly important, as it consists of cemented silt and sandy gravel, while the Ghachowk Formation contains sediments ranging from boulder to silt size with limestone fragments. These geological formations have different bearing capacities and susceptibility to erosion, sinkhole development, and other geological phenomena, which in turn affect the suitability of the land for urban development, availability of construction materials, and assessment of potential geological hazards in relation to the growth of Pokhara. The Bhim Kali boulder, weighing 3,000 tonnes, is located on the Prithvi Narayan Campus in Pokhara. It represents the final stage of gravel deposition in Pokhara, delivered by a muddy flow fed by coarse debris from the High Himalayan Front. The geology and soil composition of Pokhara Metropolitan City (PMC) reveal a diverse and complex landscape. The area is predominantly covered by bedrock geology, which accounts for 64.44% of the total area, amounting to 297.39 km² (Fig. 3). The Kunchha Formation is the most extensive bedrock formation, covering 242.03 km² (52.44%), characterized by sloping hills that surround the flat regions of Pokhara. The Fagfog Quartzite covers 30.37 km² (6.58%), while the Benighat Slate spans 16.75 km² (3.63%), and Quartzite (QZ) accounts for 8.25 km² (1.79%).

In contrast, quaternary deposits cover 164.10 km², or 35.56% of the area, with significant contributions from the Pokhara formation (71.58 km², 15.51%) and the Ghachok formation (21.31 km², 4.62%). The Pokhara formation mainly occupies the flat areas to the east of the Seti River, extending from Phulbari to the International Airport and Lekhnath area. On the other hand, the Ghachok formation encompasses the western parts of Pokhara, including Hemja, Lamachaur, Parsang, Baidam, Chhorepatan, and Simaltuda. Other notable quaternary deposits include the Begnas formation (1.67 km², 0.36%), lake sediments (8.92 km², 1.93%), colluvial soil (3.70 km², 0.80%), residual soil (13.80 km², 2.99%), Sal formation (31.77 km², 6.88%), Undifferentiated Debris Flow (UNDF) (2.49 km², 0.54%), and Undifferentiated Lake Deposit (UNCL) (8.86 km², 1.92%). These diverse geological formations and soil types are significant for the urban expansion and environmental dynamics of Pokhara.

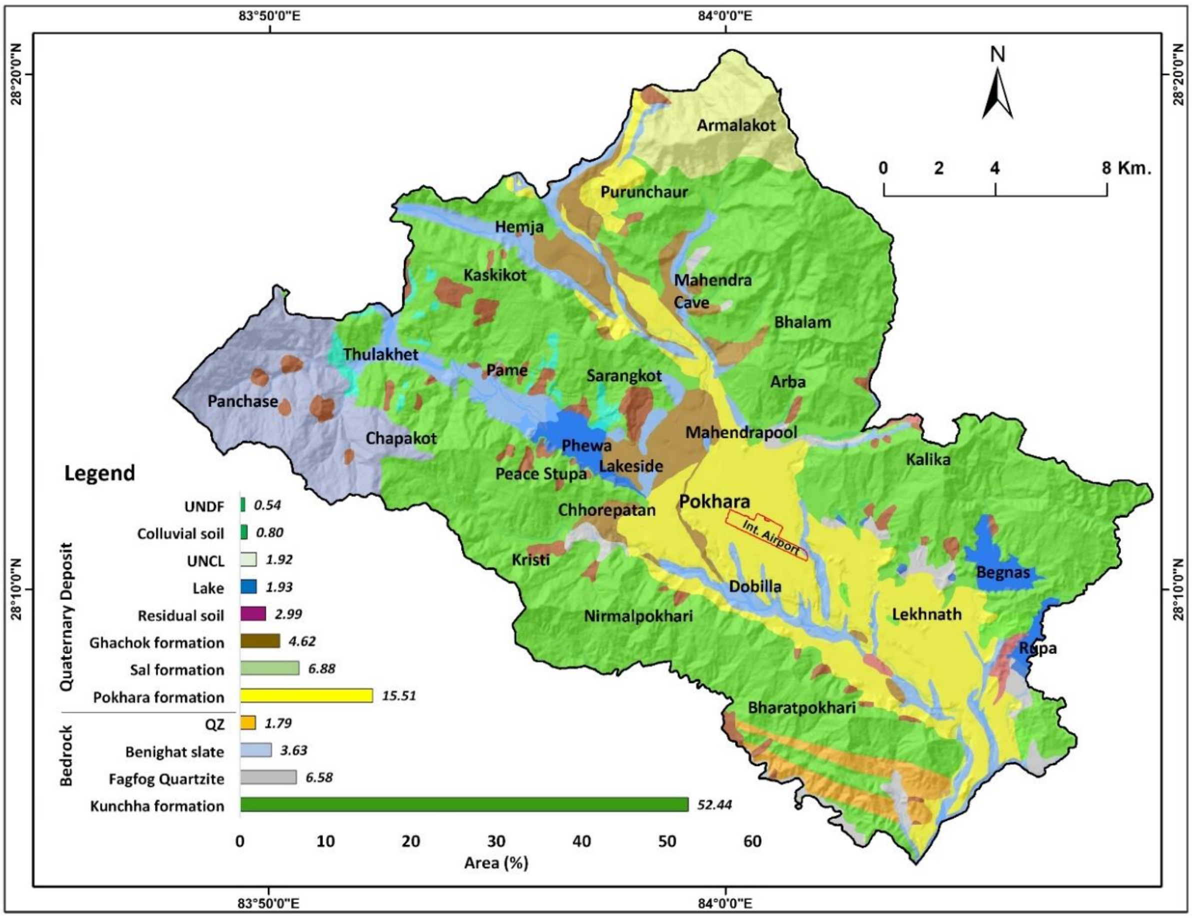

Figure 3. Geology and soil map of Pokhara Metropolitan City (Source: DMG, 1998)

