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RESEARCH ARTICLE

Geological hazards in Pokhara valley, central Nepal: types, distribution, impacts and implications for hazard management

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ABSTRACT

Pokhara Valley is one of the most remarkable intermontane basins of the Nepal Himalaya and is characterized by a unique geological and geomorphological setting. The valley is occupied by extensive Quaternary sediments derived largely from catastrophic sediment-transport processes originating in the Annapurna region. The valley is traversed by the deeply incised Seti River and its tributaries and contains numerous terraces, gorges, caves, sinkholes, lakes and other distinctive geomorphic features. These geological and geomorphological conditions, together with active tectonics, steep surrounding slopes, intense monsoonal rainfall and increasing urbanization, make the valley vulnerable to a range of geological hazards. This study presents an integrated assessment of the major geological hazards in and around Pokhara Valley based on field observations, geological and geomorphological investigation, hazard inventory mapping, and interpretation of previous studies and review of published literature. The principal hazards identified include landslides, riverbank erosion and bank collapse, block fall, karstification and sinkhole development, flash floods and debris-flow-related hazards. Landslides occur mainly along the surrounding hill slopes and transportation corridors, whereas bank erosion and block failure are concentrated along the Seti River and its tributaries. Karstification is particularly important because the valley-fill sediments contain abundant calcareous materials, resulting in underground cavities, caves, solution channels, sinkholes and local ground subsidence. Flash floods represent a major high-impact hazard, as demonstrated by the 2012 Seti River disaster. The geological record of repeated large-scale debris-flow deposition also indicates that the Pokhara Valley has experienced catastrophic sedimentation events in the past and may remain susceptible to similar low-frequency but high-magnitude processes. The study emphasizes that geological hazards in Pokhara Valley should be considered within a multi-hazard framework. Detailed hazard zonation, systematic monitoring, improved drainage, control of unscientific river mining, land-use regulation, early warning systems and public awareness are essential for reducing future risk. The results provide a geological basis for hazard-sensitive urban planning and sustainable development in the rapidly expanding Pokhara Valley.

Keywords: ***Pokhara valley, geological hazards, karstification, flash flood, Seti River***

1. INTRODUCTION

Pokhara Valley is one of the most important urban and geomorphological regions of central Nepal. Located in the Lesser Himalayan region (Fig.1), the valley forms a distinctive intermontane basin that extends approximately northwest–southeast and is surrounded by hills and the high Himalayan catchments of the Annapurna region. Its geological history and present-day landscape have been strongly influenced by tectonic activity, catastrophic sedimentation, fluvial incision, karstification and slope processes (Hagen, 1969; Gurung, 1970; Hormann, 1974; Dhital, 2015).

The valley floor is mainly occupied by thick Quaternary deposits consisting predominantly of coarse-grained rudaceous materials. These deposits have been interpreted as products of repeated high-magnitude sediment-transport and catastrophic valley-filling events associated with the palaeo-Seti drainage system and the high Himalayan region (Yamanaka et al., 1982; Fort, 1984, 1987, 2010; Schwanghart et al., 2016; Stolle et al., 2017). The valley-fill materials contain abundant calcareous clasts and locally calcareous matrix, making many areas susceptible to dissolution and karstification (Koirala and Rimal, 1996). The interaction between fluvial erosion and the dissolution of carbonate-rich materials has produced remarkable landforms, including caves, underground drainage systems, gorges, sinkholes and enclosed depressions (Gurung, 1970; Sharma, 1975; Koirala and Rimal, 1996).

The Pokhara Valley is also situated within an active Himalayan tectonic environment. Major regional tectonic structures, including the Main Central Thrust system in the northern region and the Kuncha–Gorkha structural zone, have contributed to the tectonic and geomorphic development of the area (Hagen, 1969; Dhital, 2015). Continuous uplift, river incision and monsoonal erosion have produced a highly dynamic landscape. The Seti River and its tributaries have deeply dissected the valley sediments, producing steep banks and gorges that are locally unstable (Hormann, 1974; Yamanaka et al., 1982; Koirala et al., 1995).

