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Evaluating the Effectiveness of Sinkhole Mitigation and Its Impact on the Local Community: A Case Study of the Armala Sinkhole, Pokhara, Nepal

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Abstract

Sinkholes are sunken areas or cavities that appear on level ground when soluble rocks beneath the surface dissolve, often forming suddenly and without warning. The Armala area, located in the Pokhara Formation, intersects with the Ghachock Formation, forming fluvio-lacustrine terraces along the Kali Khola valley with sediments of gravel, limestone, quartz, and gneiss mixed with calcareous silt, clay, and fine sand. A significant sinkhole event in 2013 devastated the Armala area, impacting the local community who faced severe challenges due to the extent and rapid formation of these sinkholes. This study aims to assess the effectiveness of sinkhole mitigation measures and their impact on the nearby community in Armala. This research evaluates the current state of sinkhole prone areas, the effectiveness of existing mitigation structures, and the community's perception of these interventions. Field observations and surveys were conducted among 30 identified households to gather data from affected residents. Results indicate that while the mitigation efforts have positively influenced the community and reduced some immediate risks, challenges remain. Key observations reveal a need for improvement in both the number and condition of mitigation structures, many of which require reconstruction due to poor maintenance. The SPSS evaluation showed that Cronbach's alpha values exceeded 0.67 for all question groups, with an overall reliability of 0.7262, indicating consistent assessment. This study underscores the need for strengthened policies and sustained investment to enhance sinkhole mitigation and community resilience in affected areas.

Keywords: Sinkhole, Mitigation, Community Impact, Armala Sinkhole

1. Introduction

Underground dissolution of limestone and gypsum or salt rock formations creates widespread geological features known as sinkholes. Underground water erodes bedrock through natural depressions or cavities to form voids which ultimately collapse after overlying sediments bear down [1]. Sinkholes are the visible expressions of subsurface dissolution features that result from the dissolution of soluble rocks mainly through water action and are of diverse sizes, forms and kinds [2]. Sinkholes are typical geological structures resulting from subsidence which implies the ground's inability to support the structures above or simply its yielding and the subsequent formation of holes on the surface. They are most common in areas with carbonate rocks like the limestone, or dolomite, in which the rock gradually dissolves because of the water seepage [3]. It does this in such a pattern that it forms voids that may end up with ground surface failure. These cavities may be shallow or large pits. In the world, there are instances of ground subsidence: the slow, steady sinking of earth surface and it is natural and manmade, with causes being erosion, groundwater pumping, and mining [4-8].

The combination of depleted groundwater table together with heavy seasonal rainfall and the soil characteristics above influenced the formation of sinkholes [9]. Sinkholes are primarily form in the soil profile with loose, sandy, clay rich, or alluvial soils overlaying soluble rocks and soil through the subsequent subsidence of dissolution of bedrock and soil materials[10]. Sinkholes typically form in soluble rocks like limestone, dolomite, anhydrite, and gypsum [11-14]. Sinkholes in a soft, calcareous fluvial deposit were triggered by a sudden groundwater table decline, causing significant damage to infrastructure, farmland, and residential areas [10]. Water is helpful in dissolving soluble rocks and in making channels for more water to pass through which tends to expand more cavities[15]. Water flow patterns and earth's geology work together with human groundwater use to speed up sinkhole development[3].

There are generally two types of sinkholes: solution sinkholes and subsidence sinkholes[3]. Solution sinkholes generally occur through the dissolution of surface material in the presence of water whereas subsidence sinkholes arise when overlying soil surface collapse in the voids created by the underling soil material after dissolution with seepage water. Different insitu test shows that in Armala sinkhole loose layer lies over the top of gravelly layer and below it very stiff clayey silt layer which is prone to water soluble [10]. Thus Armala sinkhole is an example of subsidence sinkhole on its formation and characteristics process.

Karst features cover approximately 15 percent of Earth's land area [16]. When sinkholes emerge they create economic, social and environmental problems in both local areas and nearby regions. Entire populations must relocate to safer zones while damaged roads and other infrastructure need major repairs[1]. The development of sinkholes endangers built structures at significant financial and social cost [1, 3, 15, 17, 18]. Life-threatening collapse sinkholes which develop catastrophically result in human deaths. Destructive sinkhole formed in Jili Village China on June 3rd 2010 caused by record rainfall of 470 millimeters in a single day [19]. Six people died while 100 houses were destroyed during this event. A person sleeping in their Florida house died when a cover-collapse sinkhole opened beneath their bedroom on the date of February 28, 2013 [20]. Environmentally speaking sinkholes create major problems [21] because they generate leaks in reservoirs [22] while causing stability issues in mines and tunnels which results in sudden water flows and flooding [23]. People in Nepal and scientists worry about the sudden sinkhole development in Armala, Kaski District.

As part of mitigative efforts the government agency performed sinkhole backfilling but the problem reactivated during rainy seasons and the temporary fix proved ineffective because many sinkholes resumed activity when the rain season arrived [10]. Knowledge of the factors that promote formation and consequences of the sinkholes is crucial in risk assessment of these geological structures. Various civil and industrial engineering activities within sinkhole terrain area are considered risky. Measures should be taken to avoid the possible mishaps including effective evaluation of land quality as well as safe use of water. Proper utilization of the land in areas characterized by sinkhole occurrence needs management measures to mitigative formation of new sinkholes as well as protection of ground water [2]. Local governments, and individuals in sinkhole prone areas can take necessary precautions to prevent loss of lives, property and harm to the environment but seems inadequate [10]. Human activities make sinkholes worse and thus emphasize the importance of developing management strategies together with public education alongside ongoing research into human cause impacts [24].

