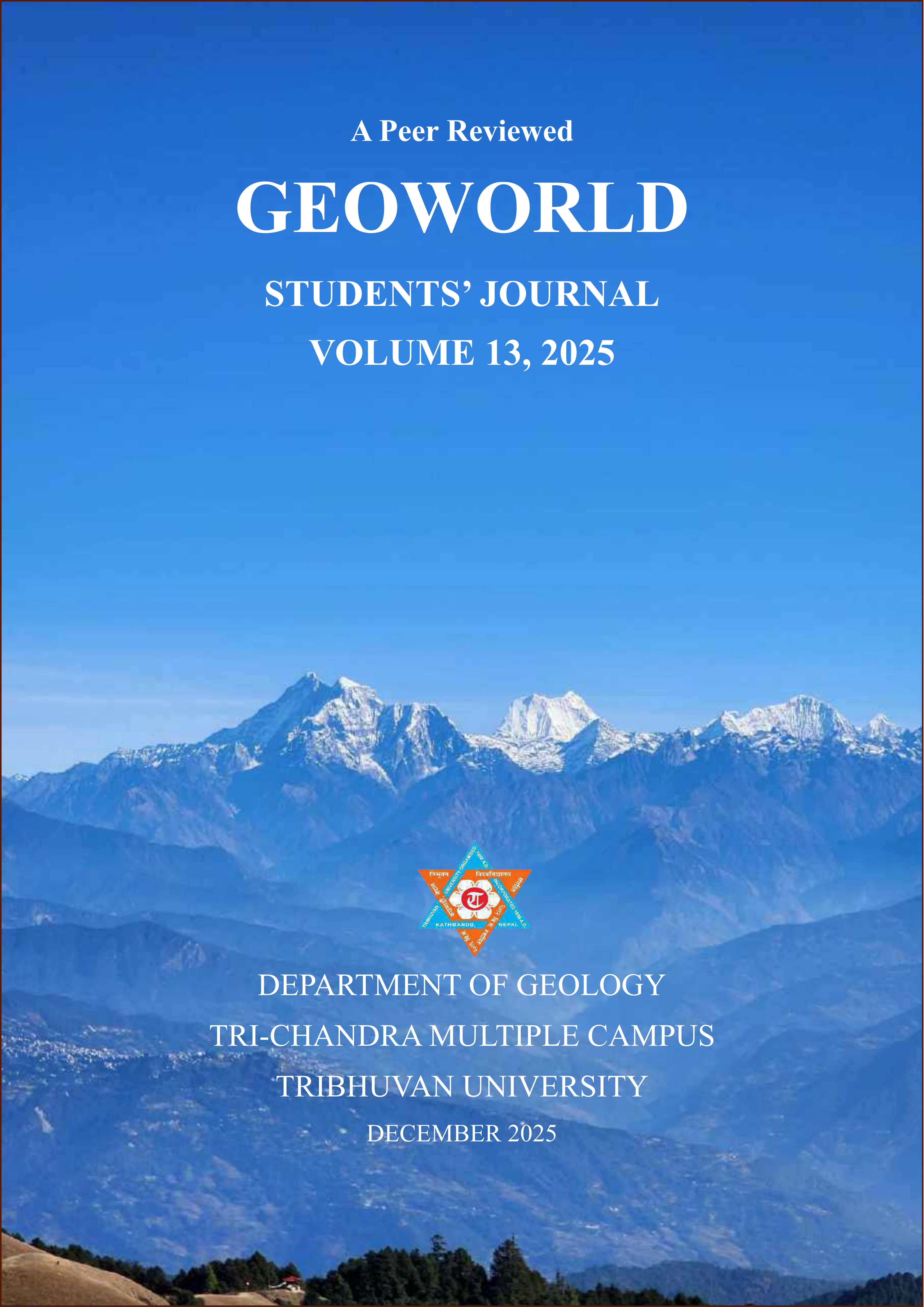
A Peer Reviewed

GEOWORLD

STUDENTS' JOURNAL

VOLUME 13, 2025



DEPARTMENT OF GEOLOGY
TRI-CHANDRA MULTIPLE CAMPUS
TRIBHUVAN UNIVERSITY
DECEMBER 2025

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ISSN: 3021-937X (PRINT)

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ISSN: 3021-937X (Print)

EDITORIAL BOARD

ISSN: 3021-937X (Print)

MESSAGE FROM THE CHIEF EDITOR

It is with great pride and excitement that we present the peer-reviewed GEOWORLD STUDENTS' JOURNAL. On behalf of the editorial team, I extend a warm welcome to all our readers. We are thrilled to share with you the 13th volume of the Geoworld Students' Journal, the annual publication of the Geology Department at Tri-Chandra Multiple Campus.

This milestone is a testament not only to our dedication to academic excellence but also to the collaborative effort that made this achievement possible. The journey of publishing this journal has been both rewarding and challenging, requiring collective effort in gathering articles, encouraging participation, and refining submissions to create a resource that truly benefits students.

GEOWORLD STUDENTS' JOURNAL continues to be an independent platform designed to support geology students in honing their research and writing skills. The journal provides a forum for sharing insights on a wide range of earth science- related topics. These include but are not limited to environmental concerns, geo- hazards, hydrogeology, geomorphology, engineering surveys, GIS applications, and much more. Contributions range from overviews and review studies to case studies, interviews, and analytical reports.

Our team has worked tirelessly to improve the quality of submissions, streamline manuscript processing, ensure fair peer reviews, and enhance the editorial workflow.

The journal reflects a research-oriented approach, bridging the gap between academic inquiry and professional practice in geology. Under the guidance of our esteemed professors, I believe we are on the right path toward achieving this goal. We also encourage more contributions from the broader scientific community and industry experts to ensure the continued growth of the journal. We welcome submissions, feedback, and suggestions to improve the quality of GEOWORLD. Thank you for your support, and we hope you find this issue both informative and engaging.

Disclaimer: The articles, views and ideas have been presented by individual authors themselves. The author is solely responsible in case of plagiarism. The publisher is also not responsible for expression of any opinion concerning the legal status of any country territory, city or areas of its authorities or concerning the delimitation of its frontiers or boundaries.

Thank you.

Subash Bhandari

Chief Editor

ISSN: 3021-937X (Print)

ACKNOWLEDGEMENT

The GEOWORLD STUDENTS' JOURNAL Volume 13 extends sincere gratitude to all individuals whose support and collaboration have been fundamental to the completion of this journal.

A special thanks goes to Associate Professor Dr. Subodh Dhakal, Head of Department of Geology at Tri-Chandra Multiple Campus. His support and encouragement are greatly appreciated. The immense support provided by the faculty members and department staffs has been detrimental in the completion and publication of this journal.

The volume is indebted to Mr. Dinesh Kumar Napit, Director General of Department of Mines and Geology of Nepal, Mr. Bhaskar Khatiwada, President of 22nd Executive Committee of Nepal Geological Society and Mrs. Arishma Gadtaula, Engineering Geologist at Nepal Electricity Authority for graciously accepting out invitation to interview despite their busy schedule. Your insight and experience shared will make a great impact on the readers.

We would like to express our appreciation to the authors, 4th year BSc. Geology students from Tri-Chandra Multiple Campus, Kathmandu and Prithvi Narayan Campus, Pokhara as well as M.Sc Geology students from Central Department of Geology, Tribhuvan University, Kathmandu for their invaluable contribution of time, energy and knowledge for the journal. Their enthusiasm in contributing an article for the journal was exceptional. We are also grateful to the review committee formed within the editorial team, who shared their suggestions and expertise in enhancing the quality of articles provided. The review committee help in maintaining the standards of the journal is recognized.

The editorial board who has endlessly and tirelessly worked and led the journal to the completion and publication is highly regarded. Their dedication to the success of the journal is invaluable. We would also like to express our gratitude to Mr. Aadit Silwal for contributing the image captured from the top of the Sailung Hills located in Dolakha District which is used as the cover.

We are also indebted to Mr. Bhaskar Khatiwada, Managing Director of Geo Hydro Consult Pvt. Ltd. for facilitating the publication of our Journal.

Last but not the least, the journal would like to thank each and every individual who has directly or indirectly been part of our journey.

Thank you.

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Tri-Chandra Multiple Campus
स्थापित : १९७५ वि.सं./Estd. 1918 A.D.

क्याम्पस प्रमुखको कार्यालय
Office of the Campus Chief
पत्र संख्या/Ref. No.:-

सरस्वती सदन, घण्टाघर, काठमाडौं, नेपाल
Saraswati Sadan, Ghantaghar, Kathmandu, Nepal

Date: 2082/08/14

TRI-CHANDRA MULTIPLE CAMPUS 1918 A.D. SARASWATI SADAN, GHANTAGHAR KATHMANDU

Message from the Campus Chief

I am pleased to commend the peer reviewed GEOWORLD STUDENTS' JOURNAL Committee and the Department of Geology, Tri-Chandra Multiple Campus, for their exceptional efforts in creating a dynamic platform for students and professionals to publish their scholarly work. Your dedication in preparing and presenting Volume 13 of the GEOWORLD Students' Journal is highly commendable and reflects positively on the academic standing of our institution.

GEOWORLD continues to serve as a significant medium for the exchange of innovative ideas and research findings. I am confident that Volume 13, with its diverse range of articles, will contribute meaningfully to the academic community and further enhance the reputation of our college as a leading center of geological education and research excellence.

I extend my sincere congratulations to everyone involved in the publication of this journal. Your commitment to advancing academic knowledge and promoting intellectual growth is truly appreciated.

Prof. Dr. Nilam Shrestha Pradhan

Campus Chief

Tri-Chandra Multiple Campus

Tribhuvan University, Nepal

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Saraswati Sadan, Ghantaghar, Kathmandu, Nepal

Institute of Science & Technology
Tri - Chandra Campus

Date: December 10, 2025

Message from the Department Head

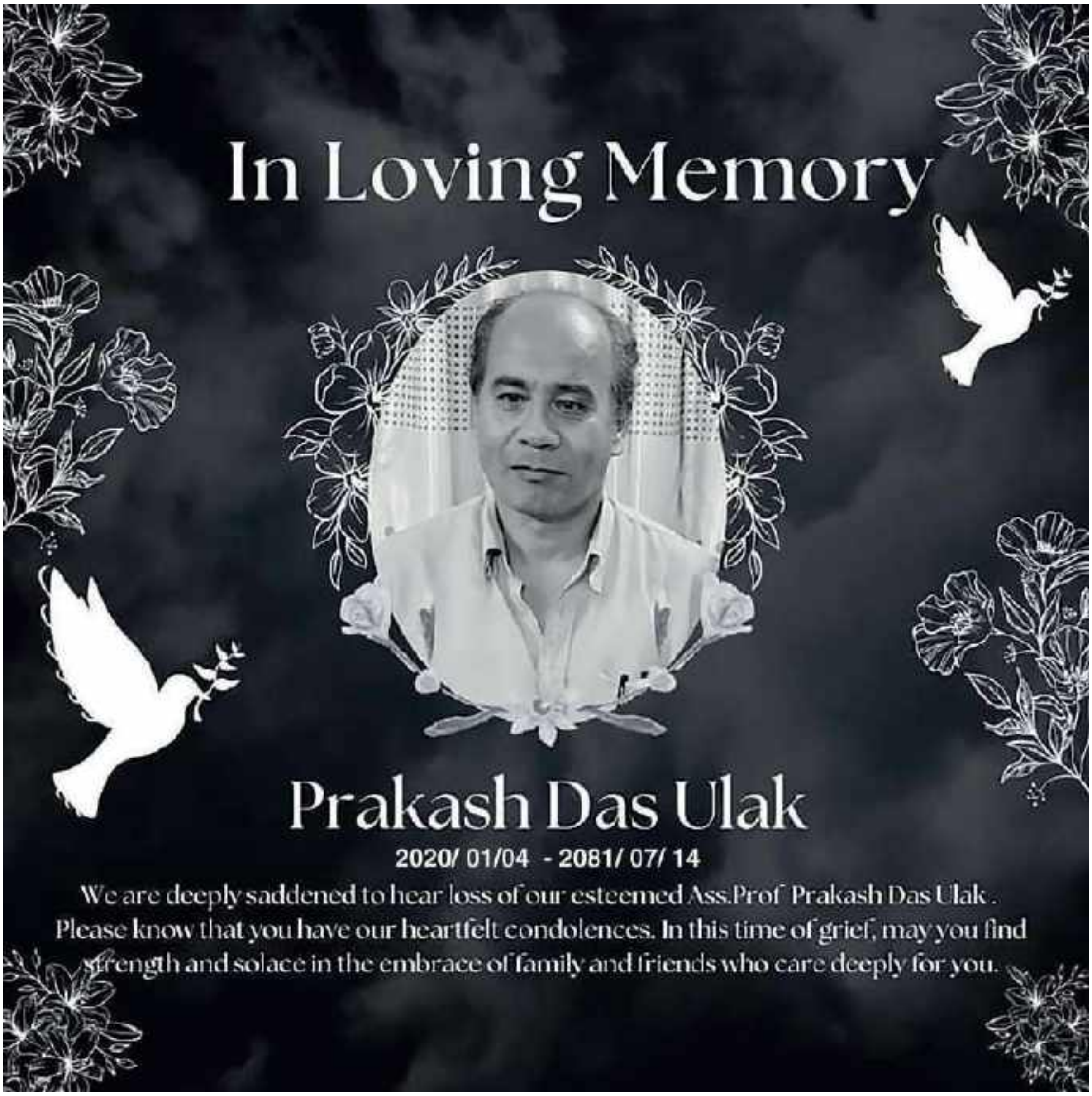
It is my privilege to write this message regarding the publication of "GEOWORLD" Student Journal, Volume 13 by the students of B.Sc. 4th Year in Geology (2077 batch) at the Department of Geology, Tri-Chandra Multiple Campus. I would like to congratulate the editorial board, contributors and all the students of B.Sc. 4th Year in Geology at our department. This type of publications from the sole endeavors of students is really a commendable work and I am happy to be a part of it as the Head of Department. I am confident that the entire process of publishing a student journal provides the ample opportunities to increase the research capacity and other academic capabilities of our students. I have been motivating students in this type of academic activities and confirm my commitment from the Department of Geology, Tri-Chandra Multiple Campus to increase such activities in future.

I encourage our students to work further in increasing the quality of the journal by incorporating the research papers from diverse field of geology and diverse group of people from within the geological community. I am confident that this will ensure the ownership of this journal by each and every student of the respective batch.

I wish all the success of our outgoing students for their academic and research endeavors in future.

HEAD
Department of Geology
Tri-Chandra Campus

Subodh Dhakal, PhD
Head
Department of Geology, Tri-Chandra Multiple Campus
Tribhuvan University, Nepal


In Loving Memory
Prakash Das Ulak
2020/ 01/04 - 2081/ 07/ 14
We are deeply saddened to hear loss of our esteemed Ass.Prof Prakash Das Ulak .
Please know that you have our heartfelt condolences. In this time of grief, may you find strength and solace in the embrace of family and friends who care deeply for you.

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INTERVIEW REGARDING ATTRIBUTES OF DEPARTMENT OF MINES AND GEOLOGY

Dinesh Kumar Napit
Director General
Department of Mines and Geology

Mr. Dinesh Kumar Napit is the Director General of the Department of Mines and Geology (DMG), Government of Nepal. With over two decades of professional experience, he has held several key positions within DMG, including Deputy Director General (Spokesperson) and Project Chief of the Petroleum Exploration Promotion Project. He has contributed significantly to Nepal's mineral exploration, petroleum promotion, and geoscience-based resource management. Mr. Napit is also active in professional societies, serving as General Secretary of the Nepal Geological Society (2013–2015). His leadership focuses on strengthening geological research, sustainable resource utilization, and policy development in Nepal's mineral and energy sectors.

Could you please introduce the Department of Mines and Geology and its major works?

The Department of Mines and Geology (DMG) is the sole government organization which is responsible for all types of geological survey, mineral exploration and administration of Mining Rules and Regulations in Nepal. The Department of Mines and Geology (DMG) has long history since its creation as an "Office of Irrigation and Geology" in 1926. In 1942, it was renamed as the "Office of Mines" which was expanded to "Bureau of Mines" in 1961. In 1967, the Government has created a new, separate institution and named as "Nepal Geological Survey'' for more geo-scientific survey and research activities. In 1977, both the Bureau of Mines and the Nepal Geological Survey were amalgamated and named as the "Department of Mines and Geology". The major activities of the department are:

- Geo-scientific Survey and Research
- Engineering and Environmental Geological studies and Hazard assessments
- Seismo-tectonic studies and Earthquake monitoring
- Mineral exploration, evaluation and promotion of mineral-based industries and administration of Mineral and Mining Rules and Regulation
- Petroleum and Natural Gas Exploration.

We wonder to know about the current priorities of DMG.

At present, DMG's priorities are aligned with national development goals and the growing need for scientific decision-making. We are focusing on exploration and evaluation of mineral deposits/prospects, promotion of mineral-based industries for the benefit of the people and support the economic development of the country. We are working on geological study and geophysical exploration of promising sites for petroleum and natural gas in the country and attract foreign oil companies to invest in petroleum exploration, development and production of oil and natural gas in Nepal. We are also prioritizing engineering and environment geological mapping and hazard assessment of fast-growing urban areas, and publication of engineering and environment geological maps which are suitable for multiple use especially in infrastructure development planning and urban area development. We are accelerating seismic/tectonic studies and earthquake monitoring to delineate the earthquake hazard/risk areas, publication of earthquake epicenter maps and conduct earthquake awareness programs in different parts of the country especially densely populated urban areas. We aim to complete geological mapping, landslide hazard mapping of the country, and regular publication of geological and landslide hazard zonation maps and make available to the organizations, institutions and individual involved in the infrastructure development works. Furthermore, we aim to promote responsible mining practices in coordination with federal, provincial, and local governments.

Can you share the recent achievements of DMG in the field of mineral exploration?

In recent years, DMG has made significant progress in expanding the country's understanding of its mineral resources. We have identified several promising new prospects for metallic minerals such as copper, lead–zinc, iron, and other valuable deposits. DMG has completed detailed investigations of important industrial minerals, including limestone, dolomite, marble, and gypsum, which are essential for Nepal's construction and manufacturing industries. We have also advanced petroleum exploration efforts, particularly through the verification of natural gas seepage in Dailekh and improved geological understanding of Nepal's hydrocarbon potential. As a result of successful mineral exploration, several mines are in operation and sixteen types of minerals are under production such as Coal, Dolomite, Granite, Iron, Kaoline, Kyanite, Limestone, Magnesite, Marble, Red Slab stone, Sand, Clay, Quartzite, Quartz, and slate. Total of 144 mining licenses have been provided for the production of these minerals. More than 50 cement industries have been established in the country and we are self-sustained in cement production. DMG has completed exploratory drilling of 4,013 m in Dailekh with the discovery of promising deposit of Natural Gas.