Urban Growth Measurement of Pokhara Metropol itan City

Population Growth

The population and administrative area of Pokhara has grown significantly over time. The population was only 3,755 in 1951 and was not declared as a municipality. By 1962, it was declared as a municipality with a population of 11,000 which increased to 20611 in 1971 (Gurung, 1981). Up until 1971, population growth was slow but, by 1981, the municipality, with an area of 49.88 Km², comprised a population of 46,642. It reached 95,286 by 1991 while it was declared as a sub-metropolitan city with 225 Km² as an administrative area. Although the area remained the same, the population increased dramatically to 255,465 between 2001 and 2011. However, the municipality experienced a major restructuring in 2017, adding 33 wards with a land area of 464.24 Km² by annexing Lekhnath municipality and part of seven other village development committees (VDC). Figure 4 demonstrates that growth rates peaked after 1971 (14.3% in 1961-1971) and stabilized at 5–7% in subsequent decades. The dramatic growth of the population is attributed to the annexing of administrative boundaries of a municipality and other VDCs.

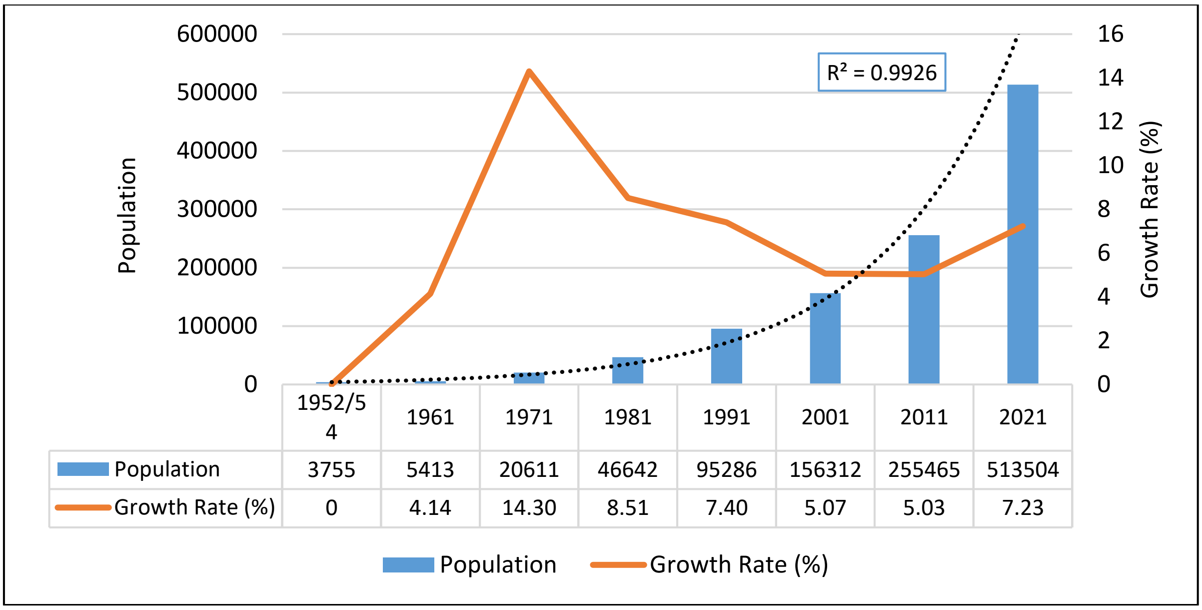

Figure 4. Population growth of Pokhara Metropolitan City (Source: CBS, 2012)

The R^2 value of 0.9795 indicates a strong correlation, emphasizing exponential growth. This trend highlights the increasing pressure on infrastructure. It underscores the need for careful urban planning, especially in geologically sensitive areas like the Ghachok Formation, to mitigate risks to life and property. The population distribution of Pokhara indicates that central areas have a high population density (Fig. 5), with densities reaching up to 12,964 people per square kilometer (WorldPop, 2023). These central areas serve as important urban and commercial centers, attracting residents due to employment and services. On the other hand, the outskirts, including semi-urban areas, have a moderate population density due to limited infrastructure, while the surrounding hilly areas have lower population densities due to their rural characteristics and infrastructure limitations.

The development of central area of Pokhara is continuously expansion through past several decades on the Ghachok and Pokhara formations. These formations are prone to geological hazards such as sinkholes and landslides, especially the Ghachok formation. Moreover, the Seti River corridor, known for its hazard-prone nature, presents additional challenges for informal settlements in Hemja and Kotre. These settlements, with their temporary housing, are vulnerable to sinkholes, flooding, and edge-cutting.