The multiple types and complex interplay of hydrological and geological factors make it difficult to measure sinkhole collapse mechanisms directly in situ [1]. Current methods for predicting and analyzing sinkholes before surface collapse remain difficult because of insufficient ground research tools alongside insufficient site studies in extensive areas [1]. During site exploration soil heterogeneity creates problems because vital information escapes detection by methods that include boring which cannot identify developing underground voids [1]. The surface depressions discovered using satellite and aerial remote sensing systems fail to always indicate sinkholes primarily due to ground settlements [25].

Local residents face alarming dangers from multiple sinkholes which emerged in the Armala section of Pokhara Valley since November 2013 [10]. The literature on sinkholes in the region of Armala, Nepal, indicates that important aspects related to sinkholes remain unexplored in detail, including the lack of long term monitoring, the poor understanding of the sinkhole subsurface characteristics, and the absence of multi-disciplinary approaches [26]. The main contributors are anthropogenic activities, such as land-use changes, while the effects are still poorly quantified. Moreover the investigation of sinkhole mitigation measures and their effectiveness to the community they impact, as the majority of current mitigation measures do not reflect the quality of the risk presented. So the research questions are as follows: What are the impacts made by the sinkhole in the community of Armala? What are the perception of the local residence by those sinkhole mitigation measures and review of the public?

This research primarily focusses on the study of effectiveness of sinkhole mitigation measures in Armala area and its impact on the community which includes.

- To investigate the impact caused by sinkholes on the community of Armala.
- To overview the public response to the mitigation strategy done by the Nepal government.

2. Study area

The study area, Armala lies in the Northern part of Pokhara valley (Pokhara Metropolitan City ward No: 16), Gandaki Province of Nepal, near Mahendra cave, is a sub basin of the Pokhara Valley. After November 2013 the Armala area experienced multiple unexpected sinkhole hazards. In May 2014, 117 distinctive sinkholes were identified, which measured depth between 1 and 5 meters and possessed diameters from 1 to 15.2 meters [27]. The analysis identified 52 filled sinkholes alongside 12 water filled pits and others were open pits whereas the depth of sinkhole was found to be in the range of 5.7m to 0.9m [27]. From November 2013 investigators spotted more than 200 sinkholes across the Armala region. Most sinkholes that appeared during the observation period formed at paddy field sites across alluvial fan deposits [28]. The Kali Khola's right bank terrace serves as the primary location for sinkhole development with the Duhuni Khola distal fan area being crucial to their development. The study area lies within the Kali Khola river valley, where the Duhuni Khola merges with the Kali Khola, (figure 1and 2). The erosion caused by underground water creates these sinkholes by dissolving silt deposits below the surface [26].

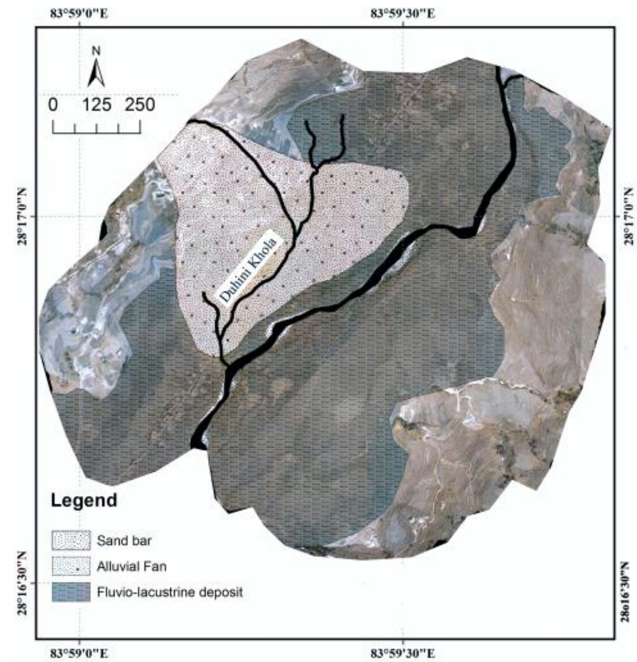
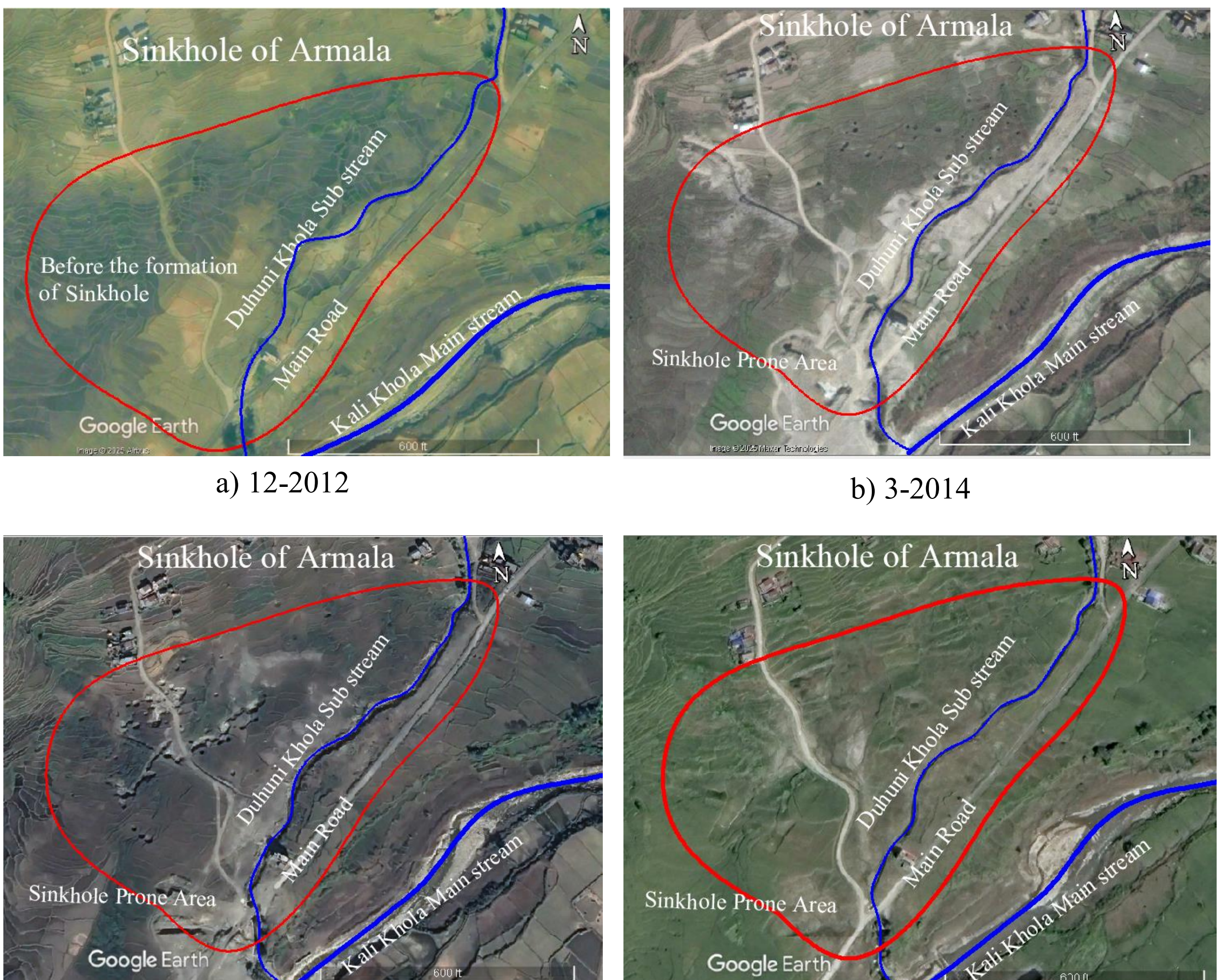