The geological setting of Pokhara Valley creates a complex range of hazards. Landslides occur along the surrounding hill slopes and road corridors, whereas riverbank erosion, block fall and bank collapse are widespread along the Seti River and several tributaries. Karstification creates underground cavities and sinkholes, resulting in localized ground instability. Flash floods and extreme sediment-laden flows pose serious threats to settlements and infrastructure located along river corridors. These hazard processes have also been recognized in earlier engineering and environmental geological investigations of Pokhara Valley (Koirala et al., 1995; Koirala and Rimal, 1996). In addition, the valley-fill deposits themselves preserve evidence of catastrophic debris-flow and high-magnitude sediment-transport events during the geological past (Fort, 1987, 2010; Schwanghart et al., 2016; Stolle et al., 2017).

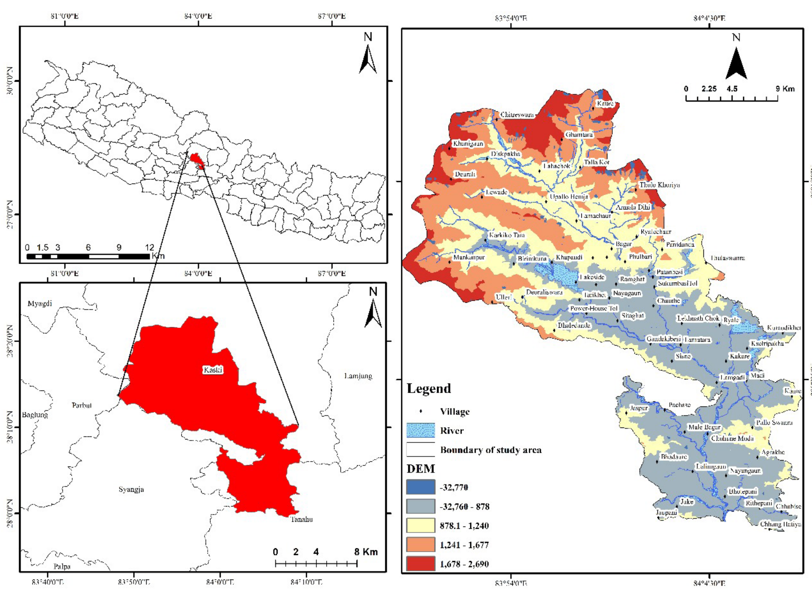

Fig. 1: Location map of the study area.

The rapid expansion of Pokhara Metropolitan City has increased the exposure of people, infrastructure and property to these hazards. Urban development has extended into river corridors, unstable slopes and areas potentially affected by subsurface dissolution. Unplanned excavation, inappropriate construction and unscientific extraction of river materials may further disturb the natural equilibrium of slopes and channels. Therefore, a systematic geological hazard assessment is essential for sustainable development.

Objectives

The main objective of this study is to investigate the major geological hazards occurring in and around Pokhara Valley and to examine their geological and geomorphological controls.

The specific objectives are:

1. To identify and characterize the principal geological hazards in and around Pokhara Valley.
2. To examine the spatial distribution and geological controls of landslides, riverbank erosion, block fall, karstification, flash floods and debris-flow hazards.
3. To prepare and interpret a multi-hazard inventory and hazard zonation framework.
4. To assess the potential impacts of the identified hazards on settlements, infrastructure and future urban development.
5. To recommend appropriate geological and non-structural measures for hazard mitigation and risk reduction.

2. PREVIOUS STUDIES AND LITERATURE REVIEW

The geological and geomorphological evolution of Pokhara Valley has attracted scientific attention for more than a century. Early investigators attempted to explain the origin of the valley and its distinctive terraces. Hormann proposed that the development of the basin was associated with tectonic processes and recognized several terrace levels. Early studies generally emphasized the relationship between valley development, tectonic deformation and Quaternary geomorphological processes.

Subsequent studies significantly improved the understanding of the valley-fill deposits. Yamanaka et al. carried out one of the most detailed investigations of the geology, geomorphology and Quaternary deposits of Pokhara Valley. Their work described the distribution of terraces and sedimentary units and proposed a stratigraphic framework for the Quaternary deposits. Their interpretation established the importance of repeated sedimentary events in the development of the valley.