What are the main challenges in mining and geological studies in Nepal?

Nepal occupies major part of the Himalaya having it's unique geological setting and varied topography with numerous challenges in mining and geo-scientific work. The rugged Himalayan terrain makes many areas difficult to access, and the lack of large-scale investment limits the scope of advanced exploration and modern mining operations. There are also gaps in specialized equipment and human resources needed for deep scientific investigations. Environmental sensitivities and the need to balance development with conservation add further complexity. Fieldwork in Nepal has frequently affected this situation. In addition, limited private-sector confidence continue to affect the growth of the mining industry.

How is DMG using modern technology like GIS and remote sensing for exploration?

DMG has been steadily integrating modern technologies to improve the accuracy and efficiency of geological studies. We are actively using GIS for geological and engineering mapping, identifying mineral targets, studying geological structures, and monitoring geo-hazards. We are increasingly using drone-based surveys to map difficult terrain and obtain high-resolution imagery. We have Remote Sensing and Geological Data Center with the physical facilities that are available in the branch: Erdas Imagine 8.4, ArcGIS 10, A0 color plotter/Scanner. DMG is using modern geophysical methods for mineral exploration and other purposes such as Electrical Resistivity Survey with IP, Ground Penetrating Radar, Proton Magnetometer Survey ERT survey with DGPS, LiDAR and Hyperspectral Imaging, Power Auger Survey, Seismic Reflection Survey, Magnetoteluric Survey, Rotary Drilling and Geophysical well Logging.

How does DMG manage and share geological data and research?

DMG maintains geological data that includes geological maps, mineral occurrence records, seismic data, and geohazard inventories. DMG publishes geological maps, annual bulletins, technical reports, and research papers, ensuring that valuable knowledge reaches policymakers, researchers, and development planners. DMG Annual Report, DMG News Letter, Informative Booklets, Brochure on petroleum exploration, National Seismological Centre and their activities, geological maps, engineering and environmental geological maps, landslide hazard zonation maps, earthquake epicenter map, mineral resources maps are the major publication of the department. We also collaborate closely with government agencies, universities, and researchers to share data and expertise.

Could you explain DMG's role in studying natural hazards like landslide and earthquakes?

DMG plays a central role in assessing and understanding natural hazards in Nepal. Regarding the landslide hazard assessment in Nepal, we are continuously engaged in the study of Large-Scale Landslides, Landslide Inventory Mapping, Landslide hazard zonation mapping, development and establishment of Awareness program and Landslide early warning system. Our teams conduct landslide mapping, slope stability assessments, and hazard zoning to support safer settlement and infrastructure planning. In the field of earthquake science, we prepare seismic hazard maps, conduct microtremor studies, and investigate active faults across the country. National Earthquake Monitoring and Research Center (NEMRC) is continuously recording and monitoring earthquakes in Nepal since 1978 and providing timely information to the public and government agencies. DMG as seismic networks that covers whole Nepal. NEMRC has 16 short-period stations, 26 Broadband Stations, 36 Accelerometric stations for strong ground motion and 51 GPS stations for crustal deformation monitoring. During major disasters, like in Gorkha Earthquake in April 2015, and flood and landslide in Monsoon 2024, our experts carry out rapid geological assessments to guide rescue operations and reconstruction planning. Some of the examples are rapid landslide assessment: Several settlements of 19 districts and 125 local bodies completed after Gorkha Earthquake in April 2015, damage assessment of Melamchi flooding, damage assessment with Drone Mapping, after Monsoon (27-29 Sept 2024) in Nallu Area, Lele Kaphal Dada area Lalitpur, Roshi area of Kavre. We carried out detailed study on landslide in different parts of the country. Some of the examples are Jure Landslide of Sindhupalchok District (2014), BhasuvanLandslide of Achham (2009), Durlung Landslide of Parbat (2020), Taparang Landslide of Kaski District (2010), Ramaroshan Landslide of Achham (2020), Melamchi Debris Flow of Sindhupalchok (2021), debris flow in Tiljung Khola, Limi Valley of Humla District (15 May 2025). We also contribute to early warning initiatives and provide technical recommendations to improve disaster resilience.

What opportunities are available for young geologists and researchers at DMG?

We are trying to have an MoU with Tribhuvan University and other universities so that young geologists and researchers have several opportunities at the Department of Mines and Geology (DMG), including involvement in geological mapping, mineral exploration, petroleum and natural gas studies, engineering geology, and geohazard assessment. They can participate in field surveys, laboratory analysis, GIS and remote-sensing work, seismological studies, and research collaborations under DMG's guidelines. DMG is ready to provides openings for junior geologists, project-based roles, internships, and research permits for academic studies, offering young professionals a platform to gain practical field experience, develop technical skills, and contribute to Nepal's resource development and disaster resilience.

What is your vision for the advancement of DMG's future targets?

My vision for DMG is to transform it into a modern, technology-driven, and internationally recognized Nepal Government's geoscience institution. I aim to enhance mineral and petroleum exploration activities to reduce Nepal's import dependency and support national economic growth. I also envision a future where geohazard monitoring and early warning systems are fully integrated into national level. Strengthening the digital geological database and promoting open access to geoscience information are key components of this vision. Furthermore, I hope to foster greater national and international collaboration in research, capacity building, and technology transfer. Ultimately, DMG also wants to ensure that all exploration and mining activities remain environmentally responsible and socially beneficial.

Finally, do you have any message you would like to share with young geologists and the readers of our journal?

For the young geologists, I would like to emphasize that geology is a discipline founded on curiosity, careful observation, continuous learning and a lot of real time challenges and difficulties. I encourage them to field based knowledge and experiences, as true geological insight emerges from direct interaction with nature. At the same time, they should embrace modern technologies and analytical tools, since the future of geoscience will increasingly be shaped by digital innovation. Their role is vital in strengthening Nepal's resource development, infrastructure expansion, and disaster resilience. To the readers of your journal, I express my sincere appreciation for your dedication to advancing geoscience knowledge. Academic platforms such as this journal plays an essential role in fostering scientific dialogue and supporting the growth of Nepal's geological community.

ISSN: 3021-937X (Print)

INTERVIEW REGARDING ROLES AND FUTURE PLANS OF PRESIDENT OF NEPAL GEOLOGICAL SOCIETY

Mr. Bhaskar Khatiwada is the current President of 22nd Executive Committee of Nepal Geological Society. He is also the youngest to be elected as the president in this long history of NGS. He is also an entrepreneur managing his personal geological consulting firm. He has worked in various fields of Geoscience, especially in land subsidence and hydrogeology. His expertise spans geological investigations, groundwater potential mapping, land subsidence monitoring and risk assessment. His experience highlights the importance of geologists in infrastructure development and disaster resilience, especially in Nepal's complex and challenging terrain.

Bhaskar Khatiwada
President
Nepal Geological Society

We wonder about your academic journey. What inspired you to choose geology?

I must admit, my journey into geology started unexpectedly. I didn't really understand what geology was, when I applied for the admission. But after I joined the B.Sc. program at Tri-Chandra, everything changed. The subject started to interest me, lecture by lecture, map by map, mineral by mineral. I truly connected with geology during our fieldwork in Malekhu and later in Palpa. Walking through those outcrops, reading the rocks, and grasping the Earth's story in real time filled me with excitement. Those field experiences showed me the beauty and purpose of earth sciences into our existence. From that moment on, I knew this was the field where I wanted to build my career and give my best.

As the newly elected President of the Nepal Geological Society (NGS), could you kindly share your main plans and priorities for the Society?

It is both a great honor and a profound responsibility to be elected as the youngest president in the Society's history. My priorities for NGS are clear and action-oriented.

- My first objective is to strengthen institutional governance and make the Society more dynamic, inclusive, and responsive to members' needs.
- One of our major commitments is capacity building. We have already initiated a series of professional development programs and are committed to delivering more than fifteen high-quality trainings completely free for our members and well-wishers.
- We are also introducing an Institutional Memory Reposition Program as a means of preserving and acknowledging the contributions, experiences, and insights of our senior geoscientists.
- Bridging generations is a central part of my vision, wherein the experience of seniors and the energy of youth work together to shape a stronger future for NGS.
- Collaboration is another key priority. We are actively expanding our partnerships with national and international professional societies to promote joint

programs, shared expertise, and broader opportunities for our members.

- The main aim on the academic front is to uplift our journal to global standards. The future issues will be published through an internationally recognized publication house, such as Springer or Elsevier, and the initiation of the process for indexing in Scopus will help improve the visibility, credibility, and scholarly impact of the journal.

In all, my vision is to have NGS become a key national contributor in earth science policy, a dynamic platform for academic excellence, and a home to nurture every geologist in their professional life.

May we request you to explain how you wish to promote professionalism and ethical practice among geologists in our country?

Professionalism and ethics are the backbone of our discipline. To strengthen these values, we have already established the Professional Advocacy and Ethics Cell within NGS. This dedicated cell will work actively to promote ethical conduct, professional accountability, and responsible practice in all areas of geoscience. Our regular awareness programs, continuous dialogue and clear institutional guidelines aim to encourage geologists to work with honesty, dignity, and a deep sense of responsibility.

Promoting ethics is not the responsibility of NGS alone, it requires collective effort. Both industry and employers must join hands to uphold standards that protect the integrity of our profession. Ethical practice builds trust; trust with government agencies, trust with communities, and trust within the scientific world. And the trust ultimately what defines the credibility and respect of the geological profession in Nepal.

Could you humbly share how you intend to raise the concerns, voices, and agendas of geologists at the national level?

NGS stands as a strong and reputable representative for Geologists at the National Level. We are holding a one-day workshop with all relevant stakeholders who are associated with Geology in some manner including Government Agencies, Regulatory Bodies, Universities, and Professional Organizations. This workshop will serve as a unified platform where we openly present the issues faced by geologists, from employment challenges to professional recognition, and collectively discuss practical solutions. Rather than continuing to have scattered groups hold dialogues and forums at the national level, we will all be brought to the same venue at the same time to present our concerns and proposed solutions in an organized manner. It is very important that our voices are clearly heard and documented.

By working together, we hope to help improve the perception of geologists to government and policy makers, so that they understand that geologists are not only the world's technical experts in Geology but also essential contributors in the success and development of the nation with the added value of helping to reduce risk.

What initiatives do you plan to introduce to enhance the quality of scientific publications and geological research through NGS?

NGS has a proud legacy of publishing one of Nepal's oldest and continuously running scientific journals, with 45 years of history and 68 volumes already being published. We need to work together to improve the Impact and reach of our journal and therefore improve the Academic impact of our Journal. I am developing a plan to partner with Internationally recognized publishing

ISSN: 3021-937X (Print)

companies, such as Springer or Elsevier, and pursue a Scopus Index. The international exposure gained through these partnerships will lead to increased numbers of High-Quality Submissions to our Journal. Improving the status of a journal, however, requires additional contributions by our own geoscience community. It requires creating a culture that permits Nepali geologists to utilize the NGS.

At the moment, the majority of the best quality papers produced within Nepal are being published in other journals, often in international journals, instead of the NGS. This must be changed. We will utilize our training workshops where we train young researchers on scientific writing to promote citation awareness of our journal. We will encourage and assist our senior scientists to submit outstanding papers to the NGS. Our efforts will improve the volume, quality and impact of our journal.

As many young graduates seek guidance, how do you wish NGS to support their career development in the field of geology?
Young geologists are truly the future of our discipline, and I want NGS to be a supportive home for them, a place where they receive guidance, mentorship, training, and real opportunities to grow. We are committed to running specialized training programs, hands-on workshops, and interactions with industry experts to help students smoothly transition from academic learning to professional practice. Through my own experience managing a private consulting firm, where six geologists are currently working full-time, I have observed that our graduates possess strong theoretical foundations but often lack sufficient practical exposure and field confidence. This gap is not their fault; it reflects the broader need for structured practical training and professional grooming. Therefore, one of my key priorities is capacity building: enhancing technical skills, improving professionalism, strengthening report-writing and communication abilities, and building the confidence needed to perform effectively in the field and workplace. By creating these supportive learning platforms, I want every young geologist to enter their career with the right skills, the right mindset, and the belief that they can excel in any professional setting.

In your humble opinion, why is it important for young geologists to develop both technical and soft skills for their future careers?
Geology is a technical discipline of study which is not only related to the development of nations, but also affects society and communities, so it is important for young geologists to acquire strong technical and soft skill sets. Technical skills provide the knowledge of the science and soft skills such as communication, teamwork, leadership and professionalism enable the geologist to effectively communicate their science and to responsibly collaborate with a variety of stakeholders. Furthermore, "soft skills" now include the critical software tools such as GIS, remote sensing, modelling and data analysis that support contemporary geoscience. When young geologists have developed their technical and soft skills, they will be better prepared to represent their profession and to make a positive contribution to their country through their profession.

Could you share how NGS can contribute to expanding Nepal's role in sectors such as hydropower, mineral exploration, and disaster management?
Nepal's development is deeply tied to geoscience. NGS can provide technical

expertise, policy recommendations, capacity-building programs, and collaborative platforms that connect geologists with government and private sectors. Through joint research, training, and advocacy, we can ensure that geological knowledge becomes central to hydropower planning, mineral exploration, groundwater management, disaster risk reduction etc.

How do you envision NGS helping to reduce the gap between academic knowledge and practical field experience?
This gap has persisted for a long time. Through the recommendations of Academic Review Committee, joint programs with universities, practical trainings, and mentorship from industry professionals, NGS will help students gain exposure to real field challenges. We have also established a Youth Geological Council, which will create continuous engagement between academic and professional platforms.

What role do you believe NGS can play in addressing national challenges like landslides, groundwater scarcity, and other geological hazards?
NGS has a national responsibility to provide scientific guidance. We will mobilize the expert groups, conduct assessments, publish technical insights, and support government agencies with data-driven recommendations. By promoting geoscience literacy and conducting public outreach, we can help communities understand and mitigate geological risks more effectively.

Why do you think strong and responsible leadership is important in a professional organization like NGS?
Leadership shapes the culture and future of any professional organization. NGS needs leadership that listens, respects, unites, and takes action with sincerity. A responsible leader ensures transparency, inclusiveness, and steady progress; where every member, whether senior or junior, feels valued and represented.

Our Society has a long academic legacy, with 68 continuously published journal volumes and more than 20 international conferences organized in its history. Yet, despite this strong foundation, we still lack journal indexing, participation in our congresses has declined, the institutional role of geologists is shrinking, and interest in becoming an NGS member has weakened. This should not happen at a time when the number of geologists in Nepal is increasing and their importance in national development is growing every day. In such a critical moment, NGS requires strong, responsible, and committed leadership; not someone seeking recognition or titles, but someone willing to work, reform, and revitalize the Society. That is the kind of leadership I believe NGS truly deserves.

ISSN: 3021-937X (Print)

INTERVIEW REGARDING HER EXPERIENCE AS AN ENGINEERING GEOLOGIST AT NEPAL ELECTRICITY AUTHORITY

Arishma Gadtaula
Engineering Geologist
Nepal Electricity Authority

Mrs. Arishma Gadtaula is a seasoned engineering geologist with extensive field experience and a strong academic foundation in engineering geology. She completed her Master's in Engineering Geology from Tribhuvan University and currently serves as an Engineering Geologist at the Nepal Electricity Authority. Her expertise spans geological investigations, landslide susceptibility mapping, and risk assessment. Her professional journey includes collaborative work on landslide and debris flow assessments, consulting roles with organizations like Oxfam, and academic contributions as a lecturer in multiple engineering institutions. Her experience highlights the importance of geologists in infrastructure development and disaster resilience, especially in Nepal's complex and challenging terrain.

We wonder about your academic journey. Could you share us a little about your academic journey?

My academic journey has been deeply rooted in geology and disaster risk management. I completed my Bachelor's degree in Geology, which helped me build a solid foundation in earth sciences and field-based geological investigations. My interest in landslide risk and engineering geology led me to pursue a Master's degree with a thesis on the susceptibility assessment of landslides in the Rasuwa District of Nepal. This was further supported by my participation in various national and international training programs and conferences on disaster risk reduction, landslides, and geohazards during my academic years. My involvement in field studies, research collaborations, and projects on GIS-based hazard modeling greatly enriched my technical and analytical skills. This strong academic grounding has formed the basis of my transition from academic research into professional practice. It has allowed me to apply scientific understanding to real-world geotechnical challenges, particularly within infrastructure development and disaster risk assessment.

What inspired you to start your services at NEA?

I was inspired to join the Nepal Electricity Authority because it provided me a platform to apply my geological and disaster risk expertise directly to national infrastructure development. Having worked extensively on landslide research and hazard assessment, I felt a strong motivation to contribute to projects that have long-term impact on energy security and public safety. NEA's involvement in major hydropower and transmission line projects allowed me to integrate scientific understanding with practical engineering solutions. I wanted to ensure that geological risks, particularly landslides and slope instability, were properly assessed and mitigated to protect critical energy infrastructures.

ISSN: 3021-937X (Print)

What are some of the common geological problems you face while working on hydropower or infrastructure projects?

In hydropower and infrastructure projects, we frequently encounter a range of geological challenges that have significant implications for safety, design, and long-term stability. Some of the most common issues include:

• **Landslides and slope instability**: Particularly in hilly and mountainous regions, unstable slopes pose serious risks to access roads, transmission lines, powerhouses, and dams.

• **Weak or fractured rock mass**: Geological discontinuities, jointed rock, or weathered formations often lead to stability problems during excavation or tunneling.

• **Seepage and groundwater-related issues**: Unexpected water ingress during tunneling or foundation works can lead to slope failures, erosion, or construction delays.

• **Erosion and sedimentation**: High erosion rates and sediment deposition affect reservoir capacity, structural longevity, and slope conditions.

• **Faults and seismic risk**: Presence of active faults or high seismic zones requires detailed investigation to ensure safety in design.

• **Difficult access to geologically complex terrain**: This affects field investigation, drilling, and monitoring activities. Managing these challenges requires detailed geological and geotechnical investigations, GIS-based hazard assessments, continuous monitoring, and close coordination between multidisciplinary teams. Early identification and proactive mitigation play a crucial role in ensuring the safety, sustainability, and resilience of the project.