Figure 1: Morphological setting of the study area [26]

Figure 2: Sinkhole affected area Armala [27]

Figure 3 shows the Google Earth image of Armal region from December 2012 to May 2025. Figure 3(a) shows Google Earth image of 2012 before the formation of sinkholes, figure 3(b) and figure 3(c) shows the Google Earth image of March 2014 and December 2014 respectively after the formation of sinkholes, and figure 3(d) and figure 3(e) shows the Google Earth image of December 2016 and May 2025 respectively after the formation of sinkholes. Until March 2016 sinkholes are still seen. After the October 2016 sinkholes are demolish and regular terraced farmland, indicating active agricultural use which combined with high rainfall and irrigation, may have contributed to increased water infiltration and subsurface erosion. The area lies to the west of the main road, near the convergence of Duhuni Khola and Kali Khola. The underlying soil in the region is likely calcareous and loose, making it highly susceptible to dissolution and cavity formation over time.

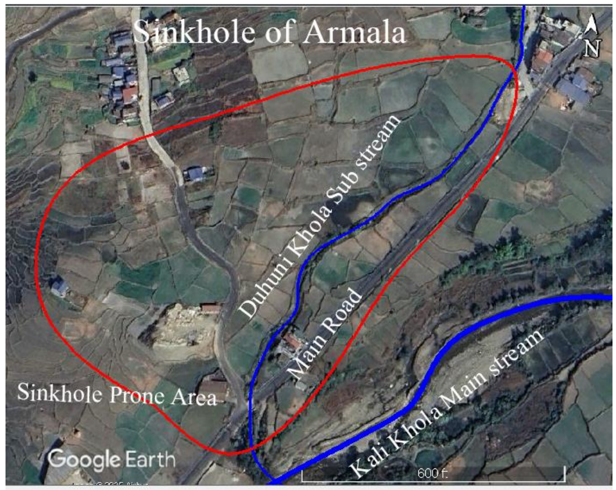


a) 12-2012

b) 3-2014

c) 12-2014

d) 12-2016



e) 5-2025

Figure 3: Different google maps from 2012 AD to 2025 AD indicating different senario of sinkholes of Armala

The topography of the study area is generally gentle, reflecting the influence of these geological processes. Major morphological features in the region include the river channel, the broader river valley, and the fan-shaped deposit. Additionally, these characteristics make the area notable for studying the interactions between river systems, sedimentation, and landform development [26].