Fort (1984, 1987) conducted important geomorphological investigations and emphasized the catastrophic nature of sediment accumulation in the Pokhara basin. Her studies related valley development to episodic high-magnitude processes operating in the Himalayan environment and argued that rapid and catastrophic geomorphic events played a major role in the formation of the extensive valley-fill deposits. Later work further described Pokhara Valley as a product of exceptional natural processes associated with the Himalayan landscape (Fort, 1995, 2010).

Adhikari (1996) and other researchers continued to refine the stratigraphic classification of the Quaternary sediments. Koirala and Rimal (1996) conducted one of the most relevant earlier investigations specifically related to geological hazards. They identified debris flows, karstification and slope or riverbank failures as major hazards of Pokhara Valley. Their study demonstrated that the carbonate-rich valley-fill deposits are susceptible to solution processes, resulting in channels, cavities and underground features. Related engineering and environmental geological mapping was also carried out by Koirala et al. (1995).

The possibility of catastrophic valley-filling events has received renewed attention in recent years. Schwanghart et al. (2016) suggested that repeated catastrophic sedimentation may be associated with large Himalayan earthquakes and subsequent mass movements. Stolle et al. (2017) further examined catastrophic valley fills and their relationship to large-scale Himalayan events. These studies are particularly important because they indicate that the Pokhara basin preserves evidence of exceptional low-frequency but high-magnitude geomorphic processes.

Although considerable research has been undertaken on the stratigraphy, geomorphology and sedimentary evolution of Pokhara Valley (Yamanaka et al., 1982; Fort, 1984, 1987, 2010; Adhikari, 1996; Schwanghart et al., 2016; Stolle et al., 2017), relatively fewer studies have integrated the different geological hazards into a single multi-hazard framework. Earlier hazard studies mainly emphasized individual processes, particularly debris flows, karstification and slope or riverbank failures (Koirala et al., 1995; Koirala and Rimal, 1996). The present study therefore focuses on integrating the principal geological hazards and interpreting their relationship with the geological and geomorphological setting of the valley.

3. METHODOLOGY

The study was based on an integrated geological hazard assessment approach. The methodology included field investigation, hazard inventory preparation, geological and geomorphological interpretation and review of previous studies.

Field observations were carried out at representative locations in and around Pokhara Valley. Particular attention was given to landslide-prone slopes, unstable road sections, riverbank erosion sites, areas of block fall, karst features, sinkholes, river gorges and locations affected by flooding or debris-flow processes. Observations were made regarding slope condition, sediment characteristics, erosion processes, failure mechanisms and their potential impacts on settlements and infrastructure.

A geological hazard inventory was prepared by identifying the location and type of visible hazard features. The principal hazard categories considered were landslides, riverbank erosion and collapse, block fall, karstification and sinkholes, flash floods and debris-flow-related hazards. These observations were combined to prepare a multi-hazard inventory map at a regional scale.

The interpretation also considered the relationship between hazards and geological factors. These included the distribution of unconsolidated and weakly cemented valley-fill sediments, carbonate-rich materials, steep slopes, river incision, drainage conditions and human disturbance. Previous geological, geomorphological and hazard studies were reviewed to place the field observations within the broader geological evolution of Pokhara Valley.

Finally, the identified hazards were evaluated in terms of their probable impacts and mitigation requirements. The study emphasizes hazard occurrence and geological susceptibility rather than a quantitative probabilistic risk analysis.

4. RESULTS

4.1 Landslide Hazard

Landslides are among the major geological hazards affecting the hills surrounding Pokhara Valley. They commonly occur on steep slopes where weak or weathered materials are exposed and where intense rainfall increases pore-water pressure. Road construction, slope cutting, inadequate drainage and erosion at the slope toe may further reduce slope stability. These controls are consistent with the regional geological and geomorphic conditions of the Nepal Himalaya, where steep slopes, weathered materials and monsoonal rainfall strongly influence slope instability (Dhital, 2015).

Active and old landslide features are observed along several transportation corridors surrounding Pokhara. The northern part of the valley contains landslide-prone slopes, while road sections toward Syangja (Fig.2) and other surrounding hill regions show evidence of slope failure and localized subsidence. In southern areas, rockfall and localized slope failures are also important.

The consequences of landslides include road blockage, damage to retaining structures, disruption of transportation and possible threats to settlements. During intense monsoon periods, even relatively small failures can become significant where roads or buildings are located immediately downslope.