Built-up Area Growth

To understand the relationship between human activity and the environment, it is necessary to consider land use and land cover (Chapagain et al., 2018; Rai et al., 2020). Changes in land use and land cover are influenced by both natural and human factors. The study spanned five periods over a duration of 55 years. The focus was on the growth and ratio of the built-up area, which was calculated using the equation (1) provided. Throughout this period, significant urban expansion occurred in the study area, increasing from 3.36 sq. km to 50.49 sq. km (Table 2; Fig. 6). The annual urban growth rate varied between 2.52 percent and 21.43 percent from 1965 to 2020.

The built-up area of Pokhara experienced substantial urban expansion from 1965 to 2020. Initially, the area was 3.36 sq. km in 1965 (Gurung, 1965). By 1978, it had increased to 5.31 sq. km, with a compound annual growth rate of 9.46 percent. From 1978 to 1990, it reached 10.84 sq. km, growing at an annual rate of 8.68 percent. Between 1990 and 2000, the area more than doubled to 21.85 sq. km, with a growth rate of 10.16 percent per year. The growth slowed from 2000 to 2010, reaching 32.46 sq. km at an annual rate of 4.86 percent. From 2010 to 2020, the area expanded to 50.49 sq. km, with a growth rate of 5.55 percent per year. These figures demonstrate dynamic urbanization and socio-economic changes occurring in Pokhara over the decades.

The urban expansion in Pokhara, particularly in areas covering the Ghachok Formation, raises significant geohazard concerns. The Ghachok Formation, which includes Bharabari, Hemja, Lamachaur, Parsang, Baidam, Chhorepatan, and Simaltuda, is known for being prone to karstification. Karstification is a geological process that involves the dissolution of soluble rocks like limestone, creating subterranean voids that can lead to sinkholes.

The rapid urban growth in these areas, accounting for 18.2 percent of the building footprints in Pokhara city, exacerbates the risks associated with karstification. The expansion of built-up areas places additional stress on the already fragile geological structures. Urban infrastructure and buildings constructed over these sensitive deposits are particularly vulnerable to subsidence and sinkhole formation, posing significant hazards to both property and human safety.

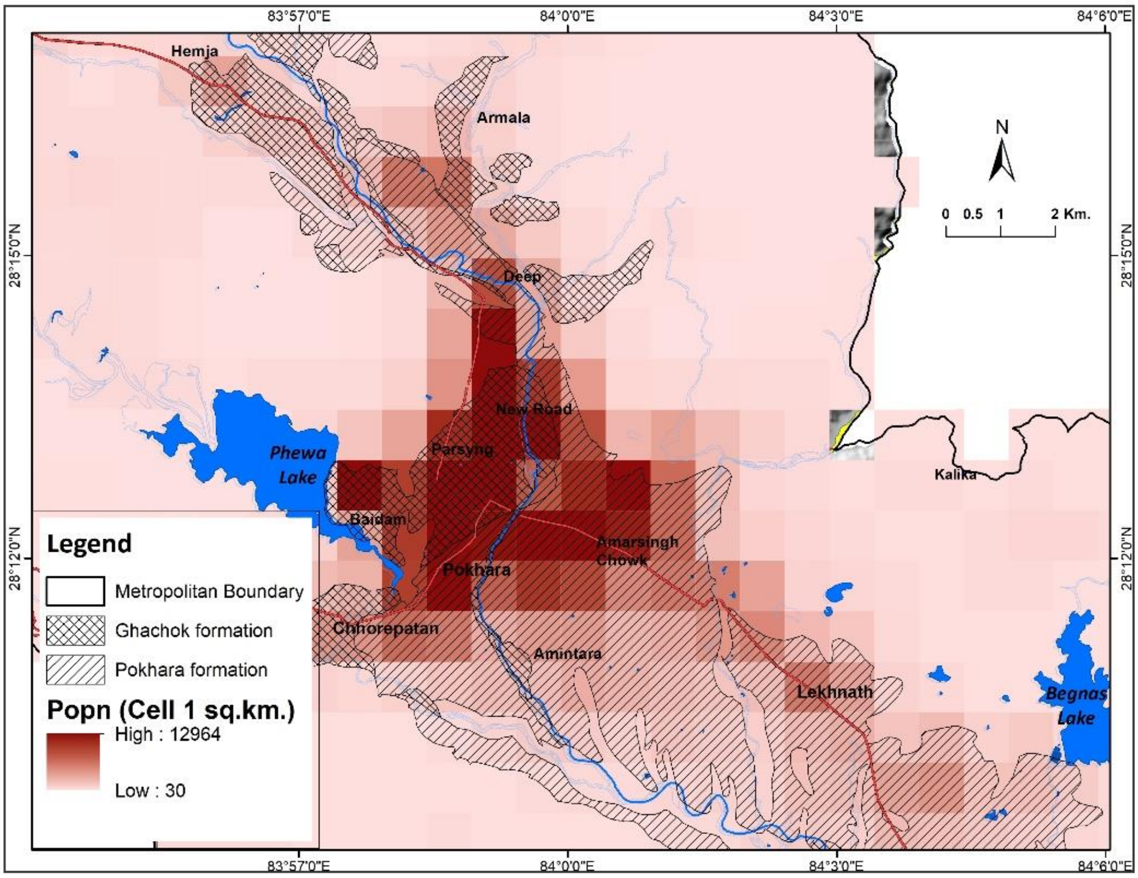

Figure 5. Population distribution and density distribution of Pokhara Metropolitan City. Sources: Koirala (1998) and WorldPop (2023)