The area consists of a sequence of ancient lake and fluvial sediments and forms part of the current floodplain of the Kali Khola. The study area comprises the Ghachok Formation and the Pokhara Formation [29]. The intersection between the Pokhara Formation and Ghachock Formation produced fluvio-lacustrine terraces that shape the Kali Khola river valley throughout the Armala area. The Ghachok Formation [29-31], with its compacted, matrix supported conglomerates and diverse clasts, is highly stable and resistant to erosion. Its features include terrace-like landforms, red-weathered cliffs, and deep gorges, contrasting with sinkhole prone areas where loose, soluble deposits enable collapse. These materials are prone to dissolution, creating voids that collapse into sinkholes. The Pokhara Formation [29-31] consists of fluvial gravel deposited by hyper concentrated flows and lacustrine sediments within tributaries. It overlays the Ghachok Formation in many areas, with vertical contacts observed in some incised valleys. The formation includes clasts of limestone, marble, and occasionally gneiss, phyllite, and quartzite, with clast sizes ranging from cobbles to boulders. Beds vary in thickness, structure, and composition, with fill strath terraces along the Seti River marking distinct levels. Water infiltration could erode finer sediments like silt or clay in the distal parts, potentially leading to voids and collapse. Additionally, the presence of soluble components such as limestone and marble could dissolve with slightly acidic groundwater, forming cavities that may eventually collapse. Variations in the consolidation of sedimentary beds could also create weak zones that become susceptible to collapse under water infiltration. The leaching of calcite from the outer walls may also weaken the structure, creating voids that could collapse. Differential erosion of softer clasts within the formation could further create cavities, making sinkhole development more likely in those areas [31]. Despite both formations being generally resistant to sinkholes, the presence of soluble materials and structural weaknesses increase the potential for sinkhole formation [31].

3. Methodology

This study employs a mixed method approach, combining both quantitative and qualitative techniques for data collection and analysis [32]. Identification of sinkhole of Armala was through study of literature. The methodology involved an extensive review of literature, followed by conducting a questionnaire survey and interviews for the study. The questionnaire was designed using a five point Likert scale. In the scale, 1 denotes ‘strongly dissatisfied’ or ‘strongly disagree,’ 2 indicates ‘disagree’ or ‘dissatisfied,’ 3 stands for ‘neutral,’ 4 signifies ‘satisfied’ or ‘agree,’ and 5 represents ‘strongly agree’ or ‘strongly satisfied.

This research follows a structured methodology, seven-step approach [33]:

1. Step One: Select a research topic, identify the problems, define the research objectives, and create a detailed research plan.
2. Step Two: Conduct an in depth literature review focused on sinkholes.
3. Step Three: Design a questionnaire to be used in the field survey.
4. Step Four: Carry out the field survey, including discussions with relevant stakeholders.
5. Step Five: Distribute the questionnaire to individuals impacted by the sinkholes in the Armala area.
6. Step Six: Analyze the responses collected during the survey.
7. Step Seven: Conclude the research by interpreting the analysis results and providing actionable recommendations.

The questionnaire underwent a pilot survey to evaluate its clarity, ease of use, and the usefulness of the information it could collect. The pilot study ensured the instructions and questions were clear to respondents [34]. It is divided into two sections. The first section covers general information such as name, age, and similar details. The second section focuses on assessing the satisfaction levels of local residents, the impact of sinkholes, the mitigation measures implemented, and their effectiveness.

A total of 30 households were identified in the area, making the study population for this research 30 households located in Armala. Consequently, the sample size for data collection through the questionnaire survey was set at 30, with one member from each household participating. Additionally, data collected through direct observation of sinkhole mitigation structures constructed on the ‘Kali Khola’ and ‘Duhuni Khola’ were studied and analyzed separately, independent of the questionnaire survey.

The data for this research were gathered by visiting the Armala sinkhole and talking to local people. The condition and usefulness of the structures built to control the sinkhole were checked through direct observation. Additionally, a questionnaire survey was conducted among the residents affected by the sinkhole to gather insights into their experiences, perceptions, and the impacts on their daily lives.

4. Reliability and Validity

Cronbach's alpha (α) was used to determine the reliability level of the five-point rating scale within the survey. Studies defining reliability thresholds vary but typically accept 0.7 as the baseline minimum and may accept 0.6 for exploratory investigative studies [35]. Researchers examined each question category's consistency level when they combined the results from all stakeholders interviewed. The SPSS software produced Cronbach's alpha reliability statistics for our questionnaire which are presented in Table 1.

Table 1: Coefficient of Cronbach's Alpha

SN	Factors/variables	Cronbach's alpha
1	To investigate the impact caused by the sinkhole on the community.	0.726
2	Regarding the structure constructed to mitigate the sinkhole.	0.673
3	To study the effectiveness of sinkhole mitigation measures.	0.778
4	Regarding the socio-economic aspect of the sinkhole mitigating measures.	0.759
5	To overview the public response to the sinkhole mitigating strategy done by the Government body.	0.695

The evaluation in SPSS showed that the Cronbach's alpha (α) values exceeded 0.67 for all test data collected at the probability level for each group of questions appearing in Table 1 and demonstrated high levels of consistent assessment within those groups. The questionnaire's overall α value 0.7262 demonstrates consistent reliability between all groups even though question count and consistency levels differed between groups.