Important mitigation measures include improved surface and subsurface drainage, slope modification where appropriate, retaining structures, bioengineering and reinforcement of unstable slopes. Detailed landslide mapping should also guide future road construction and settlement expansion.

Fig. 2: Landslide observed along the Pokhara-Syangja road section

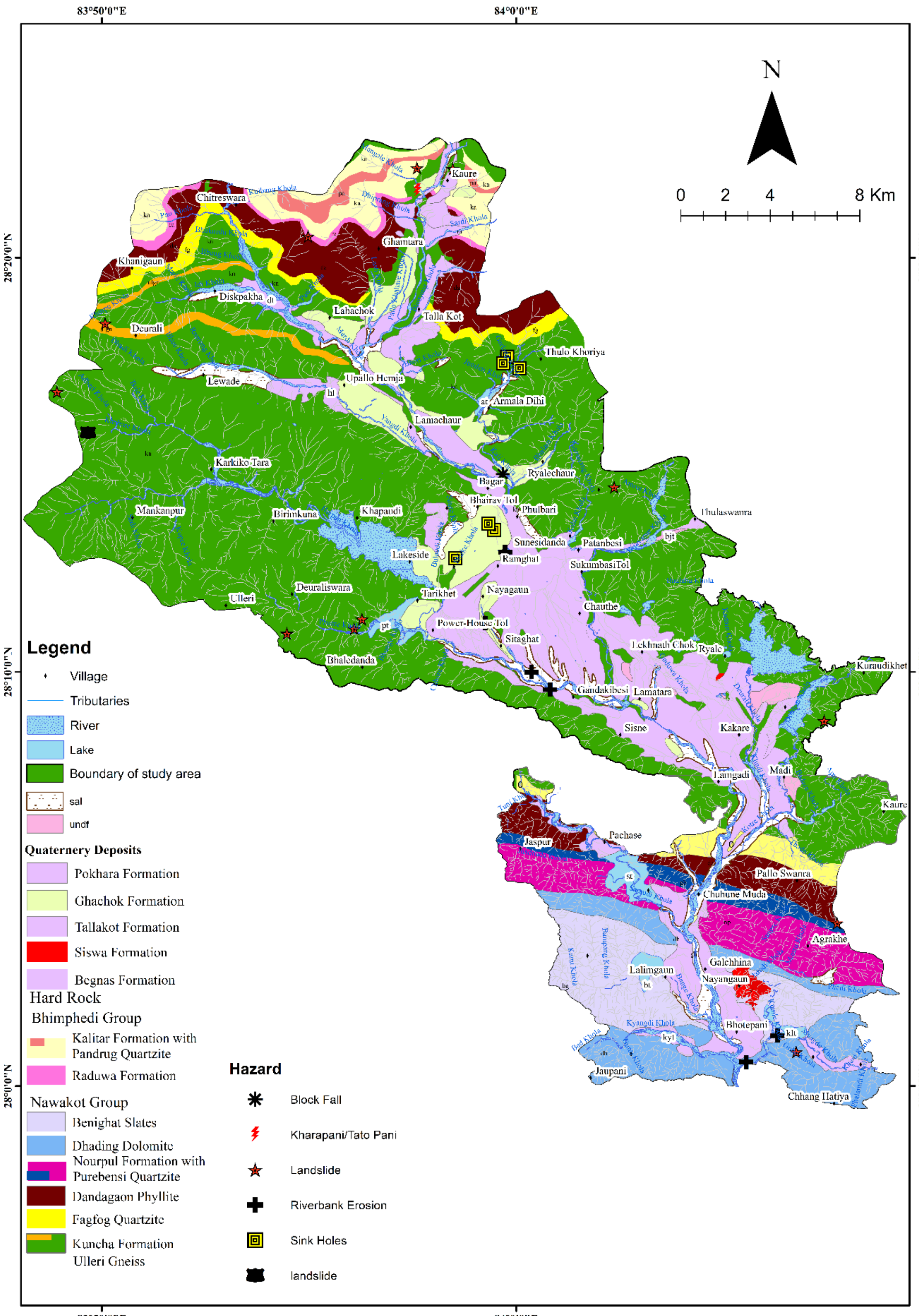

Fig. 3: Multi-hazard inventory map of the study area

4.2 Riverbank Erosion, Bank Collapse and Block Fall

The Seti River and its tributaries are major agents of landscape modification within Pokhara Valley. Deep river incision has created steep banks and narrow gorges in many locations. These conditions promote bank erosion, block fall, toppling and localized collapse. The deeply incised Seti system and its interaction with thick Quaternary valley-fill deposits have long been recognized as important controls on the geomorphic evolution of Pokhara Valley (Hormann, 1974; Yamanaka et al., 1982; Koirala et al., 1995).

Riverbank erosion is particularly important in densely populated sections of the valley where settlements and infrastructure are located close to active channels. At locations such as Ramghat and other reaches of the Seti River, active erosion can undermine the banks (Fig.4a) and threaten nearby land and structures. Similar processes occur along tributaries such as Kali Khola and Phurse Khola.

The combination of steep gorge walls, tension cracks and undercutting by river flow creates favorable conditions for block failure (Fig.4b). During periods of high discharge, erosion at the toe of slopes may accelerate instability.