Table 2. Annual growth rate of built-up area (1965–2020)

Year	Urban Built-up Area (sq.km)	Increase Urban Built-up Area (sq.km)	Annual Growth Rate (%)
1965 - 1978	5.31	1.95	9.46
1978 - 1990	10.84	5.53	6.13
1990 - 2000	21.85	11.01	7.26
2000 - 2010	32.46	10.61	4.04
2010 - 2020	50.49	18.03	4.51

Source: Aerial photo (1978), Landsat Images (1990, 2000, 2010, 2020)

Accuracy Assessment of Built-up Growth

The accuracy assessment was conducted using 150 reference pixels for built-up land and 200 for non-built-up land with a total of 350 reference points for the year 2020. The accuracy assessment of urban built-up and non-built-up areas is highly reliable. Built-up areas achieved 90.00% producer accuracy and 96.43% user accuracy, but non-built-up areas achieved 95.00% and 90.48%, respectively. The overall accuracy of 92.86% demonstrates good classification performance, as evidenced by a high Kappa coefficient of 0.85, showing significant agreement above the random chance of the year 2020 (Table 3).

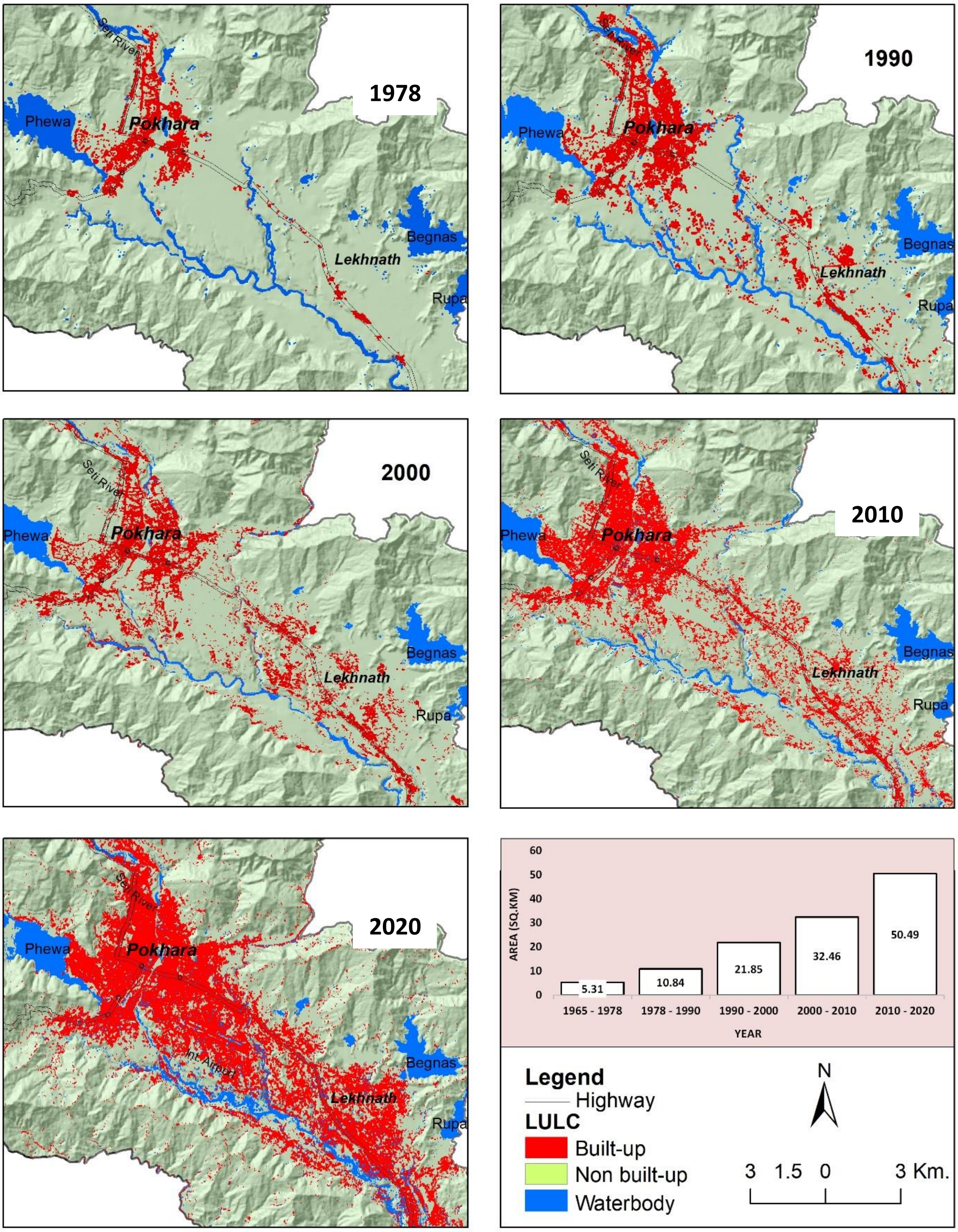

Figure 6. Urban expansions of Pokhara over the years based on visually interpreted using remote sensed data: Aerial photo 1978, Landsat images of 1990, 2000, 2010 and Sentinel image 2020