Is there any project that has been especially memorable or challenging for you? What did you learn from that experience?

One of the most memorable and professionally enriching experiences I've had was during my tenure as a Research Associate at NSET Nepal, where I worked for five months on the Sajag Nepal Project, a collaborative initiative with Durham University. This project was particularly challenging in terms of understanding research frameworks, coordinating with multidisciplinary teams, and transforming scientific observations into practical disaster risk reduction strategies. What made it impactful was that it pushed me beyond conventional field-based geological assessments and into the realm of structured academic research and evidence-based planning. I gained valuable insights into:

• How research is systematically designed and executed, from proposal formulation to data interpretation;

• Interdisciplinary coordination, including working with experts from hazard modeling, risk assessment, and community resilience backgrounds;

• Scientific rigor, particularly in data accuracy, documentation, and reporting standards;

• The importance of translating technical findings into actionable solutions for policymakers and local communities. This experience not only strengthened my analytical and research skills but also helped me appreciate the importance of integrating academic research with practical field application. It has since influenced my approach to geotechnical problem-solving ensuring that my recommendations are not just technically sound but also evidence-based and relevant to disaster resilience.

As a woman working in engineering geology, what kind of experiences have shaped your career and what are the challenges you have faced in this field? How do you overcome that situation?

As a woman working in engineering geology, my career has been shaped by a combination of field experiences, resilience, and continuous learning. Engineering geology often demands extensive fieldwork in difficult terrain, challenging weather, and remote locations. Early in my career, many people had preconceived notions about whether women could handle physically demanding geological investigations or manage site-based responsibilities. Rather than discouraging me, these challenges motivated me to perform even better. I overcome the situation:

• By consistently demonstrating technical competence, professionalism, and calm decision-making in high-pressure situations.
• Keeping myself updated through research, training, and collaboration with experts.
• Mentoring younger professionals, especially women, and advocating for gender inclusion in field-based roles.
• Maintaining confidence and assertiveness, while also being open to learning from colleagues.

What advice would you give to young students who want to build a career in geology or engineering geology?

My advice to young students aspiring to build a career in geology or engineering geology is to remain curious, committed, and open to learning—both in the classroom and in the field. Geology is not just about studying rocks; it is about understanding the earth's processes, solving real-world problems, and contributing to safer and sustainable infrastructure.

What are the essentials skills required for today's young geology students to stand out among many?

To stand out in today's competitive field of geology and engineering geology, young professionals need more than academic knowledge. They should focus on building a strong foundation in core geoscience subjects and gain practical field experience, including geological mapping, logging, drilling supervision, and hazard assessment. Technical skills such as GIS, remote sensing, and use of industry-relevant software (e.g., Rocscience, Plaxis, Leapfrog) are increasingly important, along with data analysis, research capability, and digital literacy. Equally essential are problem-solving skills, critical thinking, and the ability to clearly communicate technical findings to diverse stakeholders. Awareness of climate change, disaster risk reduction, and sustainable development is crucial in today's context. Professionalism, safety awareness, ethical decision-making, and a continuous learning mindset through training and workshops also help young geologists stay competitive.

What humble message would you like to convey to geology students of Nepal regarding their career choice and future in this field?

I would like to tell geology students in Nepal that you have chosen a field with immense potential and meaningful impact. Our country's diverse geology and high vulnerability to natural hazards make your role extremely important. It may not always be an easy path—field challenges, technical responsibilities, and sometimes limited resources can be demanding—but if you stay committed, your work can directly contribute to saving lives and supporting sustainable development. Be proud of your career

ISSN: 3021-937X (Print)

choice, stay curious, and keep learning. Focus on building strong fundamentals, gaining field experience, and aligning your work with disaster resilience and environmental responsibility. Nepal needs skilled, passionate geologists who can combine local understanding with global knowledge. The journey may be tough at times, but if you walk with purpose, dedication, and integrity, geology can be one of the most rewarding careers.

Finally, do you have any message you would like to share with young geologists and the readers of our journal?

As geologists, we are privileged to interpret the Earth's story. Every rock and landscape teaches us resilience and evolution. I encourage young geologists to look beyond studying the past and focus on shaping a safer and more sustainable future. In this era of climate challenges, be curious, courageous, and responsible. Embrace fieldwork, technology, and continuous learning. Stay grounded in ethics, collaborate openly, and let your passion guide your work. Keep learning, keep exploring, and keep inspiring.

ISSN: 3021-937X (Print)

ENGINEERING GEOLOGICAL PERSPECTIVE ON THE JHYAPLE KHOLA LANDSLIDE

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ABSTRACT

Landslides are among the most frequent and devastating geological hazards in Nepal, primarily triggered by monsoon rains, unplanned infrastructure development, and the country's rugged terrain. This article examines the Jhyaple Khola Landslide which highlights the geological and geotechnical factors contributing to these disasters and discusses mitigation strategies. Through an analysis of field observations, geological formations, satellite images and slope stability conditions the study aims to understand the failures and propose recommendations for reducing future landslide risks along critical transportation corridors.

Key words: *Landslides, Jhyaple Khola Landslide, Geotechnical, Failures*

1. BACKGROUND

1.1 INTRODUCTION

Nepal's topography is characterized by steep slopes, active tectonics, and intense monsoon rainfall, making it highly susceptible to landslides. The increasing number of road construction projects without adequate engineering considerations exacerbates slope failures. Landslide risk assessment in the Lesser Himalayas has highlighted the fragile geological conditions of the region (Nepal Geological Society, 2024). The Jhyaple Khola Landslide disaster serves of how geological and anthropogenic factors contribute to slope instability. As highlighted in NHSRP Bulletin (September 2024), the consequences of the Jhyaple Khola Landslide affected local settlements and infrastructure.

1.2 AIM

The study aims to assess the geological and engineering factors that contribute to Jhyaple Khola Landslide and recommend measures to enhance slope stability in similar terrains.

1.3 OBJECTIVES

The primary objectives of the study are:

- To analyze the geological characteristics of the landslide-prone areas.
- To evaluate the geotechnical conditions leading to slope failures.
- To identify the role of human activities in triggering landslides
- To propose engineering solutions to mitigate future hazards

1.4 RESEARCH QUESTION

The research questions for the study are:

- What are the primary geological and engineering factors responsible for the Jhyaple Khola Landslide?
- How can engineering geology principles be applied to mitigate such hazard?

2. MATERIALS AND METHODOLOGY

2.1 STUDY AREA

The Jhyaple Khola Landslide occurred along the Tribhuvan Highway in Dhading District near Nagdhunga from September 26 to 28, 2024. This site is part of the Lesser Himalaya, which consists of highly weathered and fractured metamorphic rocks, including schist, phyllite, quartzite as well as some calcareous rocks (Acharya & Paudyal, 2015). The region's steep slopes combined with monsoon-induced water infiltration and anthropogenic activities, create conditions conducive to landslide.

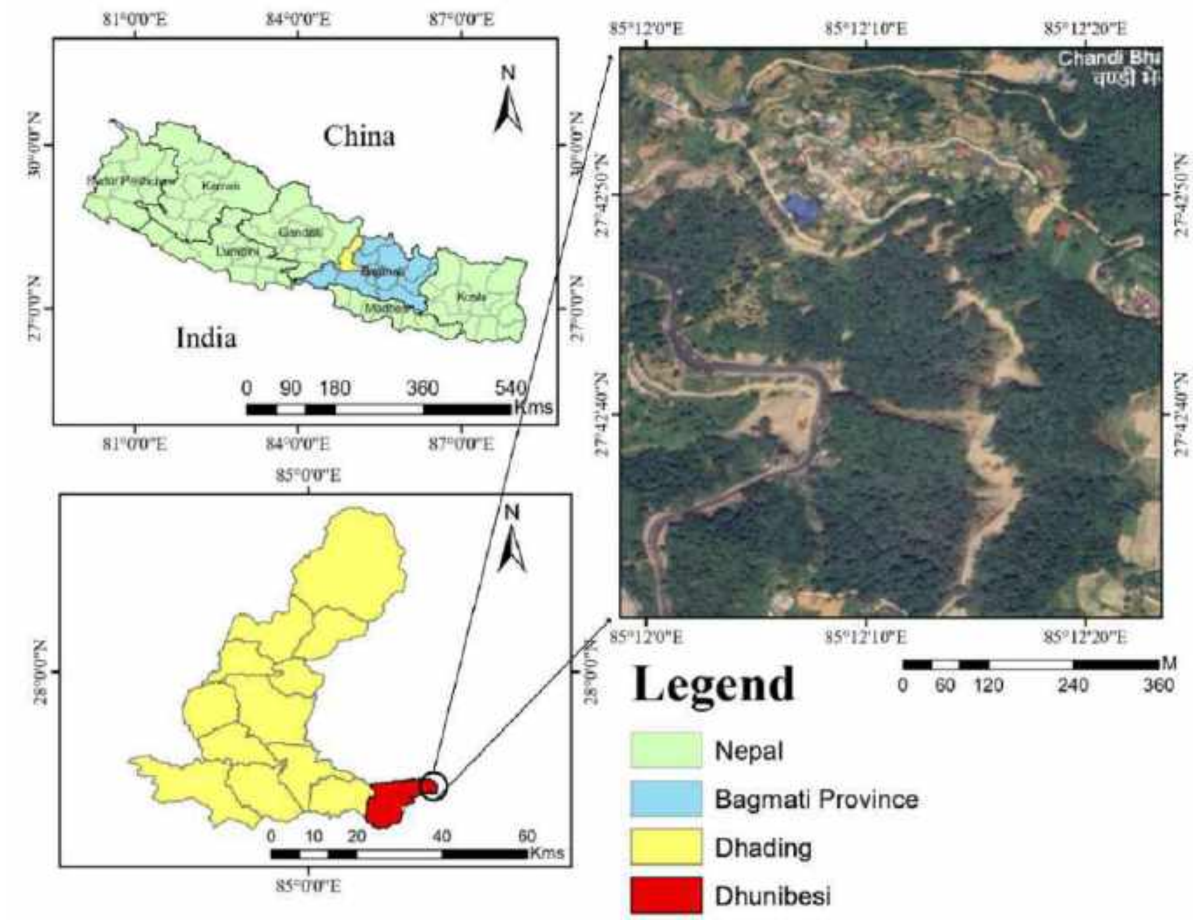

Figure 1: Map of study area

2.2 GEOLOGICAL FORMATION

The Jhyaple Khola landslide site lies along the contact of the Chandragiri, Sopyang and Tistung Formations of the Pulchowki Group in the Kathmandu Complex. Here, weak phyllite, schist and fractured quartzite mix with thin layers of state and metasandstone (Paudyal & Acharya, 2019; Acharya & Dhital, 2006). This geologic boundary is fragile and disrupts with heavy monsoonal rain and rood cutting. The rocks lose strength quickly, leading to repeated failures, and structures like gabion walls have been constructed along the base to prevent erosion and help stabilize the soil.

2.3 METHODOLOGY

The various methods used for this study are discussed below:

- **Field Surveys:** Conducted to assess slope conditions, soil profiles and geological structures.

ISSN: 3021-937X (Print)

- **Geotechnical Analysis:** Soil samples analyzed for Atterberg limit, permeability, and cohesion.
- **Remote Sensing and GIS:** Landslide inventory mapping using satellite imagery and GIS tools.
- **Structural Mapping:** Identification of faults, fractures as well as hydrology of the region influencing slope stability.

Plate 1: Site photo of Jhayple Khola

3. **RESULTS**

The investigation revealed the following key factors contributing to the landslides:

- Jhyaple Khola Landslide may be caused by unregulated road construction on the upper section of highway, loose debris dumping, and high-intensity rainfall leading to slope failure and debris flow.
- The soil sample collected from the landslide zone was classified as CH (inorganic clay of high plasticity with minor silt content) according to the Unified Soil Classification System (USCS, 1983), based on its grain-size distribution and Atterberg limits. Such soils are characterized by high compressibility, low shear strength when saturated, and significant swelling–shrinkage potential, making them highly susceptible to slope instability and failure.
- Heavy monsoon rainfall, soil type, unplanned road construction, improper road-cut slope design, deforestation, improper drainage management, and geological weaknesses in the rock formations.

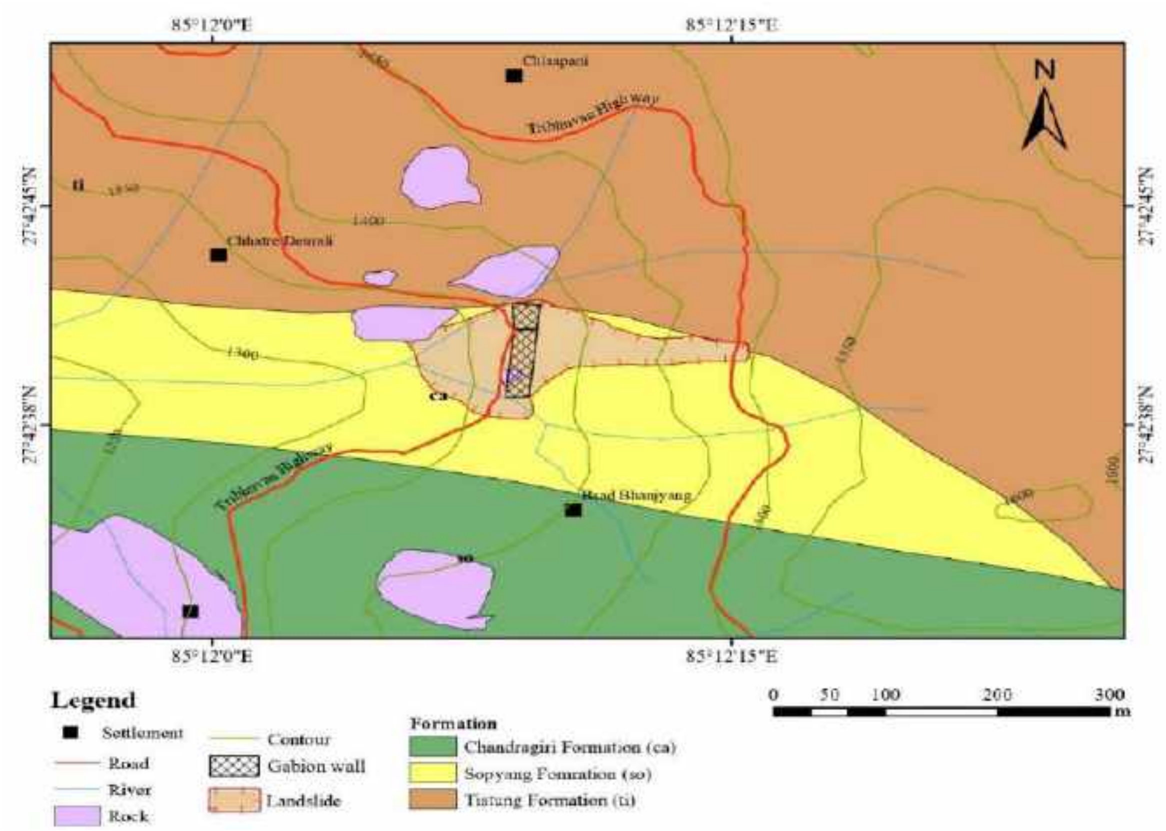

Figure 2: Engineering geological map of Jhyaple Khola

4. DISCUSSIONS

Both case studies highlight the importance of incorporating engineering geological principles in infrastructure planning. Key insights include:

- **Slope Stability Measures:** Implementation of bioengineering techniques, gabion walls, proper drainage systems, and retaining structures.
- **Geotechnical Investigations:** Need for thorough subsurface investigations before road construction.
- **Policy Recommendations:** Establishing strict regulations for land-use planning and road construction in landslide-prone areas.
- **Community Awareness:** Educating local communities on early warning systems and evacuation strategies.

5. CONCLUSION

Engineering geology plays a crucial role in understanding and mitigating landslide hazards. The Jhyaple Khola disasters underscore the need for improved slope management, scientific road construction practices and proactive disaster risk reduction measures. The landslide soil is largely composed of CH-type soil, weak, prone to failure, which further highlights the vulnerability of such terrains. As a precautionary measure, slope stability should be strictly followed by the geotechnical guidelines provided by the Department of Road (2007) to minimize future landslide risks and ensure safer road construction in fragile Himalayan terrains. By integrating geological assessments with engineering solutions, Nepal can reduce the frequency and impact of landslides along critical transport corridor.

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GEOLOGICAL AND SPELEOLOGICAL STUDY OF JHOR (BAUDESHWOR) CAVE, CENTRAL NEPAL

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ABSTRACT

Baudeshwor Cave, situated in Tokha on the northern edge of Kathmandu Valley, is developed in limestone and dolomite rocks of the Lesser Himalaya. The cave was formed by the slow dissolution of carbonate rocks as rainwater percolated through joints, fractures, and bedding planes over thousands of years, creating a small-scale karst system. The geological setting belongs to the Kathmandu Complex, where rocks have experienced folding, faulting, and metamorphism due to mountain building processes. Field observation shows that fractures and minor faults played a major role in groundwater circulation and cave development. Although large speleothems are not present, the cave still represents an active environment where dissolution and deposition are ongoing. The surrounding area near Shivapuri National Park supports rich biodiversity, making it environmentally important. In addition, the cave is home to the Baudeshwor Mahadev Temple, attracting pilgrims and tourists, which gives the site cultural and religious value. This study highlights the combined geological, environmental, cultural, and educational significance of Baudeshwor Cave and stresses the need for its conservation as a natural and cultural heritage site.

Key words: *Speleological, Karst, Speleothems*

1. BACKGROUND

Baudeshwor Cave, also locally known as Jhor Cave, is located in Tokha Municipality on the northern outskirts of Kathmandu Valley, close to the southern boundary of Shivapuri–Nagarjun National Park. Geographically, the cave lies at approximately 27°48′04″ N latitude and 85°19′20″ E longitude, at an elevation of about 1,500 meters above sea level, and can be accessed from the Samakhusi–Tokha road about 11 kilometers north of Central Kathmandu. Geologically, the cave has developed within the Lesser Himalayan sequence, mainly composed of metamorphosed carbonate rocks such as limestone and dolomite, where groundwater percolation and dissolution processes have led to karst development. The presence of joints, fractures, and bedding planes has facilitated the speleogenesis, giving rise to features like stalactites, stalagmites, and dripstone columns that are commonly observed inside the cave. Beyond its geological significance, Baudeshwor Cave holds strong cultural and religious importance, as a naturally formed Shiva Linga is enshrined inside, attracting hundreds of devotees during Shivaratri, Balachaturdashi, and other Hindu festivals. The cave is therefore also revered as Baudeshwor Mahadev Cave, where locals believe worship brings prosperity and spiritual purification. In addition, the cave and its surrounding landscape of lush forests, waterfalls, and proximity to Shivapuri–Nagarjun National Park make it a growing tourist attraction, offering both eco-tourism and geoheritage potential. Although motorable roads reach Jhor Bazaar followed by a short hike to the cave entrance, the site still faces conservation challenges due to unmanaged tourism and increasing human pressure that risk damaging the delicate cave formations and sacred spaces within.