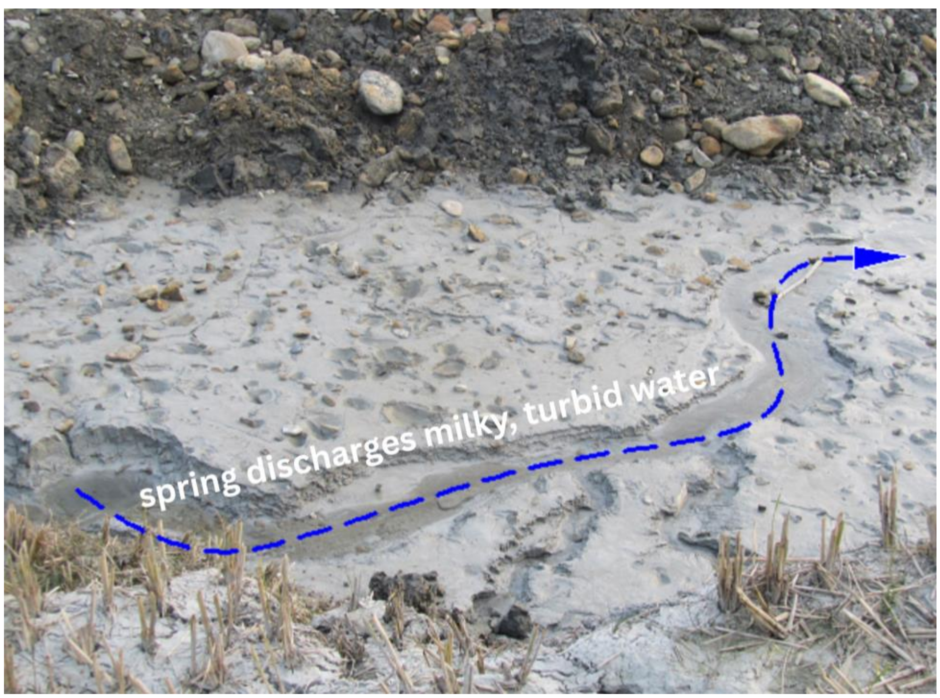
5. Results and Discussion

A total of 30 respondents participated in the questionnaire survey. The age distribution shows that the majority (56.7%) of respondents were between 30–50 years old, with 26.7% aged over 50 and 16.7% aged between 16–30, ensuring representation across different life stages. Gender distribution indicates a higher participation of males (63.3%) compared to females (36.7%), reflecting demographic trends in community leadership and technical roles.

In terms of educational background, respondents ranged from illiterate (13.3%) to those with higher education (3.3%), with the majority holding secondary (36.7%) and informal education (30%). This variety ensures that perspectives from both formally and informally educated members were captured, which is vital for understanding community awareness and responses to sinkhole risks and mitigation.

The field visit was performed in February 2014 and January 2023. Series of sinkholes was observed during 2014 (figure 4(a)). Muddy, silty water observed at the sinkhole (Figure 4(b)) serves as proof of underground erosion and cavity formation in the impacted area. Local people reported seeing muddy water flowing from the riverbank of Kali Khola, just below where Duhuni Khola joins it. Figure 4(c) shows signs of a subsurface water flow at the base of a sinkhole. Soil pipe had formed within a white silty clay layer and was surrounded by milky, turbid water.

(a) Series of sinkhole formation and accumulation of spring and precipitated water



(b) A sinkhole showing the formation of milky water spring

(c) One of the sinkholes revealed the presence of a soil piping

Figure 4: Photographic evidence from February 2, 2014, showed a series of sinkholes that had appeared in the Armala region

The study evaluates data gathered from the direct inspection of structures built after the sinkhole formation in 2013. A total of 11 mitigation structures were identified during the field inspection (figure 5). The assessment of eleven sinkhole mitigation structures constructed in Armala, Pokhara, reveals varying conditions and effectiveness. Most of the structures are gabion check dams and gabion walls, with lengths ranging from 15 to 35 meters, and heights up to 3 meters. While some structures, such as the gabion check dam with side protection and the random rubble stone masonry wall, are in good and workable condition, others show signs of significant damage. Notably, three check dams are reported as fully damaged or non-functional. Additionally, one gabion wall is partially affected by a landslide. As per RM Pokhrel et. al. during the formation of sinkhole in 2013, the government agency attempted to backfill several sinkholes as a countermeasure, but this proved to be a temporary and ineffective solution, as most of them reappeared during the rainy season [10]. Although many suggestions from many researchers [10] have not yet been implemented, appropriate engineering countermeasures were considered to reduce sinkhole risks. But from the field observations, it is found that some mitigation measures remain effective, many require maintenance or redesign and reconstruction to enhance their performance and resilience against future sinkhole activity.

a) Gabion wall in the verge of failure at the right bank of Kali Khola

b) Concrete channel to convey Duhuni Khola

c) Bulging gabion wall

d) Dry masonry retaining wall

Figure 5: Different mitigating structures constructed in regions of sinkhole formation area of Armala

Many of them are either partially or completely damaged, and no significant efforts have been made by the responsible authorities to repair or reconstruct them. The materials used in construction were also found to be of poor quality, as concrete layers have been eroded by water. Additionally, the Bio-Engineering and Geo-Textile measures were poorly constructed and inadequately implemented. By comparing the field inspection results with public perceptions collected during the survey, it is evident that the authorities have failed to provide adequate attention, maintenance, and reconstruction of the existing structures. Moreover, minor sinkhole formations have been reported recently in certain parts of Armala (Figure 6).

a)