Urban Growth over the Geological Area

The geology and soil composition of Pokhara has a significant influence on housing distribution and population density (Table 4). The area can be divided into bedrock geology, covering 297.39 sq. km (64.44 percent), and quaternary deposits, covering 164.10 sq. km (35.56 percent). Despite covering a larger area, the bedrock geology supports a smaller proportion of the population. There are 41,763 houses and 151,339 people, representing only 29.49% of the total population. The

Kunchha formation makes up 52.44% of the area and is predominantly sloping. It supports 39,851 houses and 144,411 people (28.14%). The Fagfog Quartzite, Benighat Slate, and QZ formations collectively cover 11% of the area but house less than 2% of the population. This reflects their challenging terrain and lower suitability for urban development.

Table 3. Accuracy assessment and kappa coefficient of 2020.

Class	Reference Pixels	Classified Pixels	Correct Pixels	Producer's Accuracy (%)	User's Accuracy (%)
Built-Up	150	140	135	90.00	96.43
Non-Built-Up	200	210	190	95	90.48
Total	350	350	325		
Overall Accuracy					92.86
Kappa Coefficient					0.85

Source: Authors' calculation

Table 4. Urban growth over the geological area of Pokhara Metropolitan City

Geology and Soil *	Area		Building and Population		
	Area (Sq.Km)	Percent	House**	Population#	Percentage
A. Bedrock Geology:	*297.39*	*64.44*	*41763*	*151339*	*29.49*
- Kunchha formation	242.03	52.44	39851	144411	28.14
- Fagfog Quartzite	30.37	6.58	1048	3798	0.74
- Benighat slate	16.75	3.63	138	500	0.10
- QZ	8.25	1.79	726	2631	0.51
B. Quaternary Deposit:	*164.10*	*35.56*	*99831*	*361765*	*70.51*
- Pokhara formation	71.58	15.51	57008	206584	40.26
- Ghachok formation	21.31	4.62	25713	93178	18.16
- Sal formation	31.77	6.88	10807	39162	7.63
- Others	39.44	0.54	6303	22841	0.25
Total	*461.49*	*100.00*	*141594*	*513104*	*100.00*

Note: Others includes (Colluvial & residual soil, Begnas formation, UNDF, UNCL and Lake)
Source: *Engineering and Environmental Geological Map of Pokhara Valley-1998, Department of Mines and Geology, Nepal. ** Open Street Map (OSM), (NSO, 2021).

In contrast, the quaternary deposits, although occupying a smaller area, are more densely populated. They support 99,831 houses and 361,765 people, accounting for 70.51% of the population. The Pokhara formation, which features cemented silty and sandy gravel, is relatively strong and stable. It supports 57,008 houses and 206,584 people (40.26%). The Ghachok formation contains weaker sediments and is prone to sinkholes. However, it still accommodates 25,713 houses and 93,178 people (18.16%). The Sal Formation and other minor formations together house about 17,110 people. This distribution highlights the preference for building on more stable quaternary deposits despite the inherent risks. It also emphasizes the need for careful urban planning to mitigate geological hazards.

Urban Expansion and Geo-Environmental Risk Area

The geological landscape of Pokhara, particularly the Ghachok Formation, is extremely fragile. This was highlighted by studies conducted by the Department of Hydrology and Meteorology in 1974 and later supported by Koirala in 1998. The Ghachok formation, consisting of calcareous silt and conglomerate dating back 12,000 to 4,000 years, is highly susceptible to sinkholes and cave formations due to karstification. As a result, it is unsuitable for major urban development. The Ghachok formation stretches approximately 12 kilometers from the Mahendra Cave area to Chhorepatan and has been identified as a high-risk zone for dense populations.

The formation of sinkholes is closely linked to heavy rainfall and surface water drainage (Stolle, 2018). These factors can result in dangerous incidents, such as sinkholes, terrace collapses, and even liquefaction. Despite being aware of its fragility, 18.2% of the buildings in Pokhara City currently occupy this formation. This rapid population growth has direct implications for urban development, with 25,713 structures and a population of 93,178 residing in this area (Table 3). The sensitivity of this area to karstification presents significant challenges for sustainable urban growth.

Social factors exacerbate the problem. Residents in these high-risk areas often conceal the presence of sinkholes to maintain their land value and social reputation. They quickly fill in sinkholes with external materials, making it difficult for researchers to gather accurate data. In contrast, when a significant sinkhole event occurred in Armala in November 2012 (Fig. 7), affecting nearly 100 hectares of open land, it received considerable attention and a swift response from the government (Bhandari et al., 2019).