ISSN: 3021-937X (Print)

2. METHODOLOGY

The study of Baudeshwor Cave was carried out through desk study and field study.

- **Desk Study:** It included the review of geological and topographical maps, previous reports, and articles related to the geology of Kathmandu Valley and karst cave formation.
- **Field Study**: Filed study was done by visiting the cave and observing the rocks, structures, and cave features directly. The types of rocks, joints, and fractures were noted, and simple measurements were taken with a compass. GPS was used to locate the cave, and information about the surroundings, access, and cultural importance was also collected from local people and visitors.

3. OBJECTIVES

The objectives of the study are:

- To study the geology and rock types of the cave.
- To observe structural features such as joints, fractures, and bedding.
- To document speleological features like stalactites and stalagmites.
- To understand the formation process (karst development) of the cave.
- To highlight the cultural, religious, and tourist importance of the cave.

4. RESULTS AND DISCUSSIONS

4.1 PROCESS OF CAVE FORMATION

Caves are formed mainly in limestone rocks through a long process of dissolution. After rainfall, water seeps into the cracks and pores of soil and rock, eventually reaching a zone where all the spaces are already filled with water. Since calcite, the main mineral of limestone, is only slightly soluble in pure water, the rainwater first combines with carbon dioxide from the air and soil to form a weak carbonic acid. This acidic water slowly dissolves calcite, creating solution cavities and excavating underground passageways. The dissolved material, in the form of calcium bicarbonate, is then carried away by the underground drainage system. The first stage of cave development occurs just below the water table, in the saturated zone, where cavities and passageways form. Later, as the water table lowers, these cavities are left in the unsaturated zone, where air can enter. In this stage, dripping water deposits calcite, giving rise to dripstone features such as stalactites hanging from the ceiling and stalagmites rising from the floor. Over thousands of years, these natural processes together create the vast and beautifully decorated cave systems we see today.

4.2 GEOLOGICAL SETTING

Baudeshwor Cave is situated in the Lesser Himalayan zone, which forms a major tectonostratigraphic unit of Central Nepal. The Lesser Himalaya mainly consists sedimentary rocks (shale, limestone, dolomite, conglomerate etc.), low to medium-grade metamorphic rocks such as slate, phyllite, quartzite, and marble (metamorphosed limestone and dolomite), ranging in age from Precambrian to Paleozoic (Stocklin & Bhattarai, 1978). These rocks have been subjected to multiple phases of deformation and metamorphism associated with the Himalayan orogeny (Upreti, 1999).

The cave has developed particularly within carbonate-rich lithologies, most likely limestone and dolomite beds, where groundwater percolation along fractures and joints has caused

ISSN: 3021-937X (Print)

dissolution and formation of karst features. Structurally, the Lesser Himalaya is bounded to the north by the Main Central Thrust (MCT) and to the south by the Main Boundary Thrust (MBT), and local folds and faults have influenced groundwater circulation and cave development. Regionally, the cave area belongs to the Kathmandu Complex of the Lesser Himalaya, underlain by metamorphosed sedimentary rocks. Based on stratigraphic position, the rocks belong to the Precambrian to Paleozoic time scale, representing ancient marine sedimentation later deformed during Himalayan tectonism (Fort et al., 1982).

4.3 LITHOLOGY AND STRUCTURES

Baudeshwor Cave is developed inside limestone and dolomite rocks of the Lesser Himalaya. The rocks are fine-grained and light grey, but the bedding planes are not very clear, making it difficult to observe the original layering. Thin bands of phyllite and quartzite are found nearby, showing that the area consists of a typical Lesser Himalayan rock sequence. The rocks are cut by joints and fractures, which allowed rainwater to slowly enter and dissolve the carbonate rock, gradually forming the cave passages. Some small folds can also be seen around the cave area, indicating strong compression during Himalayan Mountain building process. Minor faults or shear zones may have helped guide groundwater flow and increased dissolution. Inside the cave, stalactites and stalagmites are not very well developed. This may be due to limited dripping water carrying dissolved calcium carbonate, or because the cave passages are relatively young and have not had enough time for large formations to grow. The presence of small dripstone features, however, shows that dissolution and deposition are still active processes inside the cave. Overall, the combination of carbonate lithology, fractures, and groundwater flow created ideal conditions for karst processes. Even though bedding planes and speleothems are not very clear, the cave represents a good example of a small-scale karst system in the Lesser Himalaya.

5. SIGNIFICANCE

5.1 GEOLOGICAL SIGNIFICANCE

Baudeshwor Cave is a natural limestone cave that has been formed over thousands of years. The cave was created by the process of chemical weathering, where slightly acidic water slowly dissolved the limestone rock. Over time, this created tunnels, chambers, and unique rock formations inside the cave. These geological features are important because they show how natural processes shape the land and provide evidence of the long-term evolution of the earth's surface. Caves like Baudeshwor also help scientists study karst landscapes, underground water systems, and the effects of natural erosion. By observing the formations inside the cave, researchers can understand the movement of water through rocks and the development of underground structures.

5.2 ENVIRONMENTAL SIGNIFICANCE

The cave is located near Shivapuri National Park, one of the ecologically rich areas in the Kathmandu Valley. The park and surrounding regions host a wide variety of plants and animals, making it an important area for biodiversity. Inside and around the cave, there are unique ecosystems that provide shelter to organisms adapted to low light and high humidity, including special insects, bats, and small plants. The nearby Jhor Waterfall contributes to maintaining the local water cycle, which helps support both the cave ecosystem and the surrounding environment. Protecting this area is important because it preserves the natural habitats of these species and maintains the balance of the local ecosystem.

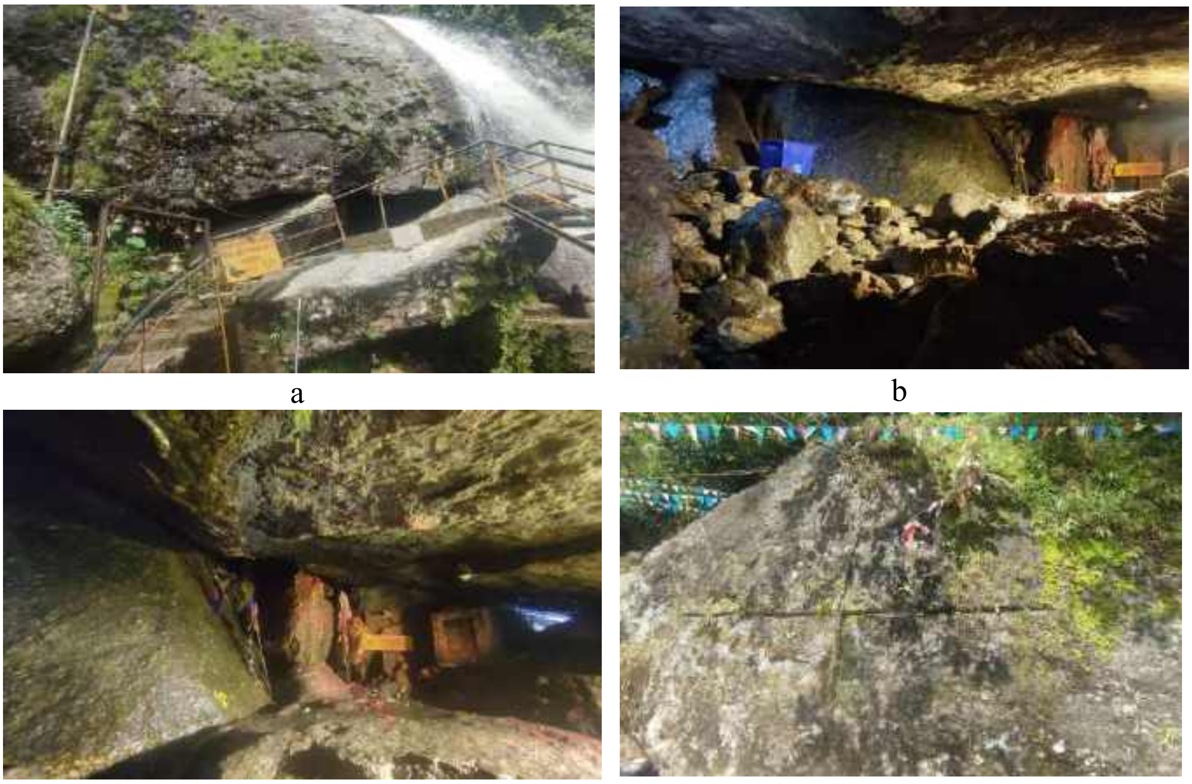

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Plate 1: (a) Entrance of Baudeshwor Cave with waterfall. (b) Interior with boulders and narrow passage, (c) Vertical opening with rock walls and offerings, and (d) Jointed carbonate rock outside showing plant trunk impression.

5.3 CULTURAL AND RELIGIOUS SIGNIFICANCE

Baudeshwor Cave is not only important geologically and environmentally, but it is also a sacred place. Inside the cave is the Baudeshwor Mahadev Temple, dedicated to Lord Shiva. This temple attracts many devotees, especially during religious festivals and holy days. The spiritual importance of the temple combined with the natural beauty of the cave makes the site a unique place for both worship and tourism. Pilgrims often visit to pray and meditate, while tourists and nature lovers explore the cave and its surroundings. This combination of cultural and natural significance adds to the value of Baudeshwor Cave as a heritage site.

5.4 TOURISM AND EDUCATIONAL VALUE

The cave is located about 9 km from Kathmandu, making it easily accessible for day trips. Visitors can explore the geological features of the cave, enjoy the surrounding natural scenery, and learn about the environment and local culture. Schools and universities can organize educational trips to study the cave's geological formations, understand karst landscapes, and learn about the local biodiversity. Tourists benefit from experiencing a site where natural history, culture, and spirituality meet. By visiting the cave, people also become more aware of the importance of environmental conservation and the need to protect such natural and cultural landmarks.

6. CONCLUSION

Overall, Baudeshwor Cave is one of Nepal's most remarkable natural and cultural treasures. Its limestone formations reveal thousands of years of geological processes, while the surrounding Shivapuri National Park supports rich biodiversity, making it an ecological hotspot. The Baudeshwor Mahadev Temple adds deep cultural and religious significance, transforming the cave into a place of worship, learning, and exploration all at once. By protecting Baudeshwor Cave, we ensure that future generations can study its geology, experience its natural beauty, and connect with its spiritual essence. This unique combination of nature, culture, and history makes Baudeshwor Cave not only a scientific and ecological landmark but also a symbol of Nepal's heritage and enduring legacy near Kathmandu.

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ENGINEERING GEOLOGICAL ISSUES ALONG THE BUTWAL-PALPA ROAD, WESTERN NEPAL

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ABSTRACT

The Butwal-Palpa road section along the Siddartha Highway has many geological problems. Terai is a foreland basin, which is filled by Himalayan River. Inundation and sediment piling problem are main problems in Terai. In Siwalik and Lesser Himalayan section, rock-fall and landslides are main problems, which affect in infrastructure as well as human being during rainy season. This study examines the major engineering geological issues in the Tinau basin affecting through a review of existing literature, field observations, and geological study. Findings indicate that the dominant hazards arise from weak rock formations, intense monsoonal rainfall, and anthropogenic activities such as road cutting and unplanned slope modifications. The spatial distribution of hazards highlights key sections of the corridor that are at particularly high risk, demanding urgent attention for mitigation. The study highlights the importance of comprehensive slope stabilization techniques, hazard zoning, and integrating geotechnical assessments into infrastructure planning. Ultimately, strengthening resilience along the Butwal-Palpa corridor is not only essential for transportation safety but also for ensuring sustainable socio-economic development in Western Nepal.

Keywords: *Butwal-Palpa road section, Rockfall, Landslides, Slope failure, Western Nepal.*

1. INTRODUCTION

Butwal-Palpa corridor, which is part of the Siddhartha Highway in Western Nepal, traverses diversified geological environments including the Indo-Gangetic Plain, Siwalik Hills, and Lesser Himalaya. The region is highly susceptible to engineering geological problems due to steep gradient, unfavorable lithology, intensifying rainfall, and man-made forces like road cuts and construction activities (Burbank & Anderson, 2011; Pokhrel, 2017). Engineering geological problems like rockfall, debris flows, slope failures, and landslides pose significant threats to human life, transportation infrastructure, and regional socio-economic development (Petley, 2012).

To comprehend these problems, marrying field observations with geotechnical analysis and geological mapping is needed. Engineering geology provides the tools and techniques to assess soil and rock mass properties, slope stability, and hazard zones with which to plan protection from infrastructure and societies. Previous studies in Nepal have shown the chronicity of highway landslides, floodplains, and bridges and tunnels as susceptible elements to natural hazards (Bhandary & Pokhrel, 2022). This study is intended to identify and characterize the engineering geological hazards of the Butwal–Palpa road. The objectives are:

- To know the geogenic problems in Terai.
- To know the road-cut and slope failure occurrences along Siwalik and Lesser Himalayan terrains.
- To observe the Landslides along HFT, CCT and MBT sections.
- To provide mitigation measures for the construction of safe infrastructure.

2. STUDY AREA

The Butwal-Palpa road section, spanning nearly 75 km on the Siddhartha Highway, connects the Butwal Terai plain to the hill town of Tansen in Palpa District, Western Nepal. This road was made along the Tinau watershed, the main problematic section lies around HFT, CCT and MBT zones. It traverses three important geological regions: the Indo-Gangetic Plain, Siwalik Hills, and Lesser Himalaya. The Indo-Gangetic Plain is made of alluvial deposits and is flood-prone during monsoons. The Siwalik Hills consist of weak sedimentary rocks, gentle slopes, and frequent landslides. The Lesser Himalaya consists of phyllite and schist formations with high fractures and weathering, which cause rockfall and slope instability.

In the past, there are different researchers studied geology, hydrogeology, hydrology, hazard mapping. Tokauka et al (1990) studied the Siwalik of Arung-Tinau section naming; Arun Khola Formation, Binai Khola Formation, Chitwan Formation and Deurali Formation. Pandey et al. (2021) has been prepared a hydrological model using the Soil and Water Assessment Tool (SWAT) to know the hydrological behavior of the Tinau watershed in focusing Siddhababa area. The Tinau catchment receives an average annual rainfall of 1,801 mm, while the Siddhababa area records 2,390 mm, yielding an average annual surface runoff of 0.107 m^3/s. Rainfall induced landslide in the Lesser Himalaya and Siwalik is the main causative factures to start landslide during monsoon season. Due to which hundreds of thousand properties as well as human being are lost (Bhandari et al., 2024).

In 1983, Sakai studied the Tansen Group of the Lesser Himalaya and in 1985, he studied Kaligandaki Supergroup of Lesser Himalaya of Butwal-Tansen-Malunga area of Western Nepal. Based on this study, the necessary information of Palpa section is very easy to do.

Key infrastructure along the corridor consists of tunnels, bridges, hydropower projects, and major road cuts, all prone to geological hazard. The Siddhababa Tunnel, 1,089 m long bypass tunnel being developed, is a typical example of the engineering challenge of developing infrastructure within landslide-prone terrains.

3. METHODOLOGY

The study integrates field survey, laboratory investigations, and engineering geological study to assess the problems along the road section. The following procedures were followed: Detailed site observations were made for identification of flood hazard areas, landslides, rockfall areas, and road-cut failures. These observations were documented by photo and GPS locations. Topographic maps and field measurements were used to prepare engineering geological maps. Key parameters such as slope direction, slope angle, soil type, rock type, and hazard areas were digitized for spatial analysis. Field information, laboratory testing, and engineering geology parameters were integrated to map out high-risk zones along the corridor. Mitigation suggestions were made by taking into account slope stability, drainage control, and structural reinforcement.

4. RESULTS AND DISCUSSION

4.1 FLOOD-PRONE AREAS IN THE TERAI

The Indo-Gangetic Plain region of Butwal was highly flood-prone during monsoon. The field observations at Danav Bridge (~100 m of Mahendra Highway) revealed a wide floodplain with high inundation risk. High intensity rain, meandering of rivers and inadequate drainage system are the primary causes of flooding. Flooding is hazardous to infrastructure and agricultural land, on which there is a need for appropriate embankments, drainage maintenance, and flood zoning.

4.2 TINAU SUSPENSION BRIDGE COLLAPSE (2016)

On 26 July 2016, a heavy monsoon rainfall triggered a severe flood in the Tinau River in Butwal. The Tinau Suspension Bridge collapsed due to flooding, which was an important pedestrian and vehicular crossing over the river. High discharge, early abutment undercutting, and extreme debris flow were the failure causes and beyond the capacity in bridge design. The event did not only interfere with communication between Butwal and neighboring towns but also showed the susceptibility of infrastructure to destructive hydrological processes in Nepal's Indo-Gangetic Plain.

This shows how inadequate hydrological thinking, sediment load, and absence of bank protection can lead to the sudden failure of infrastructure. This flood incident has time and again affected the Tinau basin, which is the evidence of the urgent need for improved river training works, flood warning, and strong bridge construction in the area (Onlinekhabar, 2016).

4.3 ROAD-CUT FAILURES IN SIWALIK HILLS

Along Siwalik Hills, cutting failures were observed at different places, e.g., 1 km from Butwal towards Tansen. Slope steepness, soft sedimentary rock, and drainage deficiency promote landslide activation. The history indicates recurring landslides over the past 15 years with some sites still active (Pokhrel et al., 2022). Soil and rock mass investigation at these sites indicated high susceptibility to shallow-seated slides, particularly in high clay content areas with poor compaction.

4.4 ROCKFALL SITES IN LESSER HIMALAYA

In Lesser Himalaya, rockfall and toppling failures were encountered at numerous sites, e.g., ~800 m from Hiude Khola. Kinematic analysis by stereographic projections revealed the probability of plane failure across some joints and wedge failure across crossing discontinuities. The combination of steep slope gradients, weathered rock, and foliated phyllite increases susceptibility to sudden rockfall activity, which is dangerous for travelers as well as infrastructure.