Unscientific extraction of sand, gravel and other river materials can intensify these processes by disturbing channel geometry and reducing bank stability. Therefore, river-resource extraction should be scientifically regulated.

Mitigation should include the establishment of riparian buffer zones, controlled use of vegetation, bioengineering, gabion protection and carefully designed bank stabilization measures. Excessive use of rigid engineering structures should be avoided where they may increase flow velocity or transfer erosion downstream.

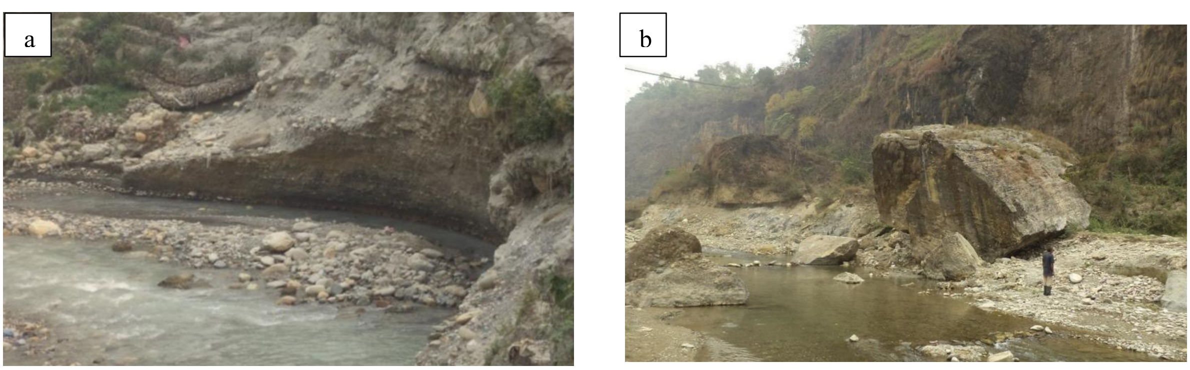

Fig. 4: (a) Riverbank erosion along Seti Khola at Ramghat. (b) Block fall of compacted Ghachok Formation observed along the Kali Khola section.

4.3 Karstification and Sinkhole Hazard

Karstification is one of the most distinctive geological hazards of Pokhara Valley. The valley-fill deposits contain abundant carbonate-rich clasts and calcareous cement. Groundwater circulating through fractures and permeable sediments can dissolve the calcareous materials, gradually producing solution channels, cavities and underground drainage systems. Similar relationships between carbonate-rich valley-fill materials, dissolution and ground instability were identified by Koirala and Rimal (1996), while the caves(Fig.5b) and distinctive karst landforms of Pokhara have also been described in earlier geological and resource studies (Gurung, 1970; Sharma, 1975).

The development of underground voids may eventually cause collapse or subsidence at the surface. Sinkholes (Fig.5a) have been reported from several parts of the valley, and the Armala area is particularly notable for the occurrence of numerous sinkholes. Other urban and peri-urban areas may also experience localized ground instability during the rainy season.