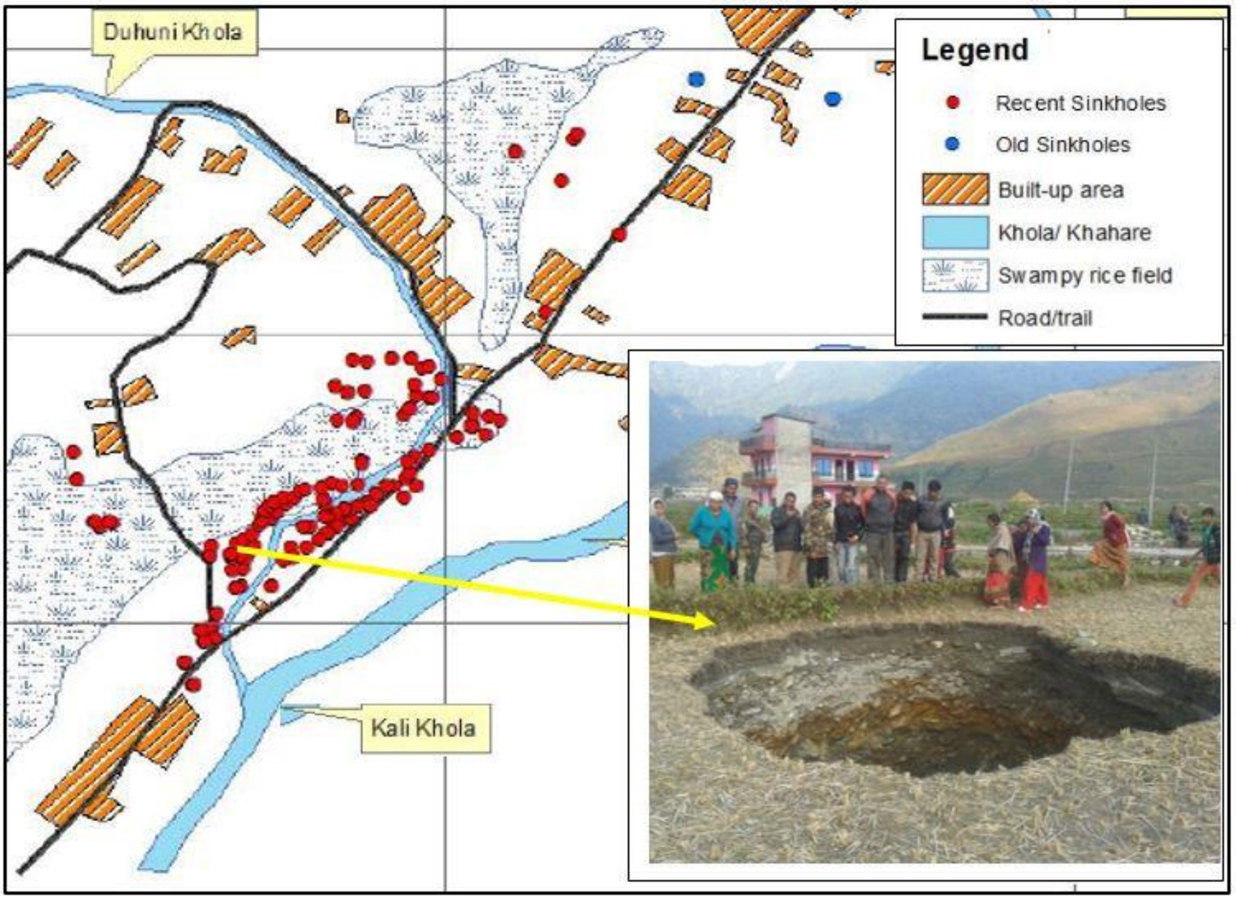

Figure 7. Spatial distribution of sinkhole in Armala (Photo by Author)

Despite being aware of the risks, people often underestimate their severity. As the city continues to expand, particularly in areas with unstable ground, the risk of hazards like sinkholes increases. Currently, 64.4% of Pokhara Metropolitan City is built on solid bedrock, while 35.6% is on softer Quaternary deposits. Notably, 18.6% of the city's buildings are located in these 21.31 sq. km softer deposit areas, with the Ghachok formation being especially vulnerable to sinkholes.

There is currently no systematic method for recording sinkhole events, which makes managing these risks even more challenging. However, researchers have mapped several sinkholes in the main built-up areas based on personal observations and experiences. Despite this evidence, the government has proceeded with plans to develop the New Road area, one of the busiest parts of the city, despite its known geological instability. The issue of rapid population growth in Pokhara is exacerbating the problem at hand. Stolle (2018) warns that if current trends continue, the city will expand into more vulnerable areas prone to sinkholes. This concern was dramatically demonstrated on November 20, 2013, when over 50 sinkholes appeared in a 100-hectare area in the northern part of the city. These sinkholes, each measuring 15 to 20 meters wide and 10 to 15 meters deep, formed when surface water seeped into the ground and caused the collapse of the top layers of soil and gravel. This incident highlights the vulnerability of areas where softer ground and bedrock meet.

The distribution of sinkholes in the Pokhara Valley's geologically fragile Ghachok formation, heavily impacted by urban expansion from 1990 to 2020, is depicted in Fig. 8. The Ghachok formation, known for its easily erodible and calcareous rock, is particularly susceptible to sinkhole formation. This vulnerability is evident in areas like Simalchaur, Prithvi Chowk, Baidam, Parsyang, and Nayabazar, where a concentration of sinkholes has been identified. The map, utilizing data from field surveys conducted in 2023, a 1998 geological map by Koirala, and three decades of Landsat images, underscores the increasing risk associated with urbanization in these geologically sensitive areas.