4.5 LANDSLIDE CHARACTERIZATION

A number of landslide zones were identified along the corridor, with the Bhalebas Landslide (~900 m from Dumre Bazar) being a notable one. This landslide features steep slope angles (70–80°), inadequate drainage, fissured phyllite rock, and shallow-to-deep-seated movement. Field observation revealed 4 gullies, tension cracks of 5–6 inches at the crown, and active creeping. Debris flows were also seen near Charchare Bazar, which would have the potential to dam the Bhainsekati River during intense rainfall events.

4.6 SIDDHABABA TUNNEL OBSERVATIONS

The 1,089-meter Siddhababa Tunnel, currently under construction, is located in an extremely landslide-prone area near Siddhababa Temple on the Siddhartha Highway. As of field observation on Poush 2082 B.S, breakthrough of the tunnel was almost 90% and overall construction was approximately 60-65%. Tunnel alignment passes through weak and weathered rock mass, and therefore systematic support measures such as rock bolts, shotcrete lining, and drainage control are essential. Besides that, three emergency bypass tunnels have been planned to ensure operational security.

One of the most critical issues in this project is the risk of rockfall and debris sliding caused by the steep slope over the portal areas. The same hazard has also been encountered in other Himalayan Road and tunnel constructions where high relief, fragmented rock masses, and heavy rainfall foster slope instability (Liu et al., 2019). To reduce rockfall threats, rockfall net usage is an accepted practice. Rockfall nets prevent shattered blocks from falling onto roads, tunnel entrances, or working faces directly. Rockfall nets have been successful in reducing the number of blocks that fall and the impact energy per falling block in unstable slopes (Badger & Lowell, 2012). At the Siddhababa Tunnel, such protection systems, together with toe retaining structures, proper slope drainage, and periodic slope scaling, are recommended to ensure long-term stability and safety.

Figure 1: Photograph showing- a. Active landslide at Dumri Formation, b. Bhalebas Landslide at Bhalebas, Palpa, c. Under constructing tunnel of Sibbhababa, d. Sedimentation by Tinau River at Butwal.

4.7 ENGINEERING IMPLICATIONS

Flooding is an extremely significant hazard in the Terai section. Road-cut collapses and landslides are common in Siwalik Hills. Rockfall and toppling are threats in Lesser Himalayan terrain. Engineering structures such as bridges and tunnels must consider local geotechnical hazards. Mitigation methods include drainage, slope stabilization, retaining walls,

ISSN: 3021-937X (Print)

bioengineering, hazard zoning, and planning with geotechnical investigations (Bieniawski, 1989).

5. ENGINEERING GEOLOGICAL IMPLICATIONS AND MITIGATION

The integrated assessment along the Butwal-Palpa corridor recognizes some of the engineering geological problems that influence infrastructure stability and public safety. Some of the key implications include:

- **Flooding in the Terai**: The wide alluvial plains near Butwal are highly prone to seasonal flooding, which endangers bridges, road sections, and human settlements. Proper embankments, river training works, and regular maintenance of drainage systems are necessary.
- **Road-Cut Failures in Siwalik Hills**: Steep slope, poor rock, and absence of drainage initiate shallow landslides. Slope grading, retaining structures, rock bolting, shotcrete, and bioengineering techniques for stabilization are measures for mitigation.
- **Landslide in Lesser Himalaya**: Jointed phyllite and steep slopes pose dangers of sudden rockfall. Protection nets, catchment trenches, and controlled blasting during road construction can reduce hazards (Hoek et al., 2013, Dhakal et al. 2025).
- **Landslide Mitigation**: Both Bhalebas and Charchare landslides have shallow and deep-seated failures. Mitigation strategies include hazard and risk assessment, landslide zoning, and database management, drainage reshaping and slope geometry reshaping, retaining structures, toe protection, and bioengineering, awareness, education, and public involvement in early warning systems.
- **Infrastructure Design Considerations**: Design considerations of the Siddhababa Tunnel project are an excellent case example of design problems in landslide-prone terrain. Tunnel support systems, bypass tunnels, and real-time slope stability monitoring are essential in ensuring safety.

Overall, a synthesis of geotechnical investigations with slope stabilization measures, hazard zonation, and community-based risk management provides an integrated framework for mitigating engineering geological hazards along the corridor.

6. CONCLUSION

Butwal-Palpa corridor is a difficult engineering geological terrain under which flood, landslide, rockfall, and road-cut failure are serious concern issues. Field observation, soil and rock mass assessment have following conclusions.

- High flood hazard in Terai due to river processes and monsoon rainfall.
- Aggregation of sedimentation in Terai is another problem, due to immaturity of Himalayan River.
- Shallow and deep-seated recurrent landslides in Siwalik and Lesser Himalayan slopes around HFT, CCT and MBT zones.
- Sharp bending of Highway in Spur, which cause zigzag of road.
- Major infrastructure such as bridges and tunnels requires continuous monitoring and hazard-specific mitigation.
- Stabilization of slope, drainage, retaining structures, zoning of hazards, and bioengineering methods are required to enhance safety and resilience. The study

highlights the necessity of incorporating engineering geological evaluations into highway planning and infrastructure development to provide life, property, and socio-economic development protection in Western Nepal.

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ISSN: 3021-937X (Print)

RIVER OLDER THAN HIMALAYA

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ABSTRACT

The article shows the light in relation between the river and Himalayas; their formation, origin and the factors which lead to form present time landforms in and around the Himalayan region specially in Nepal Himalaya. The article is written based on the facts and detailed geological knowledge in the Himalayas and its history and relation with river.

Keywords: *River, Himalayas, History, Geology, Landforms*

1. INTRODUCTION

Nepal is the nation with different landform and geology with the different types of geography from the plain of terai (Indo-Gangetic plain) to the lust green sub-tropical forest of Chure (Siwalik) to the green and high-altitude hill of the Lesser Himalaya to the 12-month snow cap peak of mighty Higher Himalaya to rain shadow zone of Tibetan Plateau. And there flows the different types of river system and the river originate from different places, geological and geographical region. In South Asia, Southeast Asia and in around Himalayan region, the Himalaya are the source or origin point of most of river. Himalaya and river are the major factors which have made the geology and geography of this region so diverse in comparison to other places in planet.

Himalaya is the massive mountain range, lies in the Asia which is formed due to tectonic activities. Himalaya is form due to the orogeny which is alpine orogeny. Age of rock found here are of Cretaceous to Cenozoic Period. Himalayan mountain chain is the highest mountain chains which is about 3000 km long from Myanmar, Yunnan in east to Afghanistan, Tajikistan in west. Highest peak in Himalaya is Mt. Sagarmatha in world. There are 14 peaks higher than 8000 m which all lie in Himalaya. Himalaya consists of metamorphic and sedimentary rocks.

River is the large stream of fresh water or substance which flow in channel to the sea or another river which may be originated from glacier, rainfall or forest; which flows in the surface of the planet. Rivers are source of the civilization and natural resource which help human and ecosystem to develop and evolve which are very important in irrigation, power generation, etc. Like human have blood vessels in their body, rivers are blood vessels of the earth; without them, earth will not be living planet and can't support life. In Nepal, there are mainly two types of rivers; meandering and braided.

As we know that Gondwana used to be one massive continent in the past where present-day India, Australia and Africa were a single land mass. When the Indian region broke apart from it, started drifting around 70 million years ago towards past Tethys Sea area and collided with Eurasian Plate. By this process, the Himalaya is formed gradually and grown massive due to their collision. The flora and fauna found in Indian Sub-continent match with African flora and fauna more than any other region as both being part of Gondwana.

ISSN: 3021-937X (Print)

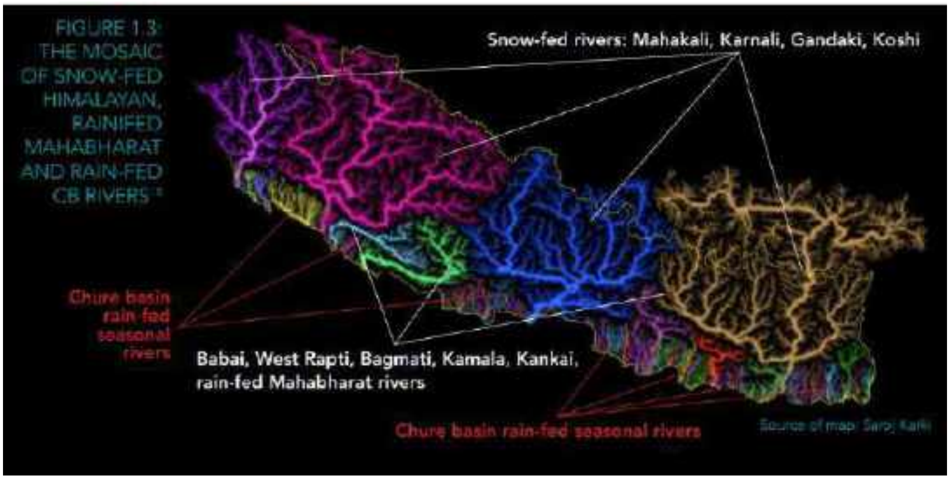

Figure 1: River system of Nepal (Saroj Karki)

2. RESULT AND DISCUSSION

Nepal is the country where we see most of the rivers which are snow-fed as well as rivers which originated from Lesser Himalaya and Siwalik region, which are rainfed and smaller in length and volume of water it possesses in comparison to the Higher Himalayan River. Nepal has major three river systems which all are snow-fed river system. Snow-fed river system is that river system where the river gets its source of water from the glacier or the melting of snow. Some rivers origin in Tibet Plateau within Nepal or Tibet. Those rivers can be considered rivers older than Himalaya. The rivers like Arun, Bhote Koshi, Trishuli, Karnali and Kali Gandaki can be called the rivers older than Himalaya. At the present time due to the size and massiveness or mightiness of Himalaya, no river can erode the Himalaya and make the gorge or path so big so long and deep by flowing now. The rivers mentioned above are flowing in the time when the Himalaya have not grown this big and mighty; in the early ages of the collision of the Indian Plate and Eurasian Plate. These rivers flow by making its own path and continue to do so in time when the Higher Himalaya started to uplift in rapid pace around 50-40 million years ago. These rivers started to erode the mountain and start to make their path. While doing that, the world deepest gorge in Kali Gandaki was formed. In the east of Kali Gandaki, there is Annapurna Himal-8091 m and in west Dhaulagiri Himal-8167m. Dhaulagiri was considered to be the highest peak on the world from 1808 to 1838 AD. The gorge is more than 6500 m deep near the Rupse waterfall in the Kali Gandaki corridor where Kali Gandaki flows in altitude of 1575 m. The eroded material from Himalaya by river is deposited in the plain of Terai so Chure (Siwalik) was formed after upliftment. The water shed of Himalaya in southern slope of eastern Nepal is all collected by Sunkoshi and Tamor rivers whereas the water melted in the northern slope of Sagarmatha and another eastern region of Himalaya is collected or fall under the catchment of Arun River. The Karnali River originated from southern slope of Mt. Kailash, is another evidence of river being older than Himalaya because it cuts the Himalayan chain and enter via Humla district.

River of Nepal is eroding and deepening its gorge from thousands of years so that we are able to see the rounded or spherical shape of stones in the gentle slope as well in about 50-80 meter higher in altitude and about 500 m away from present river channel. In present time, due to the

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extraction of construction material such as sand, boulder, gravel and pebble; the rate of erosion of Himalayan is increasing.

Figure 2: Kali Gandaki Gorge

Chance of flooding and landslide have also increased more in recent time. River of the Himalayan region also have shaped the geology, history, politics and geography of the region. River flow initiates the flow of civilization which is the reason why Indus Valley civilization and Nile River civilization were developed in the banks of river. Himalayan river has also played great role in the civilization of the Himalayan region. The river has made the valley which is good for the cultivation and has supported the population as well as helped people to navigate between places.

3. CONCLUSION

Rivers and Himalaya are the gifted features of the nature. It is our duty to protect and preserve them and maintaining the present ecosystem is necessary for the long-lasting human development, development of nature and infrastructure; which should go hand on hand. By fighting climate change, global warming and rapid glacier melting, we should make the planet safe and good for upcoming generations. If there is Himalaya and the rivers, earth can support life and we can enjoy its view and be able to get different resources from it.

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ISSN: 3021-937X (Print)

HYDROGEOLOGICAL CONTROLS ON HEAVY METAL CONTAMINATION IN KATHMANDU VALLEY: A CASE STUDY FROM RAMKOT, NAGARJUN MUNICIPALITY

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ABSTRACT

Groundwater is a significant source of drinking and domestic water in Kathmandu Valley, supplying nearly half of the population's demand. Groundwater quality in the Ramkot region of Nagarjun Municipality was studied here, particularly in regard to heavy metal contamination of shallow dug wells. It was evident from data that the predominant contaminants were iron (Fe) and manganese (Mn) and frequently exceeded WHO and Nepal standards, while chromium (Cr) and lead (Pb) at times exceeded safe limits. The Water Quality Index (WQI = 59.74) indicates the water is safe for non-drink purposes but not safe for direct drinking purposes. Pollution hazard assessments reveal children, in particular, are most vulnerable (HI = 1.39) and there is a possible risk of cancer from chromium. Pollution sources include natural sources like clay-dominated aquifers releasing Fe and Mn and anthropogenic activities such as sewage and surface water pollution, resulting in a "double exposure" phenomenon. Regular monitoring, safeguarding of shallow wells, and proper management of groundwater have been revealed through findings necessary for safeguarding public health and safety in Kathmandu Valley.

Keywords: *Groundwater, Kathmandu Valley, Ramkot, Heavy metals, Iron (Fe), Manganese (Mn), Water Quality Index*

1. INTRODUCTION

The groundwater is a significant supply for Kathmandu Valley, supplying nearly half of the domestic and drinking water demand (Shrestha et al., 2017). With increasing demand, particularly in the periphery and rural area, shallower dug wells remain the predominant water source. Nevertheless, this significant resource is at risk of natural and human influences.

It is simple for groundwater in the valley's geology to become contaminated. Sediments rich in minerals, more so in clay aquifers, deposit iron and manganese in water under favorable conditions. Concurrently, quick urban development, improper sewage control, and poorly constructed sanitation infrastructure contribute artificial contaminants (Sarkar et al., 2022).

Shallow dug wells are the most exposed since they are subjected to natural and human agents. Such wells carry a "double burden" of contamination, which threatens the health of the population around, of their water. To achieve a greater degree of overall understanding of these challenges, this current study analyses groundwater contamination in the Ramkot area of Nagarjun Municipality in the northwestern part of the valley. Utilizing information obtained directly from Kandel et al. (2025), this study evaluates levels of contamination in dug wells by heavy metals, compares these results to national and international regulatory standards, and examines the associated health consequences. Special attention is paid to associated hazards

ISSN: 3021-937X (Print)

faced by vulnerable groups such as children and the broader overall implications on sustainable groundwater management in the valley.

2. STUDY AREA

Ramkot is located on the west side of Kathmandu Valley in Nagarjun Municipality. People in this area rely a lot on shallow wells for their daily water needs. The ground here is made up of layers from the Kalimati Formation, which mainly contains clay, silt**,** and fine sand (Kandel et al., 2025). These layers hold back water, making it easier for iron and manganese to move around, while nearby human activities add more pollutants.

The region is significant culturally, with ancient settlements and agriculture increasing the demand on water supplies. Earlier studies randomly surveyed dug wells at Ramkot (Kandel et al., 2025), and this informs this review. Hydrogeological conditions here, which are comparable with those of the nearby Kathmandu Valley, make Ramkot a useful example for examining broader groundwater problems.

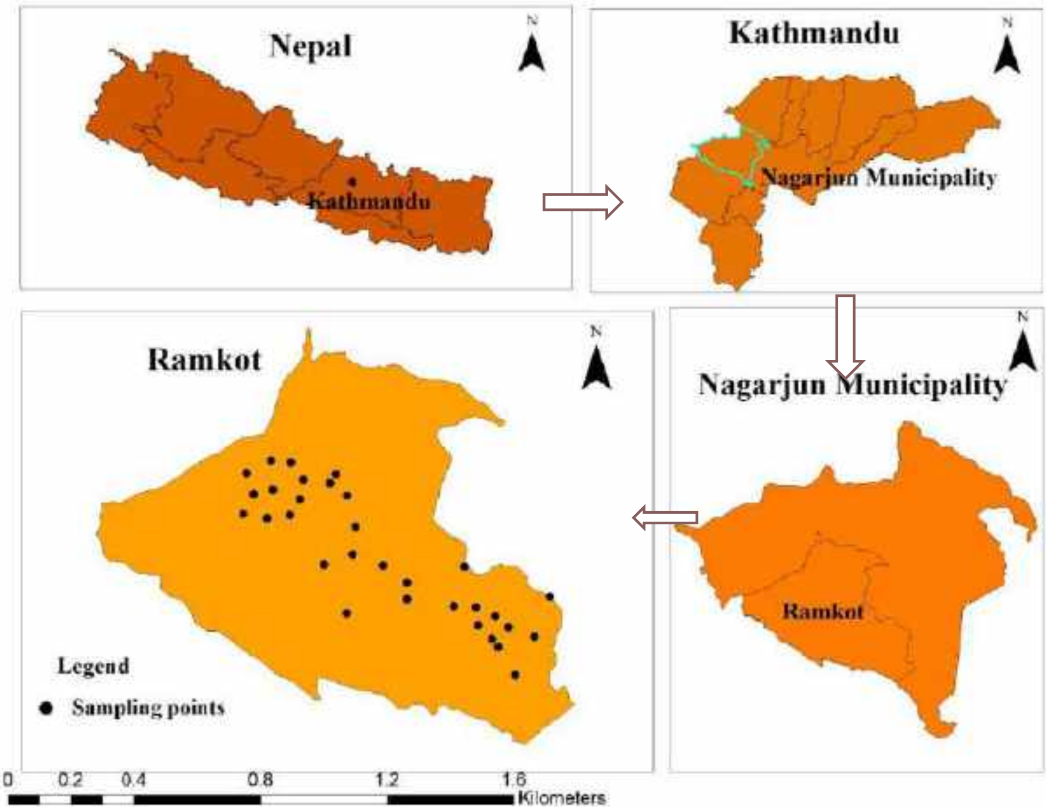

Figure 1: Location map of the study area showing the distribution of water sampling points in Ramkot, Nagarjun Municipality, Kathmandu, Nepal. The map illustrates the position of Ramkot within Nepal, Kathmandu District, and Nagarjun Municipality. Sampling points, (Kandel et al., 2025)

3. GEOLOGICAL AND HYDROGEOLOGICAL SETTING

The Kathmandu Valley is located in a basin covered in thick sections of ancient lake and river sediments over older Lesser Himalayan metamorphic rock. The base of the basin is covered by clay-rich sediments deposited by an oversized ancient lake, whereas the outer parts of the valley contain more sand and gravel from ancient riverbeds. This combination of soil and rock forms varied types of aquifers. Some are "confined" (lodged in by layers), while others are "unconfined" (near the surface).