The karst hazard is closely associated with the geological nature of the valley-fill sediments. Areas containing highly calcareous and permeable deposits may be particularly susceptible. The presence of gorge (Fig.5d) caves, underground channels, solution features, sinkholes and waterfalls (Fig.5c) indicates that subsurface erosion and dissolution remain active geomorphic processes.

The hazard has major implications for urban development because buildings, roads and underground infrastructure may be constructed above hidden cavities or weakened subsurface zones. Site investigation is therefore essential before major construction in susceptible areas.

Mitigation should include systematic monitoring, geophysical investigation where necessary, improvement of drainage and restriction of uncontrolled infiltration. Construction should be avoided or carefully designed in areas with known sinkholes or significant subsurface cavities.

Fig. 5: (a) Sinkhole at Gairapatan, Pokhara (b) Mahendra Gufa reveling the beauty of karst topography (c) Davis Fall at Chorepatan (d) Seti gorge at K.I. Singh Bridge.

4.4 Flash Flood Hazard

Flash floods represent one of the most destructive hazards in the Seti River system. These events may result from intense rainfall, sudden release of temporarily impounded water (Fig.6a), mass movements into river channels or other high-energy processes originating in the upper catchment.

The 2012 Seti River flash flood demonstrated the destructive potential of sudden high-energy flows in the Pokhara Valley. The event caused major loss of life and extensive damage to settlements and infrastructure downstream (Fig.6b) and emphasized that areas far downstream from the high Himalayan source region may still be exposed to sudden catastrophic flows. In the broader geological context, the event also illustrates the continuing capacity of the Seti system to transmit high-energy water and sediment flows through the valley landscape.

The hazard is particularly serious because the travel time between initiation and downstream impact may be short. Warning time may therefore be limited. Settlements, bridges, water-supply systems and other infrastructure located within or close to active flood corridors are particularly vulnerable.

Risk reduction requires monitoring of upstream catchments, real-time communication and effective early warning systems. Remote sensing and satellite-based observations can assist in identifying major slope failures, temporary river blockages and changes in high-altitude catchments. Flood-prone areas should also be incorporated into land-use planning.

Fig. 6: (a) Flooded Seti River disrupting the connectivity within Pokhara Metropolitan City (source: Nepal News) (b) Flash flood in Seti River eroding the foundation of the bridge

4.5 Debris-Flow Hazard

The extensive coarse-grained sediments of Pokhara Valley provide evidence of major debris-flow and catastrophic sediment-transport events during the geological past (Fig.7). Previous studies have recognized several phases of large-scale sediment accumulation and suggested that some deposits were emplaced during exceptional geomorphic events (Yamanaka et al., 1982; Fort, 1984, 1987, 2010). More recent investigations have related repeated catastrophic valley infill to large Himalayan earthquakes and associated mass movements (Schwanghart et al., 2016; Stolle et al., 2017).

The presence of repeated debris-flow deposits demonstrates that the Himalayan catchment upstream of Pokhara is capable of generating very large sediment-laden flows. Such events may be associated with extreme rainfall, large slope failures, glacial or avalanche processes, river blockage and, potentially, major earthquakes.

Although catastrophic events may have long recurrence intervals, their potential magnitude is extremely high. Therefore, they should not be ignored simply because no event of comparable scale has occurred during recent decades.

Assessment of debris-flow hazard should include identification of potential source areas, investigation of past deposits, and reconstruction of possible flow pathways and estimation of areas that may be affected. Continued dating and investigation of prehistoric deposits could provide important information regarding the frequency of major events.

Fig. 7: Debris flow sediment deposited along the bank of Seti River with Terrace topography.

5. DISCUSSIONS

The results demonstrate that geological hazards in Pokhara Valley are strongly controlled by the geological history and geomorphological evolution of the basin. The same processes that created the unique landscape of Pokhara have also generated the conditions responsible for present-day hazards. This interpretation is consistent with previous work showing that Pokhara Valley is the product of interacting tectonic, fluvial and catastrophic sedimentary processes (Hormann, 1974; Yamanaka et al., 1982; Fort, 2010; Schwanghart et al., 2016).