Figure 6: Picture of Sinkhole Affected Building

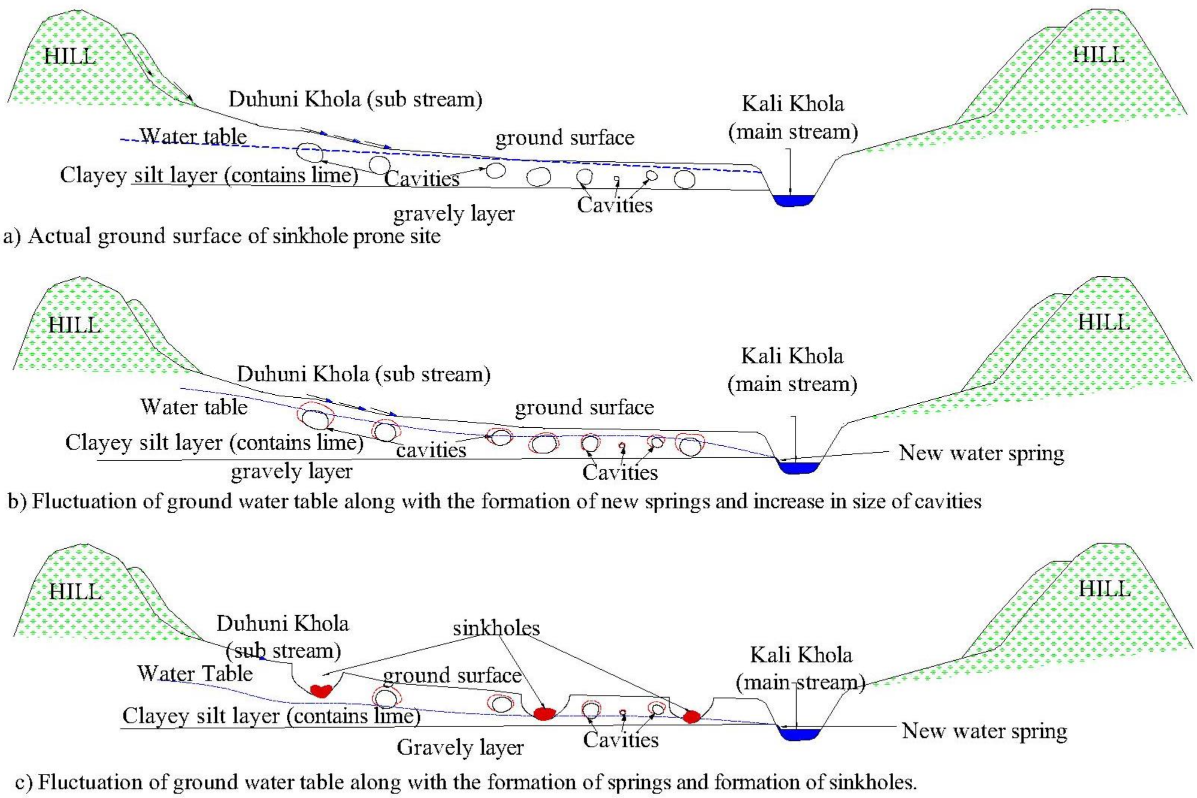


Figure 7: Possible cause of sinkhole formation in Armala regions, of Pokhara Metropolitan City

The possible cause of sinkhole formation in Armala is primarily due to groundwater dynamics and internal erosion of soil. In the long run, groundwater flow gradually dissolved the soluble calcareous materials [10, 26] in the subsurface soil, creating underground cavities which were stable before 2013. However, after November 2013 new sinkholes were developed in Armala area [26]. This all was attributed by formation of new water spring, sudden fluctuation of groundwater table, particularly during rainy season. Also the seepage from Duhuni Khola and lowering of water level of Kali Khola further increase the hydraulic gradient, accelerating groundwater velocity. As a result, the dissolution and washing away of subsurface calcareous soils, resulted collapsed of overlying loses and unconsolidated soils into the voids. These all activities resulted in the sudden and unstable formation of sinkholes (Figure 7).

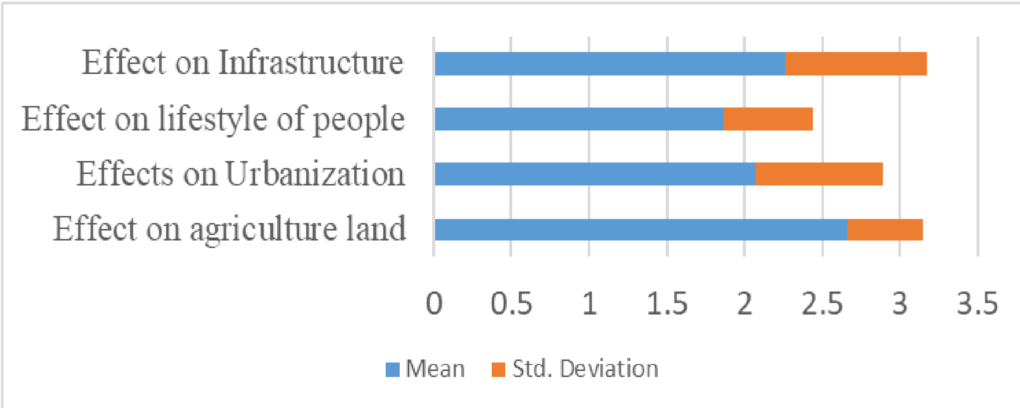


Figure 8: Respondents' View on the impact caused by sinkhole

Figure 8 illustrates respondents' perceptions of the impacts of sinkholes, with agricultural land being the most affected (mean = 2.6667), followed by infrastructure (mean = 2.2667), urbanization (mean = 2.0667), and lifestyle of people (mean = 1.8667). The low standard deviation for agriculture (0.4794) indicates consistent responses, while the higher deviation for infrastructure (0.9071) reflects varied opinions [36, 37]. The overall mean of 2.2166 suggests a moderate impact across all categories, with agriculture and infrastructure experiencing the most significant effects. These findings highlight the need for targeted measures to address damages to agriculture and infrastructure to mitigate sinkhole impacts effectively. Mostly, the agricultural land was found to be affected due to the sinkhole and also the urbanization of the place is impacted. As per the public, the fear of the sinkhole has caused the people to migrate to other safe place that result in the decrement of the development of that area as residential hub [20].