ISSN: 3021-937X (Print)

Confined aquifers located in gravelly or sandy regions are very permeable and thus readily open to the infiltration of water and other contaminants. They reduce the movement of groundwater but simultaneously create chemical environments to release naturally abundant elements like iron (Fe) and manganese (Mn) in the earth. These geologic differences and formations like the Chobar fault are also accountable for the huge discrepancies in contamination in the groundwater in the valley.

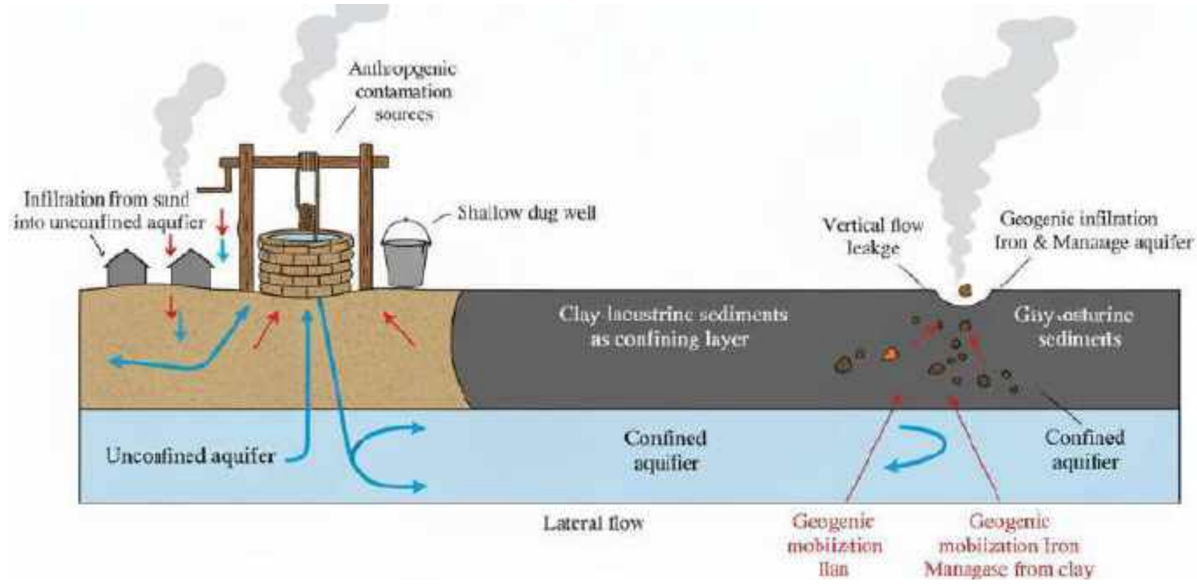

Figure 2: Modified conceptual model of aquifer contamination and Fe–Mn mobilization; based on Erickson & Barnes, 2023

4. CONTAMINATION PATHWAYS

The various contamination pathways for contamination are:

- ❖ **Human Activities**: In Kathmandu, city and nearby areas add pollution from homes, building projects, sewage, and small businesses. This pollution harms shallow dug wells and makes groundwater at risk of being polluted from the surface.
- ❖ **Natural Geology**: Weathering of mineral-rich lake bottom sediments deposits iron (Fe) and manganese (Mn) into aquifers. It continues unabated even under slightly disturbed conditions, thus establishing a base level of contamination.
- ❖ **Vertical Leakage**: Even though clay layers often stop the flow, pollutants from the surface or deeper areas can still reach unconfined aquifers, which affects the quality of water in shallow wells (Shrestha et al., 2017).
- ❖ **Shallow Dug Wells**: These wells get water straight from weak aquifers, which can easily be polluted by nature or people. Regular checks are important for safe home use (Kandel et al., 2025; Sarkar et al., 2022).
- ❖ **Controlling Factors**: Type of aquifer, composition of sediments, and redox conditions regulate the release of metals. Fe and Mn become more readily available under reduced conditions of aquifers, resulting in localized differences in water quality (Shrestha et al., 2017; Kandel et al., 2025).

5. METHODS

This study is entirely based on secondary data from published.

Data from studies such as Kandel et al. (2025) provided detailed information on heavy metal concentrations and water quality indices from dug wells. By synthesizing these findings, the study offers a comprehensive overview of groundwater contamination in Ramkot and its implications for water management.

6. RESULTS AND DISCUSSION

6.1 HEAVY METAL CONCENTRATIONS

The tested water samples showed a clear pattern, with the highest concentrations of heavy metals being Fe > Mn > Zn > Cu > Cr > Ni > Pb > Cd. Iron and Manganese were the only metals to regularly exceed the WHO and NDWQS limits.

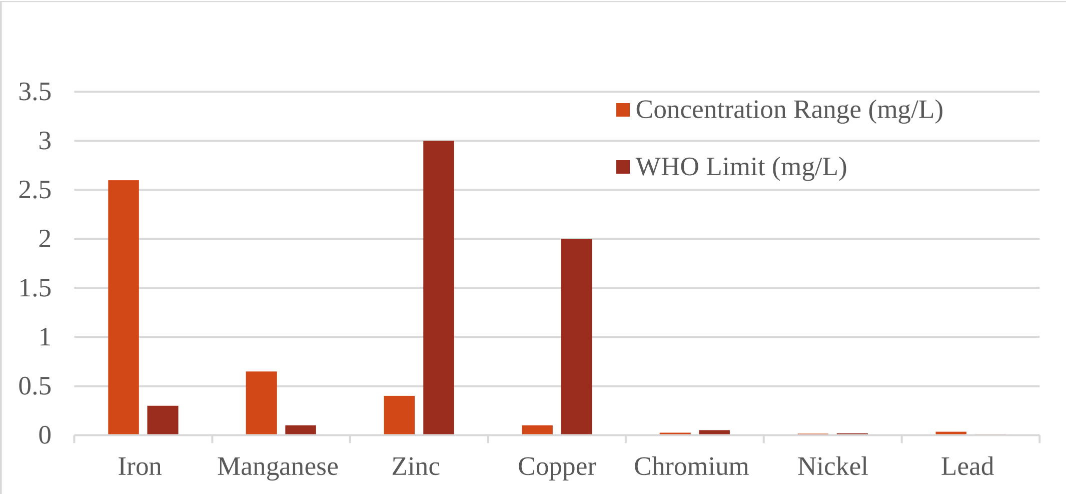

Figure 3: Bar graph of comparison of heavy metal concentration in groundwater samples to WHO limits from Ramkot, Kathmandu (Kandel et al., 2025).

The table 1 clearly shows that Iron (Fe) and Manganese (Mn) concentrations exceed the WHO limits. Iron (Fe) and manganese (Mn) were the dominant impurities in these, with 38% and 32% of the samples, respectively. The other metal like zinc (Zn) and nickel (Ni) stayed within protective levels while chromium (Cr) and lead (Pb) transcended their respective limits in several wells to reflect localized contamination. Cadmium (Cd) occurred in minute traces only. These results indicate that Fe and Mn are the dominant causes of groundwater contamination at the site with occasional possibilities of contamination by Cr and Pb.

Table 1: Data of concentration of heavy metals in groundwater samples from Ramkot, Kathmandu Valley (Data adapted from Kandel et al., 2025)

Heavy Metal	Concentration Range (mg/L)	WHO Limit (mg/L)	% Exceedance	Geological Source (Likely)
Iron (Fe)	0.15 – 2.6	0.3	~38%	Fe-bearing minerals in sediments; reducing conditions in clay layers
Manganese (Mn)	0.01 – 0.65	0.1	~32%	Mn-rich sediments and mineral weathering
Zinc (Zn)	0.01 – 0.4	3.0	0%	Geo-genic/anthropogenic minor contribution
Copper (Cu)	0.005 – 0.1	2.0	0%	Bedrock weathering, plumbing corrosion

Chromium (Cr)	0.002 – 0.025	0.05	~10%	Bedrock and anthropogenic input; potential carcinogen
Nickel (Ni)	0.001 – 0.015	0.02	0%	Geo-genic
Lead (Pb)	0 – 0.035	0.01	~12%	Bedrock + anthropogenic
Cadmium (Cd)	0 – 0.003	0.003	~5%	Geo-genic, trace amounts

6.2 INDICES AND HEALTH RISK ASSESSMENT

The Water Quality Index (WQI) of 59.74 ranked the groundwater as Grade B, indicating it is fit for non-potable usage but unsafe for direct drinking. The Heavy Metal Evaluation Index (HEI) of 8.479 indicated low overall contamination by heavy metals (Kandel et al., 2025). Yet health risk assessments showed possible issues: the total non-carcinogenic Hazard Index (HI-total) for kids was 1.39 and above the safety limit, and a possible carcinogenic risk by chrome exposure. This means that in addition to acceptable overall indices of water quality, individual metals represent strong health risks and do so specifically to sensitive groups.

7. DISCUSSION

The Ramkot groundwater data suggest that the overall rock and soil of the region are the most significant source of contamination, most notably heavy naturally occurring metals. Higher levels of manganese (Mn) and iron (Fe) result from mineral decompositions in valley deposits dominated by clay, which suggest the geochemical conditions of the aquifers. Similar patterns in the Kathmandu Valley suggest that this is a common problem (Shrestha et al., 2017).

The most exposed are shallow dug wells due to their shallowness, which allows natural metals and surficial contaminants like sewage, and thus produces a double exposure effect (Sarkar et al., 2022).

Heavy Metal Evaluation Index (HEI = 8.479) shows the general contamination is low, but the levels of Fe, Mn, Cr, and Pb are of concern. The Water Quality Index (WQI = 59.74) is of the opinion that the water would be acceptable for non-potable use but not safe for drinking purposes.

Health risk assessment indicates children have the most risk (HI = 1.39), and this is primarily due to iron (Fe) and manganese (Mn), and cancer may be caused by chromium (Cr). These observations indicate that shallow wells contain natural and human sources of pollution, and these require careful verification.

8. CONCLUSION

Contamination of groundwater in Ramkot, Kathmandu Valley, is mainly caused by natural geology and human practices. Soils dominated by clay produce iron (Fe) and manganese (Mn) in shallower water sources, and sewage, surface runoff, and improper sanitation contribute additionally toward lowering water quality. We recognize from the WQI (59.74) that the water is unsuitable for direct drinking, and HI (1.39) shows children, especially, are most vulnerable, and there will be potential health hazards of chromium (Cr) and lead (Pb).

Shallow dug wells are at risk of natural and human source pollutants, which highlights the importance of regular observation of water quality. In order to minimize these risks, it is necessary to frequently monitor wells for heavy metals. We need to safeguard shallow dug wells against contamination at the surface, employ simple treatment technologies such as filtration or aeration for iron and manganese, and consider regional soil types in designing new wells. These steps, supplemented by increasing awareness among the population and managing groundwater sustainably, can contribute toward supplying safer drinking water supplies in the Kathmandu Valley. The findings provide clear evidence of the geo-genic and anthropogenic sources of contamination and emphasize the need for sustainable water management strategies in the region.

9. ACKNOWLEDGEMENT

I sincerely thank the Geology Department of Tri-Chandra Multiple Campus for the opportunity and guidance to write this article. I am also grateful to everyone whose support, data, and insights made this work possible.

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ISSN: 3021-937X (Print)

UNSEEN RISKS IN DRINKING WATER: GROUNDWATER ARSENIC AND WELL DEPTH IN PARASI BAZAAR, NEPAL

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ABSTRACT

Groundwater arsenic poisoning is a geogenic (natural) risk to drinking-water security in South Asia. The article presents hydrochemical results from eight tubewells drilled in Parasi Bazaar (Ramgram Municipality), Nawalparasi District (West of Bardaghat Susta). Some of these wells were installed only 20 meters away from the arsenic monitoring tube wells located at the water supply compound and the Agricultural Input Corporation compound. This study also synthesizes regional data on arsenic mobilization, human health effects, and mitigation. Results demonstrate a strong depth dependence of arsenic concentration on depth: shallow wells (20–40m) frequently exceed Nepal's permissible limit 50 µg/L (50 ppb), while deeper wells generally register lower concentrations. The maximum concentration in our data set (7/20 m) was 195 µg/L (195 ppb). Our findings corroborate earlier research in Nawalparasi that links high arsenic to Siwalik-derived sediments and third-order river plains. We discuss clinical presentations of chronic arsenic poisoning, the geological source and microbiological processes of arsenic mobilization, and possible interventions such as well closure, controlled abstraction, and deep aquifer protection that could reduce exposure. The paper ends with policy-driven recommendations for surveillance, health education, and sustainable groundwater utilization in the Terai.

Keywords: *Terai, Nawalparasi, Tubewells, Aquifers, Public health, Nepal*

1. INTRODUCTION

In Parasi Bazaar, residents typically rely on handpumps as their primary household water source, which has supplied water to the community for decades. The obtained groundwater is typically clear, cold, and visibly safe to drink, meeting everyday needs such as drinking, cooking, and irrigation. However, despite its appearance, the water may harbor naturally occurring arsenic, an unseen, flavorless, and odorless metalloid poison. In groundwater, arsenic typically occurs as trivalent arsenite As (III) under reducing conditions and as pentavalent arsenate As (V) under oxidizing conditions (ATSDR,2000). As (III) is two to three times more toxic than As (V), and thus the reducing nature of aquifers, like the shallow alluvial systems of the Terai, presents a high hazard. The Agency for Toxic Substances and Disease Registry also points out that toxicity is dose-dependent, meaning even naturally occurring elements become harmful when present at elevated concentrations (ATSDR,2000). Understanding arsenic speciation and its varying toxicity is therefore crucial in assessing the safety of groundwater and in designing mitigation strategies. Long-term consumption of arsenic-contaminated groundwater through chronic exposure is a serious health concern, causing dermatological, neurological, and systemic effects that undermine both livelihoods and public health.

Arsenic contamination of groundwater is now recognized as one of the world's most pressing environmental health problems. From West Bengal in India to Bangladesh and parts of China, millions of citizens are being exposed to concentrations hundreds of times greater than the

World Health Organization (WHO) standard of 10 µg/L (10 ppb) (WHO, 2017; Chowdhury et al., 2000). Chronic exposure has been linked to a wide range of harmful effects such as skin lesions, cardiovascular disease, neurological damage, and cancers of the skin, bladder, and internal organs (Bhattacharya et al., 2007; Chowdhury et al., 2000).

Nepal's southern plain, the Terai, is no exception. Since the late 1990s, arsenic has been found in shallow aquifers in more than 25 Terai districts, with Nawalparasi among the most severely affected (DWSS/WHO, 1999; ENPHO/NRCS, 2003). Although Nepal's national drinking-water standard is 50 µg/L (50 ppb), unsafe tubewells remain in use by many rural households due to limited awareness, lack of alternative sources, and the high cost of treatment.

This paper discusses eight arsenic-sampling tubewells drilled in Parasi Bazaar, Nawalparasi District, by the Department of Water Supply and Sewerage (DWSS) and the Agricultural Input Center (AIC). We analyze arsenic levels and establish their correlation with well depth, using secondary institutional data. By combining these results with available local literature, the study aims to: (1) document arsenic concentrations and depth trends, (2) describe geological and geochemical controls on contamination, (3) outline human health effects, and (4) propose practical mitigation and policy recommendations (Chowdhury et al., 2000; Shrestha & Shrestha, 2003; Bhattacharya et al., 2007; Pokhrel et al., 2009).

This is not only a matter of presenting scientific evidence but also of emphasizing the human side of the problem. Clean water, long relied upon by families in Parasi Bazaar, should no longer remain a silent source of illness. Drinking safe water is not a luxury-it is a basic right for all Nepali citizens.

Although several studies have indicated arsenic contamination in the Terai, most have been large-scale surveys or regional maps. Few analyses have specifically examined Arsenic concentrations in relation to well depth in localized hotspots such as Parasi Bazaar. Even after two decades, local-scale well-depth correlations remain underexplored in Nepal. While the role of aquifer depth and sediment provenance in controlling contamination has been recognized regionally, it remains under-researched at the scale of communities. By reinterpreting institutional data from DWSS and AIC, this research provides a fine-scale, depth-dependent assessment of arsenic risk in Nawalparasi, directly linking scientific findings to local health concerns. This approach helps fill the gap between broad regional surveys and household realities.

2. STUDY AREA AND GEOLOGICAL CONTEXT

Parasi Bazaar lies in the Terai plain (Ramgram Municipality), near the boundary of the alluvial plains and the Churia (Siwalik) foothills. Aquifers in this area consist of Quaternary alluvium composed of a mixture of Siwalik (sedimentary) and older metamorphic/igneous rocks derived from the high Himalaya. Previous studies indicate that arsenic distribution in groundwater is strongly influenced by sediment provenance: areas dominated by Siwalik-derived sediments tend to contain higher arsenic, whereas plains with metamorphic/igneous detritus show lower concentrations (Shrestha & Shrestha, 2003; Pokhrel et al., 2009). Third-order River floodplains, dominated by Siwalik deposits, are therefore more at risk and environmentally

ISSN: 3021-937X (Print)

fragile. The location of the wells in the Nawalparasi district is shown in Figure 1.