The coarse valley-fill sediments are central to this relationship. Their weak consolidation and high content of calcareous material contribute to instability and dissolution. River incision exposes thick sediment sequences and creates steep banks, increasing the possibility of collapse and block failure. Meanwhile, the surrounding hills provide conditions favorable for rainfall-induced landslides. The importance of these deposits in controlling both landscape evolution and geological hazards has also been emphasized by Koirala and Rimal (1996), Schwanghart et al. (2016) and Stolle et al. (2017).

Karstification deserves particular attention because it represents a hazard that is not always visible at the surface. A location may appear stable while subsurface dissolution gradually creates cavities beneath roads or buildings. The rapid urbanization of Pokhara therefore increases concern regarding construction in geologically susceptible areas. Earlier hazard investigations similarly identified dissolution of carbonate-rich valley-fill materials as an important cause of subsurface cavities and localized instability in Pokhara Valley (Koirala and Rimal, 1996).

The Seti River system represents another major source of risk. Under normal conditions, the river is an important component of the valley's natural and cultural landscape. However, high-energy floods and rapid channel processes can become catastrophic. The 2012 flash flood demonstrated the importance of considering hazards generated in distant upstream areas.

The geological record of debris-flow deposition introduces an additional long-term perspective. The large sediment accumulations indicate that the Pokhara basin has repeatedly experienced extreme events. Modern hazard assessment should therefore consider not only frequent processes such as small landslides and bank erosion but also rare, high-magnitude events. This interpretation agrees with the catastrophic sedimentation model proposed by Fort (1984, 1987, 2010) and with more recent studies of earthquake-related valley filling by Schwanghart et al. (2016) and Stolle et al. (2017).

A multi-hazard approach is essential because the hazards are interconnected. Heavy rainfall may trigger landslides, increase river discharge and accelerate bank erosion. A large landslide can block a river and subsequently produce a flash flood. Karstification may weaken the ground and increase susceptibility to collapse. Human activities can also intensify natural processes through uncontrolled excavation, drainage modification and river-resource extraction.

Future hazard management should therefore integrate geological information into urban planning. Hazard-prone river corridors should be protected; unstable slopes should be identified before construction and karst-sensitive areas should receive detailed site investigation. A regularly updated multi-hazard database would support better decision-making.

6. CONCLUSIONS

Pokhara Valley is exposed to multiple geological hazards because of its unique geological, geomorphological and tectonic setting. The major hazards identified are landslides, riverbank erosion and collapse, block fall, karstification and sinkholes, flash floods and debris-flow-related processes.

Landslides mainly affect the surrounding hill slopes and road corridors, whereas riverbank erosion and block fall are concentrated along the Seti River and its tributaries. Karstification is particularly important because of the carbonate-rich nature of the valley-fill sediments, which promotes the formation of underground cavities, caves and sinkholes. Flash floods remain a major threat to downstream settlements, while the widespread catastrophic deposits of the valley indicate the occurrence of large-scale debris-flow events in the geological past.

The study confirms that hazard processes in Pokhara Valley should be considered as interconnected components of a dynamic Himalayan environment. Increasing urbanization and infrastructure development may significantly increase exposure if geological conditions are not considered during planning.

Hazard reduction should therefore emphasize detailed hazard zonation, continuous monitoring, land-use regulation, scientific river management, slope stabilization, improved drainage, early warning systems and public awareness. Particular attention should be given to river corridors, unstable slopes and karst-prone areas.

The geological history of Pokhara Valley provides an important warning for the future. Although some catastrophic processes are rare, their potential consequences are extremely large. Integrating geological knowledge into development planning is therefore essential for building a safer and more resilient Pokhara Valley.

AUTHORS' CONTRIBUTIONS

The first author initiated and carried out the main research work, including field observations, data collection, analysis, and preparation of the first draft of the manuscript. The second and third authors provided academic guidance and scientific supervision throughout the study. They also contributed to the interpretation of the findings, scientific discussion, critical evaluation, and revision of the manuscript. All authors participated in the development of the study and approved the final version of the manuscript.

CONFLICT OF INTEREST

The authors declare that no competing financial, personal, or professional interests exist in relation to the research presented in this manuscript.

DATA AVAILABILITY STATEMENT

The data generated and analyzed during this study are available from the corresponding author upon reasonable request. Interested researchers may obtain the relevant data through direct email communication with the corresponding author.

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