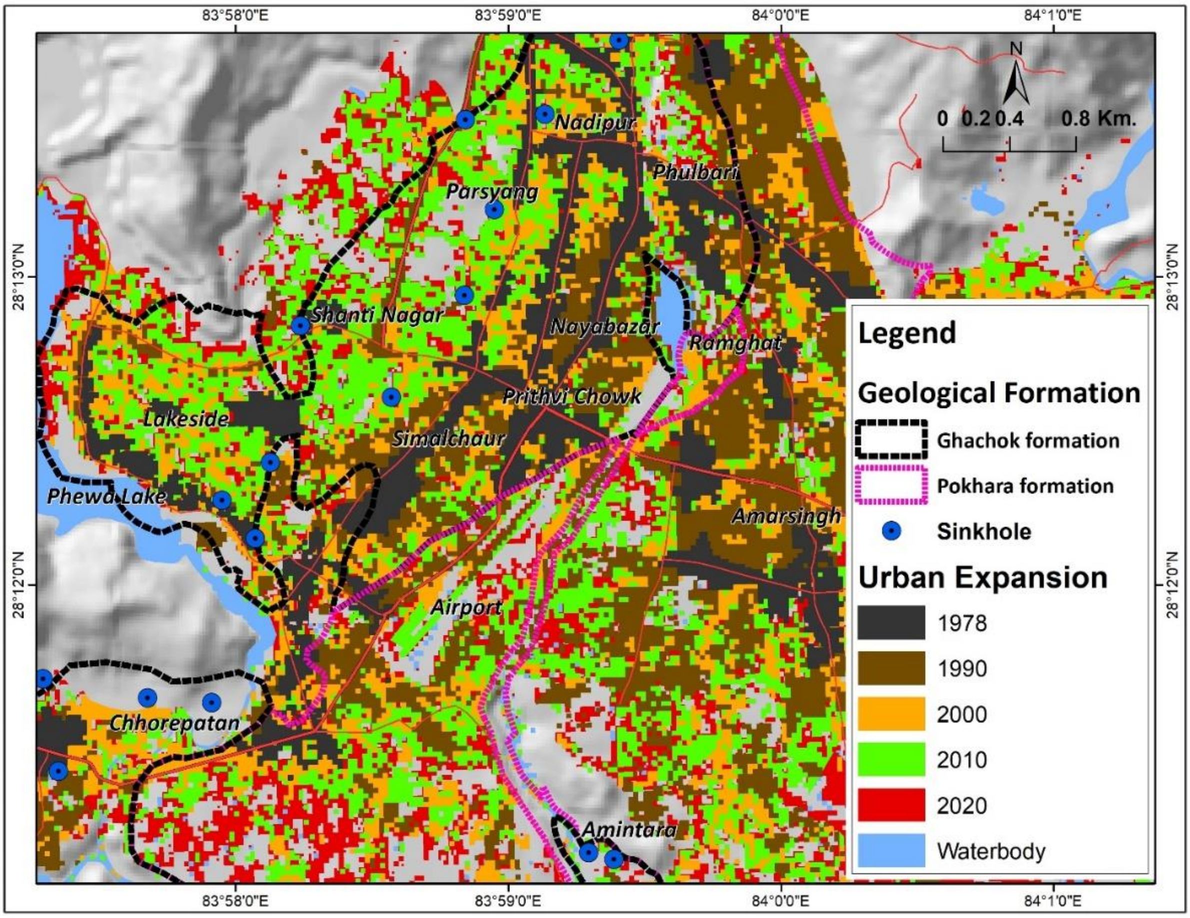

Figure 8. Urban expansion and distribution of sinkhole on Ghachok formation (Source: Field survey, 2023; Koirala,1998; Aerial photo, 1978; Landsat Images of 1990, 2000, 2010, 2020)

With ongoing urban development, especially in regions that overlay the Ghachok formation, the risk of sinkhole-related hazards intensifies due to the added stress from construction, infrastructure development, and increased water drainage. The proximity of sinkholes to densely populated areas raises significant concerns for public safety and urban planning. The trend of the growth of the built-up and the resultant formation of sinkholes over the Ghachok Formation in Pokhara shows striking contrasts. The annual growth rate from key informants' interview shows that, built-up in 1990 was 4.99%, while for sinkholes, it was 1.87%. During 2000, the growth of built-up slackened to 4.37%, while the occurrence of sinkholes decreased by -0.57% due to probably rainfall variation. It increased only up to 2.75% in 2010 due to increased rainfall and spreading in northern and central parts of Pokhara. The trend observes a massive upward increase in the year 2020, wherein the growth of sinkholes was as high as 8.74%, largely contributed by more than 50 identified sinkholes in the aftermath of road construction and check dam activities in Armala. During this time, the same period, the growth rate of a built-up increased to only 1.62 percent, which showed that urban growth was slowing down due to increased risks and hazards (Fig. 9).