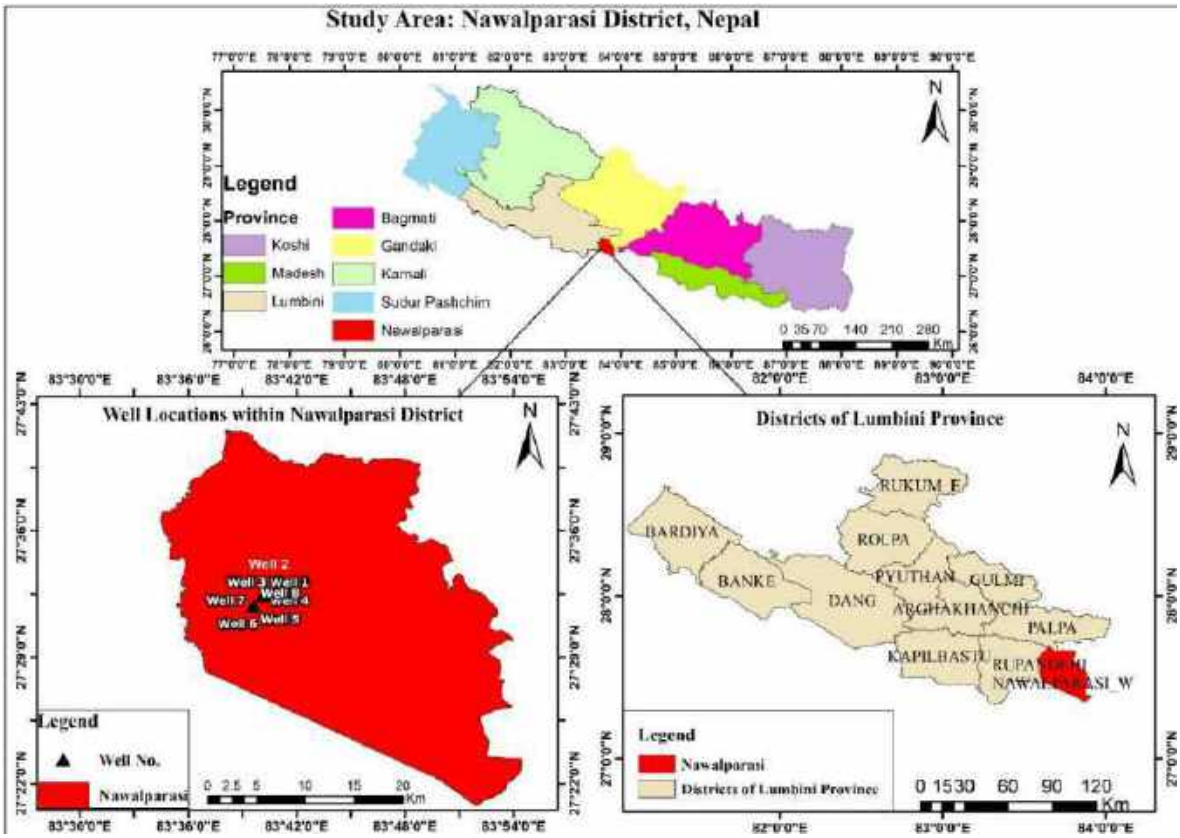

Figure 1: Study area within Nawalparasi District; Parasi Bazaar

3. METHODS

This study relies entirely on secondary data, including monitoring-well records from the Department of Water Supply and Sewerage (DWSS, Division Office, Parasi Bazaar) and the Agricultural Input Company (AIC, Parasi Bazaar). Water-quality data (tubewell arsenic concentrations, well depth, and monitoring-well details) were gathered from DWSS/AIC project reports and laboratory analyses archived by the institutions. All statistical and spatial analyses presented here were carried out on this secondary dataset. The Scatter plot and the Bland-Altman graphs are plotted using python coding and the Pearson's coefficients r and p are calculated.

4. RESULT AND DISCUSSION

The first four arsenic investigation wells were installed within the premises of the Department of Water Supply and Sewerage (DWSS), while the remaining four were drilled at the Agricultural Input Center (AIC) in Parasi Bazaar, Nawalparasi District. The monitoring data from these eight wells are presented in Table 1.

Arsenic concentrations in the eight tubewells ranged from 6 to 195 µg/L (6 to 195 ppb). The average concentration was 78.9 µg/L, the median was 73.5µg/L, and the standard deviation was 60.9 µg/L. The minimum value (6 µg/L) occurred in Well 6 (60 m depth), and the maximum (195 µg/L) in Well 7 (20 m depth) (Fig. 2). Overall, five of the eight wells (62.5%) exceeded Nepal's drinking-water standard of 50 µg/L, and seven of the eight (87.5%) exceeded the WHO guideline value of 10 µg/L (WHO, 2017).

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Table 1: Data of monitoring wells (DWSS and AIC)

Well No.	Latitude	Longitude	Altitude (ground level) (m)	Total Drilling Depth (m)	Arsenic Concentration (µg/L)	Screen Position
1	27°32'24.6" N	83°40'6" E	74.39m	80	36	75-77m
2	27°32'24.6" N	83°40'6" E	74.39m	40	120	34.25-36.25m/bgl
3	27°32'24.6" N	83°40'6" E	74.39m	20	98	14.5-16.5m/bgl
4	27°32'24.6" N	83°40'6" E	74.39m	51	93	45.5- 47.5m
5	27°31'49.6" N	83°39'35.3" E	109.15m	80	29	73.0-75.0m
6	27°31'49.6" N	83°39'35.3" E	109.15m	60	6	53.0-55.0m/bgl)
7	27°31'49.6" N	83°39'35.3" E	109.15m	20	195	15-17m/bgl
8	27°31'49.6" N	83°39'35.3" E	109.15m	49	54	45.0-47.0m

4.1 SCATTER PLOT

The scatter plot (Figure 2) shows that arsenic concentration decreases as drilling depth increases. The fitted regression line confirms a negative linear trend, which is supported by the Pearson correlation coefficient ($r = -0.799$, $p = 0.017$). Shallow wells (15–40 m) show much higher arsenic concentrations, sometimes exceeding 100–190 µg/L, whereas deeper wells (>70 m) generally show much lower concentrations (below 40 µg/L). This suggests that drilling deeper wells may reduce exposure to arsenic-contaminated water.

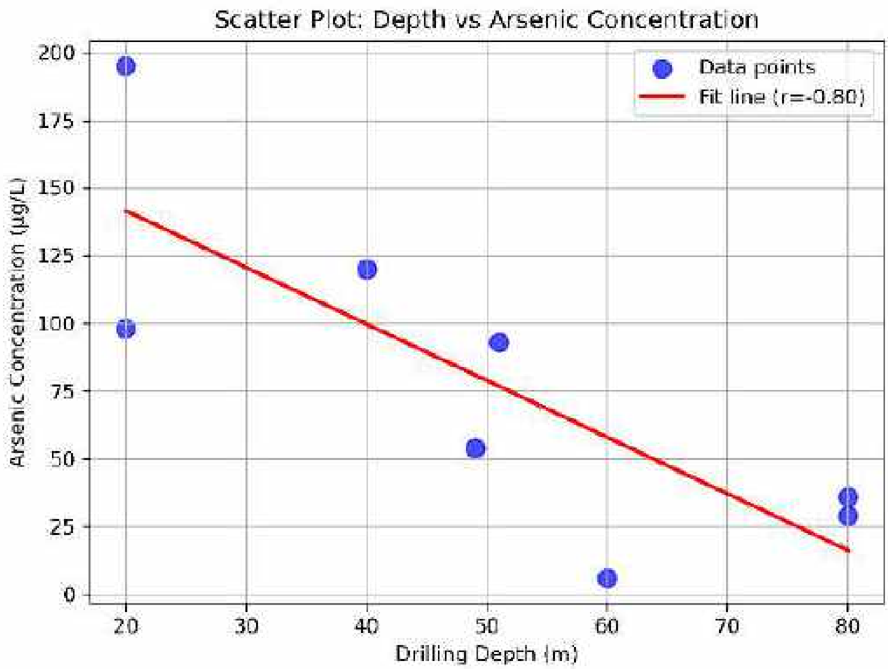

Figure 2: Scatter plot of Depth and Arsenic concentration

4.2 BLAND–ALTMAN PLOT

The Bland–Altman graph (Figure 3) compares the agreement between drilling depth and arsenic concentration by plotting the difference (Depth-As concentration) against their mean. The plot shows large variations, especially at shallow depths where arsenic concentrations are high. The mean difference is negative, reflecting that arsenic concentration values are often much higher than depth values at shallower wells. Limits of agreement (±1.96 SD) show wide scatter, indicating poor agreement between the two variables (which is expected, since they measure different physical quantities).

The Bland–Altman plot highlights inconsistency in the relationship, especially at shallow levels, supporting the scatter plot finding that shallow depths are associated with greater variability and higher arsenic levels.

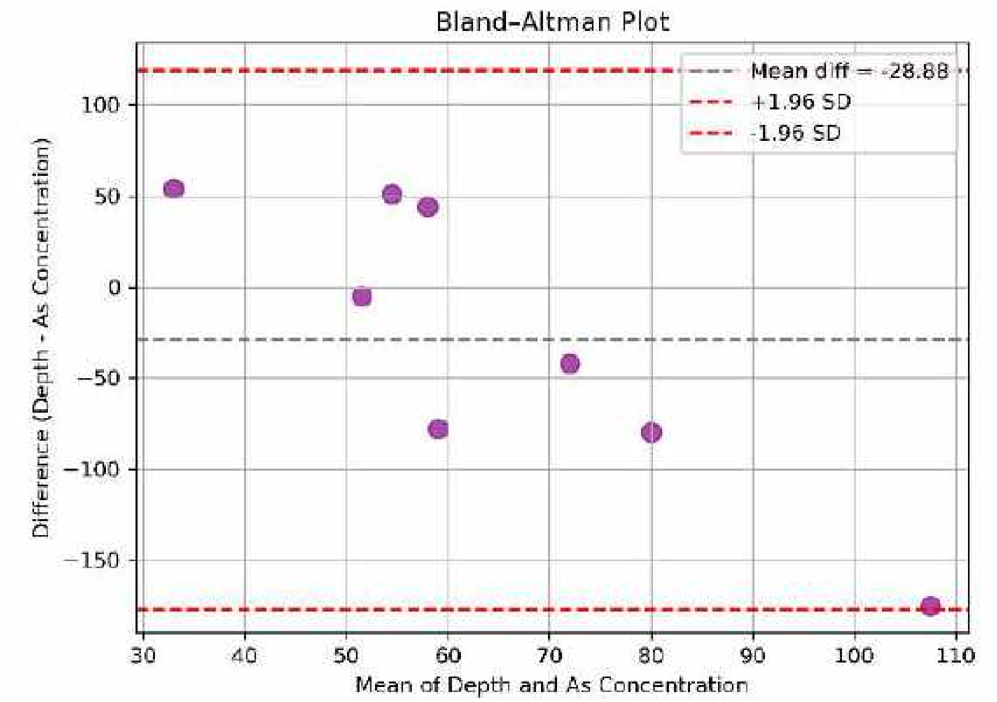

Figure 3: Bland–Altman Plot by using depth and Arsenic concentration data.

With only 8 data points, the result is not strongly significant, and it must have limitations. Collecting more well samples would likely strengthen the trend and achieve statistical significance.

This finding aligns with previous studies across the Terai and South Asia, which also reported elevated arsenic in shallow aquifers (<40 m) and comparatively safer levels in deeper aquifers (>100 m) (Chowdhury et al., 2000; Akai et al., 2004; DWSS/ENPHO, 2003).

The extreme case of Well 7 (20 m, 195 µg/L) demonstrates the acute risk of using untreated shallow groundwater for domestic purposes, especially in areas underlain by Siwalik-derived sediments, which have been shown to be high in arsenic (DWSS/ENPHO, 2003).

4.3 DEPTH DEPENDENCE AND CONTROL BY GEOLOGY

Our data clearly shows that shallow aquifers contain consistently higher arsenic concentrations. This agrees with earlier regional studies attributing elevated arsenic to Siwalik-derived alluvium and third-order river depositional environments. Sediment provenance appears to be a first-order control on arsenic occurrence in the Terai.

4.4 MECHANISMS OF ARSENIC MOBILIZATION

Reductive dissolution of iron oxides in anoxic environments is widely recognized as a principal mechanism for arsenic release into groundwater. Microbial activity, perhaps triggered by manual drilling and the presence of organic matter, may catalyze the process-an interpretation supported by research in Bangladesh and West Bengal (Akai et al., 2004; Chowdhury et al., 2000).

4.5 HEALTH IMPLICATIONS

Chronic arsenic exposure leads to typical dermatological symptoms (diffuse and macular melanosis, leuco-melanosis, palmoplantar keratosis) and systemic effects (hepatosplenomegaly, ascites). It is also associated with numerous cancers (skin, lung, bladder, uterine) after prolonged exposure. Early pigmentation changes are often reversible with safe water and improved nutrition, whereas keratosis tends to persist and carries a higher malignancy risk. Misperceptions at the community level (e.g., attributing lesions to spiritual causes) complicate public health interventions and highlight the need for culturally sensitive education campaigns (Chowdhury et al., 2000; WHO, 2017).

4.6 SUSTAINABILITY CONCERNS OF DEEP-AQUIFER EXTRACTION

Arsenic-safe water supports Nepal's commitment to Sustainable Development Goal 6, which calls for universal access to safe and affordable drinking water. Deep aquifers (>100 m) are generally arsenic-free and thus a promising long-term water source. However, unchecked abstraction without proper design and protection (e.g., sealing annular spaces, controlling pumping) risks downward migration of contaminated water. Such effective measures include sealing annular gaps with bentonite clay grout, creating a low-permeability barrier to prevent vertical leakage or inter-aquifer mixing, and are effectively implemented in several South Asian groundwater programs, like the CGWB and BGS; it is recommended that similar measures be adopted locally.

5. RECOMMENDATIONS (POLICY AND PRACTICE)

Supply of arsenic-safe drinking water is a matter of environmental justice. Therefore, follow-up action should be initiated in a time.

5.1 IMMEDIATE ACTIONS (COMMUNITY AND MUNICIPALITY)

The immediate actions include the following:

a) Clearly label unsafe shallow wells and provide household-level guidance to avoid their use for drinking.
b) Install and promote proven point-of-use technologies where feasible (e.g., iron-based adsorbents, community filters, rainwater harvesting).
c) Implement school- and community-based education programs to reduce stigma and explain health effects in local languages.

5.2 ENGINEERING AND MONITORING

The following points are incorporated in engineering and monitoring:

a) Promote best-practice construction: sealed annular spaces, properly screened deep wells, and single-aquifer monitoring wells.
b) Implement a sentinel well network for frequent testing and develop a public database mapping arsenic risk.
c) Regulate abstraction to prevent over-extraction of deep aquifers beneath contaminated shallow ones.

5.3 RESEARCH AND CAPACITY DEVELOPMENT

The following activities could be done in this sector:

a) Conduct provenance mapping of aquifer sediments (grain size, mineralogy) to enhance spatial prediction of risk.
b) Investigate the effects of drilling practices and organic additives on microbial arsenic release and promote sterile or clean drilling techniques.

6. CONCLUSION

The eight-well survey in Parasi Bazaar confirms that arsenic contamination in the Terai is a geogenic phenomenon strongly controlled by sediment provenance and aquifer depth. Shallow wells pose the greatest public health risk, while deeper, shielded aquifers are safer alternatives if designed and managed carefully. Protecting human health and preserving groundwater resources requires an integrated approach that combines hydrogeological protection, health education, targeted testing, and community-based mitigation.

7. ACKNOWLEDGMENT

I would like to thank the Department of Geology, Tri-Chandra Multiple Campus, for providing continuous support. I am sincerely grateful to Mr. Nir Shakya Sir for providing DWSS and AIC well-monitoring data with proper guidance. I also extend my gratitude to the Department of Water Supply and Sewerage (DWSS), Parasi Division Office, and the Agricultural Input Company (AIC) for making monitoring data and laboratory reports available.

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ISSN: 3021-937X (Print)

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ARSENIC CONTAMINATION OF GROUNDWATER IN NEPAL

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ABSTRACT

Arsenic contamination in groundwater is a major drinking water problem in Nepal, particularly in the Terai region where the population density is high and people mostly rely on shallow to medium depth hand tube wells and dug wells for daily water use. The National Sanitation Steering Committee (NSSC), with support from different organizations, tested 737,009 groundwater samples across 25 districts. Earlier studies on 25,058 samples from 20 districts (2003 report) showed that 23% had arsenic levels between 10–50 µg/L, and 8% had concentrations above 50 µg/L. More recent testing of 737,009 samples revealed that 7.9% contained 10–50 µg/L and 2.3% exceeded 50 µg/L. These findings confirm arsenic as both a health and environmental management issue. Research efforts now focus on reducing arsenic through sustainable approaches that communities can adopt, including identifying risk areas, raising awareness, following WHO guidelines, promoting eco-friendly treatment methods, finding safe alternative water sources, assessing their sustainability, and studying the health and agricultural impacts. Strengthening government, NGOs, and research institutions is also emphasized to tackle the issue effectively.

Keywords: *Arsenic contamination, National Sanitation Steering Committee (NSSC), Dug wells.*

1. INTRODUCTION

Arsenic (As), with atomic number 33, is a naturally occurring element found in the earth's crust, ranking 20th in abundance and 12th in the human body (Mandal & Suzuki, 2002) . While its main source is geological, human activities like mining, burning fossil fuels, and using pesticides also contribute to arsenic pollution. It can occur in four oxidation states: +5 (arsenate), +3 (arsenite), 0 (elemental arsenic), and -3 (arsine). Arsenic appears in both inorganic and organic forms, such as arsenobetaine, arsenocholine (found in fish), and arsenosugars (NG, 2005). In water, both organic and inorganic forms have been identified, with total arsenic including both soluble and particulate forms (the latter can be filtered using a 0.45-micron filter). Arsenic's behavior in water depends on pH (typically 6.5–8.5 in groundwater) and redox conditions. Arsenite [As (III)] is more common in anaerobic (oxygen-poor) groundwater, while arsenate [As (V)] is typical in aerobic (oxygen-rich) surface water, although this can vary. Arsenate is dominant in acidic conditions ($pH > 3$), while arsenite dominates in alkaline conditions ($pH < 9$), and becomes ionic above pH 9. Studies have found some groundwater sources with only As (III), others with only As (V), and some with both. Arsenic has long been known as a poison, and high doses (above 600 mg/L in food or water) can be fatal. Historically, it has been linked to the deaths of figures like Napoleon Bonaparte and George III. Inorganic arsenic compounds are known human carcinogens and can cause various health issues, from skin lesions to cancers of the brain, liver, kidney, and stomach. Generally, inorganic arsenic is more toxic than the organic forms found in living organisms (Meharg & Hartley Whitaker, 2002).

2. METHODOLOGY

The article is based on a systematic analysis of secondary data. The information was gathered from a variety of sources, such as published academic research, national level surveys, and official reports from relevant organizations.