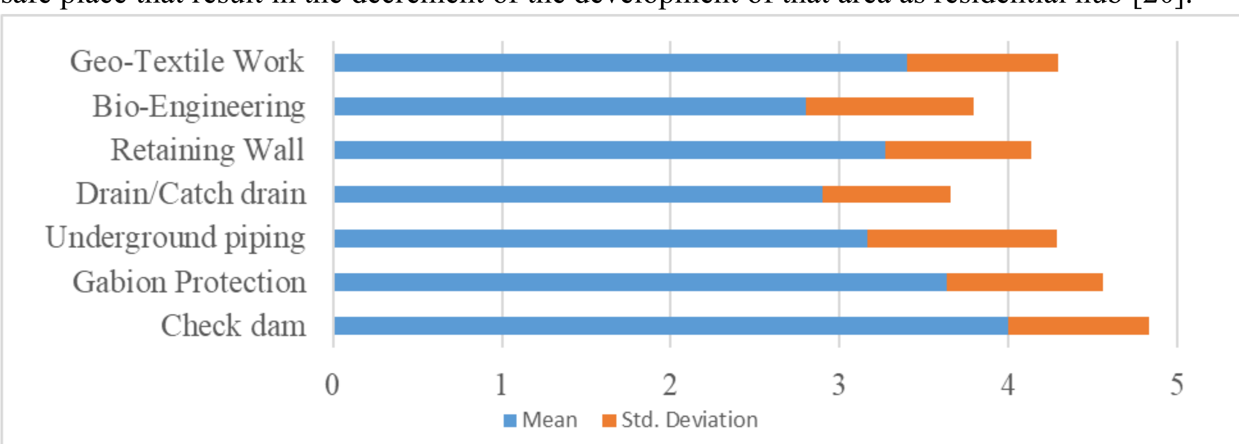


Figure 9: Respondents level of satisfaction on structure constructed to mitigate the sinkhole

Figure 9 highlights public feedback on sinkhole mitigation structures, with check dams rated the most effective (mean score: 4), followed by gabion protection (3.6333), geotextile work (3.4), and retaining walls (3.2667). Measures such as underground piping, drainage systems, and bioengineering received lower scores, with bioengineering being the least effective (2.8). Public perception aligns with field observations, indicating that while check dams and gabion structures are widely used, other mitigation methods are not effectively implemented. Thus a more effective approach for safe development is to minimize structural vulnerability by incorporating designs that can withstand subsidence [38].

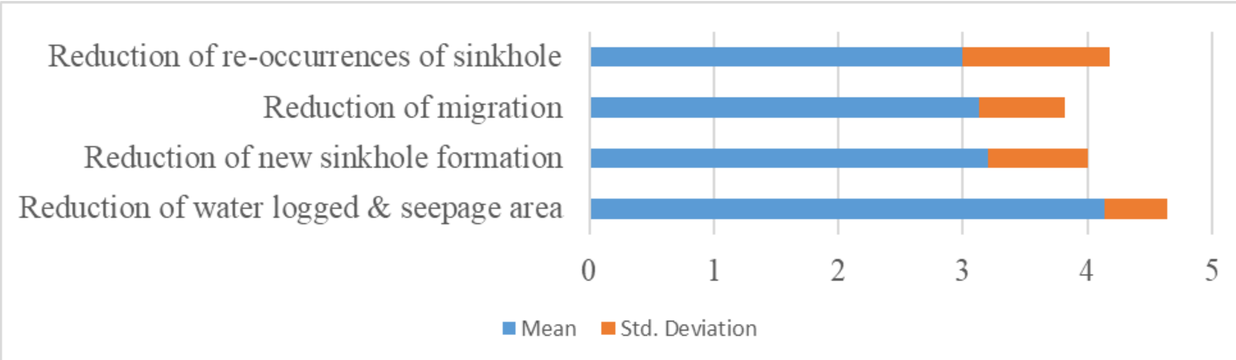


Figure 10: Respondents view on the effectiveness of existing sinkhole mitigation measures

Figure 10 shows the responses of the respondents to the question of the impact of the existing structure constructed to mitigate the sinkhole on various parameters. Public perception indicates that the existing structures designed to mitigate sinkholes have had only a minimal impact. While these structures have helped reduce seepage to some extent, residents remain dissatisfied due to the continued formation of new sinkholes and the re-occurrence of existing ones. Additionally, small sinkholes are still appearing in the area, further contributing to the community's concerns.