Geo-environmental hazards like sinkholes, and land subsidence in and around built-up areas, existing urban infrastructures, and utilities are recognized as serious problems in Pokhara City in several earlier studies (Luitel et al., 2024; Yoshida et al., 2006). The necessity of integrating geo-environmental risk into developmental policies and strategies is emphasized to minimize the consequences on environmental sustainability, infrastructure stability, and urban growth. (Luitel et al., 2024). This study also underlines the growth of geological hazards, particularly in fragile zones like the Ghachok Formation, where city development is expanding in areas of high and escalating hazard-most driven by natural processes and human interventions. Most noticeably, the geometrical appearance of sinkholes has increased in those rapidly developing areas of Simalchaur, Prithvi Chowk, and Nayabazar, where increasing infrastructure development further burdens an already highly sensitive geological substratum. In particular, fast-growing sinkholes are a critical challenge in sustainable urban planning for Pokhara, especially where heavy rainfall and construction activities are increasing. In this context, an earlier study has also shown that in northern Pokhara more than 50 sinkholes were formed within a 100-hectare area in 2013 (Pokhrel et al., 2015). However, it is found that in the period between 1990 and 2020, the trends were opposite for urban development dynamics and the process of sinkhole formation. The built-up area continued to increase, but the frequency of sinkholes varied due to rainfall amount and intensity, construction activities, and changes in the drainage system.

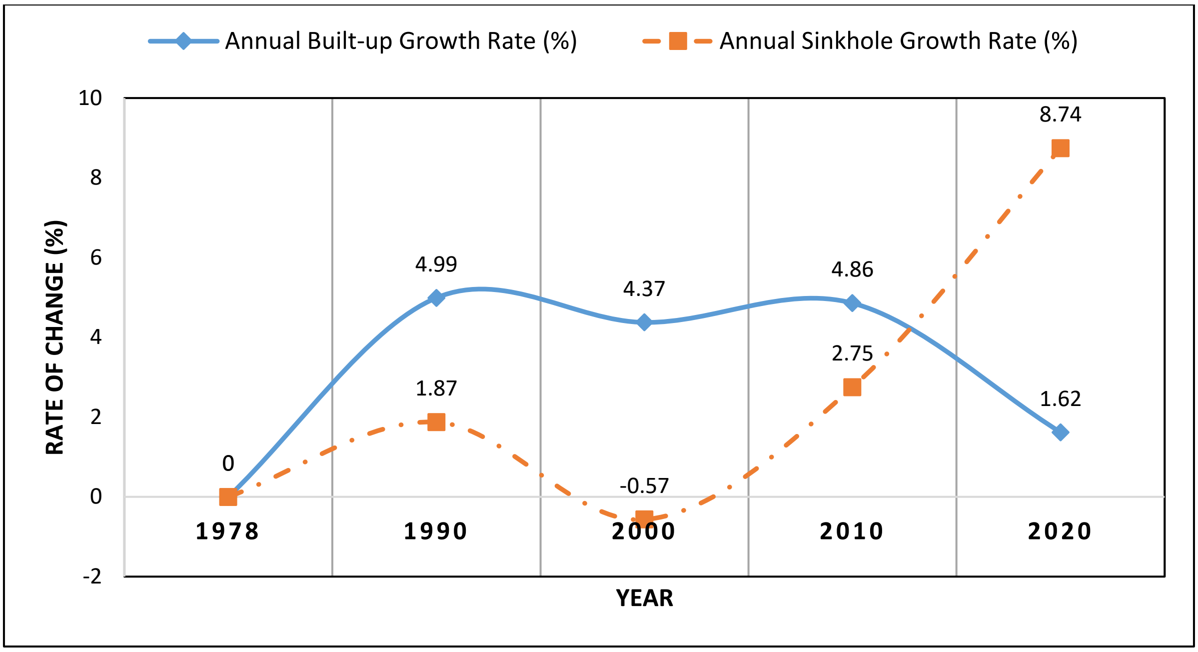

Figure 9. Urban Expansion on Ghachok Formation (Sources: Urban growth from Aerial photo (1978), Satellite images of 1990, 2000, 2010, 2020 and Sinkhole data from KII, 2023 and local knowledge of author itself)

Conclusions

This study focuses on the relationship between the geological sensitivity of Pokhara and urban growth, emphasizing the importance of long-term land use planning to prevent geo-environmental dangers. The Ghachok Formation, which is prone to karstification, sinkholes, and land subsidence, faces increased risk because more than 18% of the city's built-up area is on unstable terrain, with western Pokhara being particularly vulnerable. Rapid urbanization, fueled by administrative reorganization in 2017, raised the population to 513,504 by 2021, putting more pressure on these areas of concern.

Urban expansion trends show varying growth rates: peaking at 14.3% (1961–1971), stabilizing at 5–7%, and rising to 7.23% in 2021. Classification accuracy for urban land use mapping was high, with an overall accuracy of 92.86% and a Kappa coefficient of 0.85. Built-up areas expanded from 5.31 sq. km in 1965 to 50.49 sq. km in 2020, reflecting an annual growth rate of 4–9%.

This is very alarming, especially with the increasing frequency and distribution of sinkholes and land subsidence occurrences which are related to intense rainfall and surface water drainage conditions in the area of existing infrastructure and built-up structures. This reflects that interactions between geo-environmental hazards and urbanization must be carefully monitored and managed to avoid loss and damage to human life, properties, and infrastructure and ensure sustainable urban development.

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Author Contributions:

KRP: Conceptualization, methodology, mapping and writing; SS: Conceptualization, methodology, editing, writing, and finalization.

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