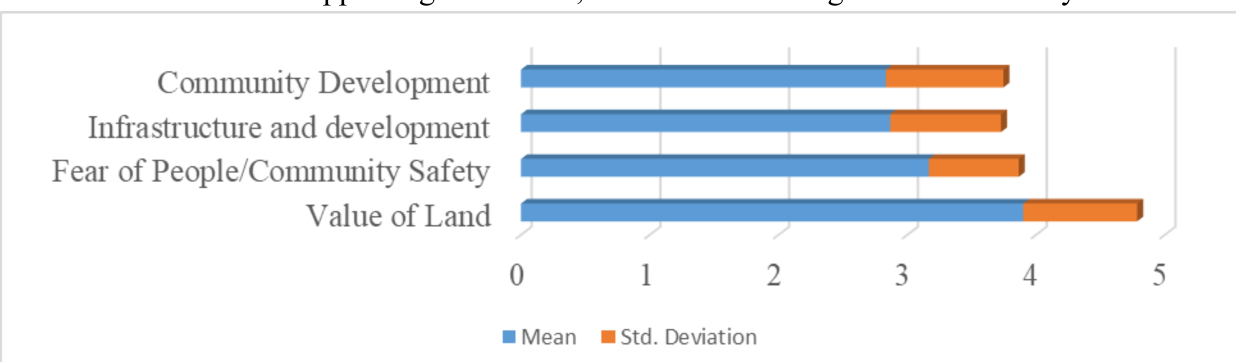


Figure 11: Social Impact of sinkhole mitigation Measures

The Socio-Economic aspect of sinkhole mitigation measures on various parameters is shown in Figure 11. The formation of sinkholes has led to strong public concern about their significant impact on land value. The results indicate that the presence of a sinkhole has a negative impact on property [39, 40]. Community safety is perceived as the second most affected area, as sinkholes create an unsafe environment for residents. The threat posed by sinkholes must be addressed to maintain the safety of communities [41]. Sinkholes are dangerous for buildings and roads because they happen suddenly and make the ground weak or collapse [40, 42]. Additionally, sinkholes negatively impact infrastructure and overall development within the community, causing delays and setbacks in progress and growth.

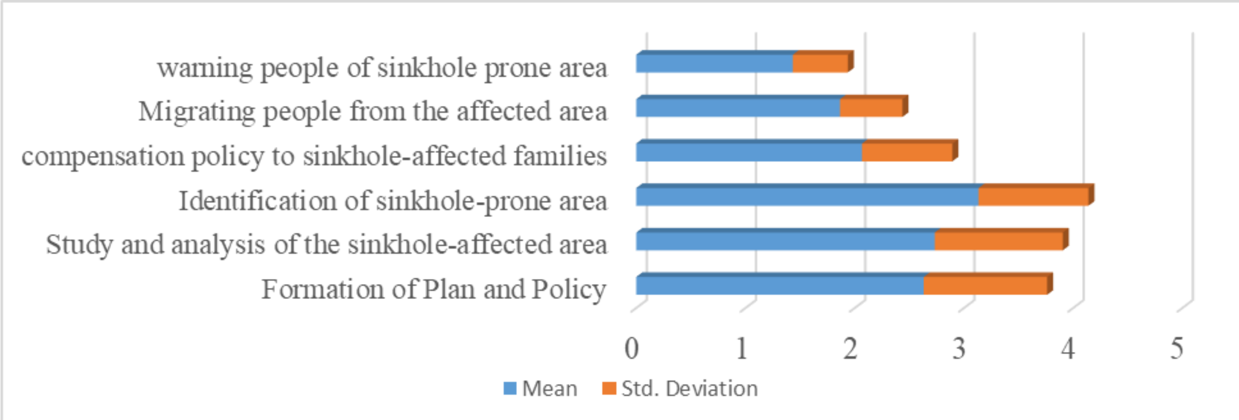


Figure 12: Respondents' View on the strategy of the government to mitigate the sinkhole

Figure 12 shows the responses of the respondents to the question of the government's strategy to mitigate the sinkhole on various parameters. According to public feedback, people are dissatisfied with the government's strategy to address the sinkhole issue. They feel the government has not prioritized developing plans and policies for areas prone to sinkholes. Additionally, there is discontent with the compensation policies for families affected by sinkholes and a lack of agreement on relocating people to safer areas. Local authorities can play a key role in managing the environmental and structural effects caused by sinkholes [43]. Moreover, the government has failed to play a significant role in warning residents living near areas at risk of future sinkhole formation.

6. CONCLUSIONS

Sinkhole formation is a significant issue in the current era, often considered a disaster due to its sudden occurrence and potential to cause severe damage to infrastructure and human life. In the case of Armala, a previously occurring sinkhole had substantial impacts on the local community, lifestyle, and economic status. To address the effects of sinkholes and prevent future occurrences, various mitigation structures have been constructed over time. However, minor sinkhole formations are still visible in some areas of Armala.

This study conducted a survey to assess the status of sinkhole mitigation structures built to address the 2013 sinkhole and reduce future risks. Public perceptions regarding sinkhole formation, the effectiveness of mitigation structures, and the government's policies and by-laws were collected and analyzed. A descriptive methodology was employed, which is more structured than exploratory research, enabling statistical inferences to be drawn from the collected data.

Based on the survey and inspections, the following findings and conclusions were drawn:

1. The sinkhole mitigation measures implemented after the 2013 sinkhole event were relatively effective, as no major sinkhole formations have occurred since. However, some mitigation structures were found to be damaged and require repair or reconstruction.
2. Sinkhole formation has hindered the urbanization and development of the community, negatively affecting the lifestyle of residents.
3. While the government has made efforts to mitigate sinkholes and applied various measures,

there has been a lack of significant progress in infrastructure development and land planning.

4. Plans and policies related to legal aspects of civil engineering, such as residential construction, roads, and land transactions, have not been effectively formulated or implemented.

In conclusion, while the initial mitigation measures were effective in preventing further major sinkholes, there is a pressing need for repairs, improvements, and comprehensive planning. Greater government effort in infrastructure development, land-use planning, and policy enforcement is crucial for addressing technical, social, and economic challenges faced by the affected community in Armala.

Conflicts of Interest Statement

The authors declare no conflicts of interest for this study.

Data Availability Statement

The data that support the findings of this study are available from the main author upon reasonable request.

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