3. STUDY AREA

Nepal is a landlocked country in South Asia, situated between latitudes 26°22′N to 30°27′N and longitudes 80°04′E to 88°12′E. It is bordered by China to the north and India to the south, east, and west. Covering an area of 147,181 km², Nepal is known for its diverse and rugged terrain, cold climate, and mountainous landscape. The elevation ranges from just 64 meters above sea level to 8,848.86 meters at Mount Everest, the world's highest peak, all within a stretch of 200 km. The groundwater arsenic has been studied in different district of five development region of terai area as shown in Figure 1.

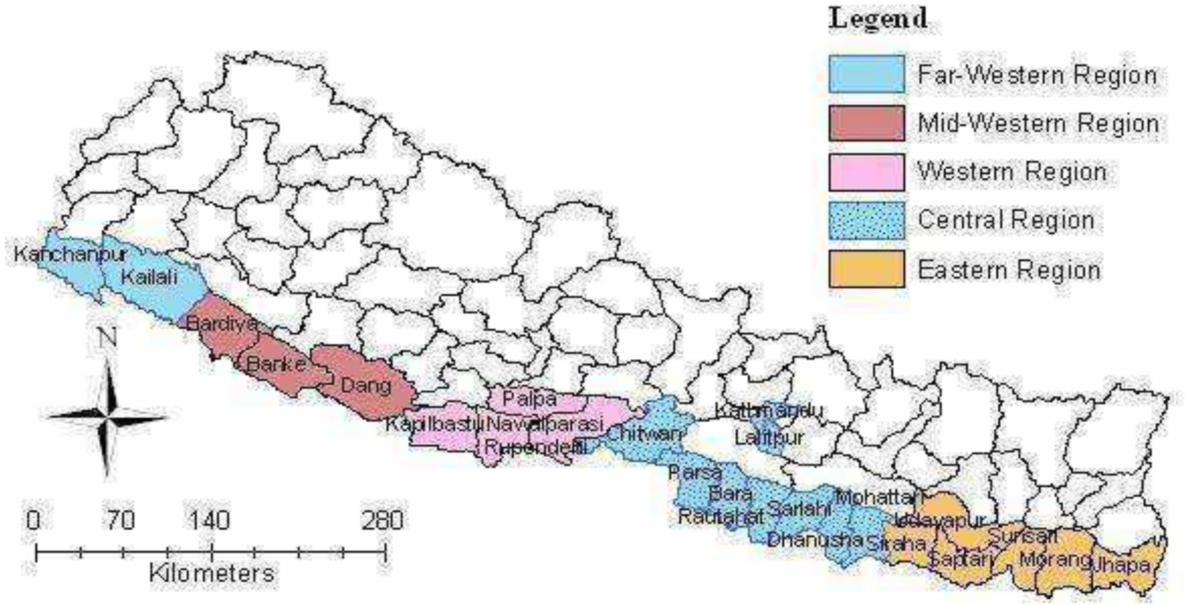

Figure 1: Groundwater arsenic tested districts in various development regions of Nepal (Thakur, Thakur, Ramanathan, Kumar , & Kumar , 2011)

3. GUIDELINE VALUE FOR ARSENIC IN DRINKING WATER

In 1993, the WHO reduced the safe limit of arsenic in drinking water from 50 µg/L to 10 µg/L due to its harmful health effects (Guidelines for Drinking-Water Quality, 1993). This new limit is considered provisional, as there's still uncertainty about the risks of long-term exposure to very low levels. However, Nepal still follows the older 50 µg/L standard because of challenges like limited technical skills, equipment, and financial resources but, Australia currently has the strictest limit, set at 7 µg/L.

4. ARSENIC CHALLENGES AROUND THE WORLD

Arsenic is a major pollutant found in soil and groundwater across many parts of the world. People are exposed to it through natural sources, industrial activities, and contaminated food or drinks. High arsenic levels in drinking water have been reported in countries like Argentina, Chile, Bangladesh, China, India, Nepal, the USA, and others. The most serious health crisis is in Bangladesh and West Bengal, India, where millions are at risk due to contaminated groundwater (Escober, Hue, & Cutler, 2005). Some countries are still discovering new arsenic-affected areas. In many developing nations, the safe limit for arsenic in drinking water remains at 50 µg/L, mainly due to limited resources, lack of proper testing facilities, and high costs of removal. While modern automated labs are now being set up in some institutions, earlier testing methods often failed to detect lower but still harmful levels of arsenic. Interestingly, high arsenic in groundwater doesn't always come from soil or rock with high arsenic content, it also depends on factors like the type of rock, how easily arsenic moves, its chemical form, and environmental conditions (Escober, Hue, & Cutler, 2005). Estimating how many people are at risk is difficult, especially in areas without detailed geological studies. These estimates usually depend on known arsenic poisoning cases, the chances of people drinking water with more than 50 µg/L arsenic, the number of people living in affected areas, and the ability of local systems to deal with the contamination.

5. ARSENIC SPECIATION

Arsenic speciation means studying the different chemical forms of arsenic found in the environment and living organisms. This is important because each form of arsenic behaves differently and has different levels of toxicity, some are almost harmless (like those found in fish), while others, like arsenite [As (III)], are extremely toxic (Mandal & Suzuki, 2002). However, there are still many problems in this area, such as difficulty keeping samples stable, not being able to detect all forms properly, and the lack of standard testing methods. Arsenic changes its form based on environmental conditions like pH, redox potential (Eh), and the presence of organic matter, sulfur, or microbes.

In water, arsenic appears in different forms depending on whether the environment is rich in oxygen or not. In oxygen-rich water (aerobic), arsenic mostly exists as arsenic acid or its ions, depending on the pH. In oxygen-poor (reducing) conditions, it exists mainly as arsenious acid or other forms depending on pH levels. Extremely toxic forms like arsine gas or metallic arsenic can form under rare, harsh conditions, but these are not common in nature. Other processes like adsorption, precipitation, and microbial activity also affect how arsenic moves and changes in water. In Nepal, we still don't fully understand the exact forms of arsenic present in groundwater, so more scientific research and cooperation from government, organizations, and the public is needed to address the problem.

6. SOURCE OF ARSENIC

Nepal's geology is complex, with major elevation differences from the Himalayas to the flat Terai region. The Terai has similar geological features to the Bengal Delta, made up of thick layers of sand, gravel, and river-deposited soil (Pokhrel, Bhandari, & Viraraghavan, 2009). Arsenic in the groundwater here mainly comes from natural sources, especially the breakdown (or dissolution) of arsenic-containing rocks and minerals. Studies have shown high arsenic levels in Terai groundwater, mostly in the toxic form arsenite [As(III)], ranging from 1.7 to 404 µg/L (Bhattacharya, 2002). High amounts of iron and manganese in the water suggest that arsenic may be released when it detaches from these minerals due to microbial activity and chemical changes.

In places like Nawalparasi, sediment samples also show high arsenic, along with iron, titanium, and calcium oxides, which may also release arsenic under changing underground conditions. Organic matter and iron oxides can trap arsenic, but under low-oxygen (reducing) conditions, it can be released into the water. Other factors like bicarbonate, phosphate, sulfide oxidation,

ISSN: 3021-937X (Print)

and underground water flow also affect how arsenic spreads. Although the exact process isn't fully understood, reducing conditions in the soil and water are a key factor in increasing arsenic levels in the groundwater.

7. TESTING METHOD IN NEPAL

There are several methods available to test arsenic levels in both environmental and biological samples, which help identify past exposure. These methods fall into two main categories: field-based and laboratory-based. Field tests are simple and often used in remote areas. They work by converting inorganic arsenic into a gas called arsine (AsH_3) using zinc and hydrochloric acid. This gas then reacts with special indicator paper (coated with mercury bromide), and the color change on the paper shows how much arsenic is present. In Nepal, commonly used field kits include the ENPHO Kit and the Modified AAN Kit. On the other hand, laboratory methods are more advanced and accurate. One commonly used technique is Inductively Coupled Plasma Mass Spectrometry (ICP-MS), where the sample is mixed with acid and sprayed into very hot plasma. This process breaks down and ionizes all arsenic forms, allowing precise measurement. However, high chloride levels in the sample can interfere with the results because chloride can form a compound (argon chloride) that has the same atomic mass as arsenic. This can lead to readings that are too high. Modern lab instruments, like the Agilent 7500ce, now have special features (reaction or collision cells) to remove this interference. With proper equipment, total arsenic can be accurately detected at very low levels down to 0.2 μg/L.

8. ARSENIC DISTRIBUTION OF NEPAL

Arsenic contamination in Nepal's groundwater was first discovered in 1999 during a WHO survey in the Terai region which is shown in Fig 2. Since then, various studies across 25 districts have shown different levels of arsenic in water samples. Most of the samples (about 89.8%) had arsenic levels below the safe limit of 10 μg/L, while 7.9% had levels between 10–50 μg and 2.3% had dangerously high levels above 50 μg/L.

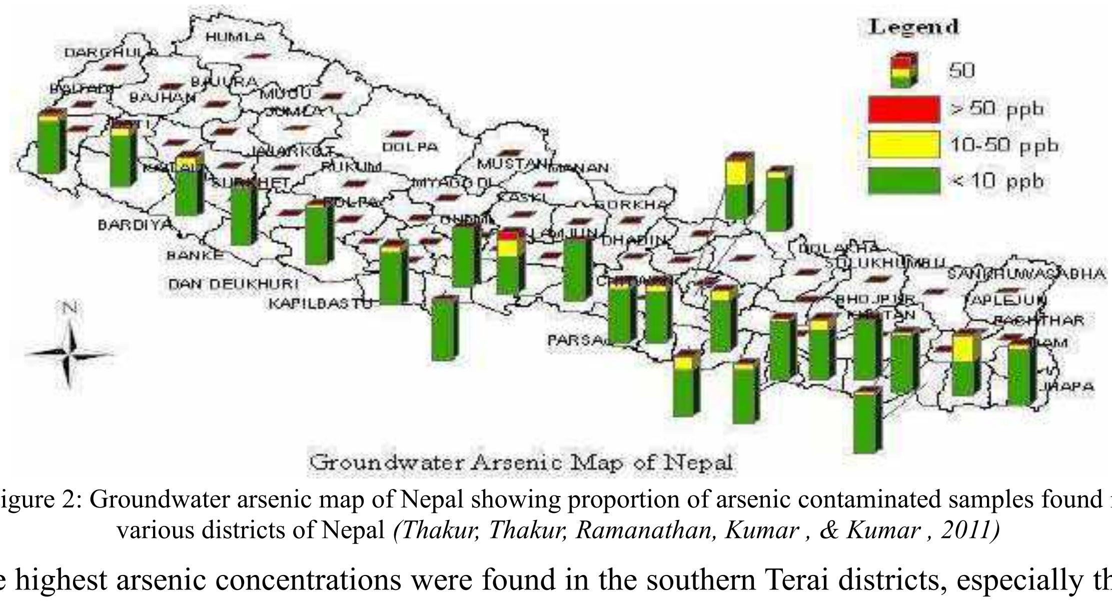

Figure 2: Groundwater arsenic map of Nepal showing proportion of arsenic contaminated samples found in various districts of Nepal *(Thakur, Thakur, Ramanathan, Kumar , & Kumar , 2011)*

The highest arsenic concentrations were found in the southern Terai districts, especially those along the Indian border such as Sunsari, Saptari, Siraha, Dhanusha, Rautahat, Nawalparasi, and others in Fig 3. On the other hand, districts like Ilam, Jhapa, Morang, Kathmandu, and Chitwan showed low arsenic levels, posing little risk at present. Although the majority of samples are within safe limits, the situation is still concerning. Changes in land use, urban growth, industrial development, and rising population may increase arsenic risks in the future. Therefore, regular monitoring is crucial, especially in areas not checked often.

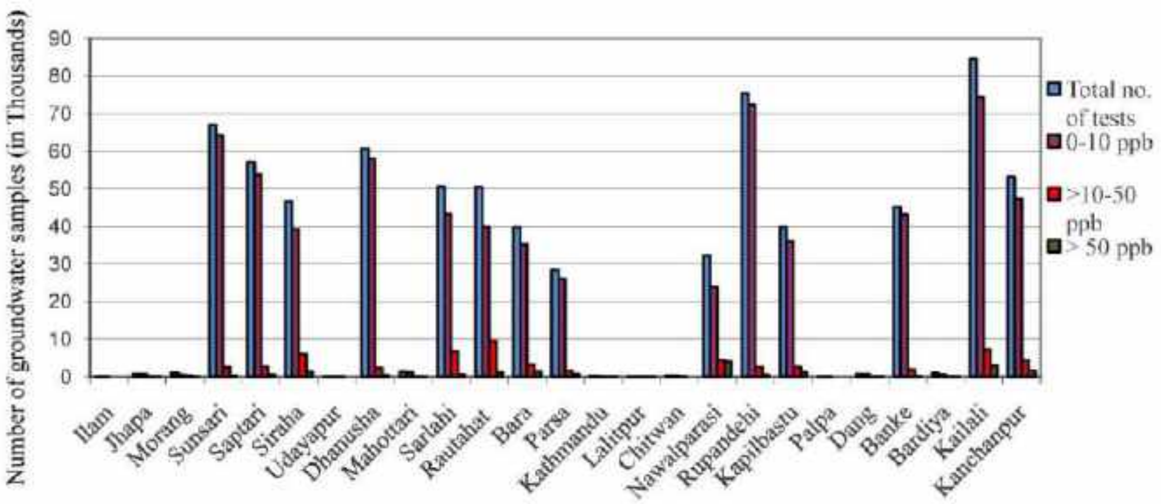

Figure 3: Arsenic (total) concentration in the samples of groundwater of different districts in Nepal *(Thakur, Thakur, Ramanathan, Kumar , & Kumar , 2011).*

8.1 INDIVIDUAL RESEARCH COMMUNITY WISE TESTED SAMPLE NUMBER

The summary of the individual research community wise tested sample is shown in Table 1. The outcome from the research shows that the sample with arsenic concentrations in the range 10-50 µg/L or greater than 50 µg/L require more attention for their management.

Table 1: Statistical summary of relative total groundwater arsenic contamination samples subdivided per institution or group *(Thakur, Thakur, Ramanathan, Kumar , & Kumar , 2011)*.

Research Organization/ Individuals	**Total no. of tests**	**Samples with Arsenic Concentrations**		
		0–10 µg/L	**>10–50 µg/L**	**>50 µg/L**
DWSS/UNICEF/WHO	670,117	91%	7%	2%
Nepal Red Cross Society (NRCS)	42,719	79%	16%	5%
Rural Water Supply and Sanitation Support Programme (RWSSSP)/Finnish International Development Agency (FINNIDA)	3,686	86%	8%	5%
Nepal Water Supply Corporation (NWSC)	30	53%	47%	0%
Nepal Water for Health (NEWAH)	5,328	83%	14%	2%
PLAN International	6,307	59%	39%	1%
Tandukar, N.	99	60%	32%	8%
Birgunj municipality, Nepal	6,670	97%	1%	1%
Rural Water Supply and Sanitation Fund Development Board (RWSSFDB)	1,021	87%	12%	1%
Department of Irrigation, MoI, Nepal	590	83%	7%	9%
Royal Institute of Technology (KTH)	53	42%	23%	36%

Japan International Cooperation Agency (JICA)/Environment and Public Health Organization (ENPHO)	389	69%	26%	5%
Total Samples	**737,009**	**82.63%**	**7.59%**	**2.64%**

8.2 DISTRICT WISE EXPECTED POPULATION DRINKING ARSENIC CONTAMINATED WATER

The detail study of expected number of populations drinking arsenic contaminated water of 10–50 µg/L and >50 µg/L in 25 districts in Nepal is as shown in Table 2.

Table 2. District wise expected number of populations drinking arsenic contaminated water containing 10–50 µg/L As and >50 µg/L As *(Thakur, Thakur, Ramanathan, Kumar , & Kumar , 2011)*.

S. N	District	Population in 2001	Expected population in 2011	Expected population in 2011 drinking water containing 10–50 µg/L As	Expected population in 2011 drinking water containing >50 µg/L As
1	Ilam	282,806	349,140	0	0
2	Jhapa	633,042	78,1527	61,832	1,014
3	Morang	843,220	1,041,003	448,500	21,985
4	Sunsari	625,633	772,380	33,792	4,790
5	Saptari	570,282	704,046	39,719	7,288
6	Siraha	569,880	703,549	112,130	19,903
7	Udayapur	287,689	355,169	6,124	0
8	Dhanusha	671,364	828,837	37,594	6,163
9	Mahottari	553,481	683,304	64,463	6,704
10	Sarlahi	635,701	784,809	113,874	9,156
11	Rautahat	559,135	690,284	144,040	15,663
12	Bara	559,135	690,284	80,297	25,766
13	Parsa	497,219	613,845	50,815	16,370
14	Kathmandu	1,081,845	1,335,600	511,916	65,433
15	Lalitpur	225,461	278,345	22,722	5,681
16	Chitwan	472,048	582,770	1,418	0
17	Nawalparasi	562,870	694,895	180,631	85,344
18	Rupandehi	708,419	874,584	35,728	5,951
19	Kapilbastu	481,976	595,027	57,468	17,784
20	Palpa	268,558	331,550	0	0
21	Dang	462,380	570,835	25,353	2,305
22	Banke	382,649	472,402	22036	2,802
23	Bardiya	382,649	472,402	97,489	14484
24	Kailali	616,697	761,348	90,802	26,026
25	Kanchanpur	377,899	466,538	51,781	13,986
	Total	**13,312,038**	**16,434,472**	**2,290,524**	**374,596**

8.3 TOXIC EFFECT AND HEALTH HAZARDS OF ARSENIC POISONING

A health survey in arsenic-affected households of Bara, Parsa, and Nawalparasi districts found that out of 5,215 individuals exposed to groundwater arsenic above 50 µg/L, about 1.3–5.1% suffered from dermatosis, mainly melanosis and keratosis, while suspected cases were also reported in Tilakpur and Thulokunuwar villages. Another survey across Rautahat, Bara, Parsa, Nawalparasi, Rupendehi, and Kapilvastu examined 19,304 people and identified 553 arsenicosis patients, showing higher prevalence in males (3.96%) than females (1.79%) as shown in Fig 4. Groundwater analysis revealed extremely high arsenic levels up to 1,200 µg/L in Nawalparasi and 2,620 µg/L in Rupendehi, far above safe limits. Biological testing showed that 95% of hair samples exceeded normal arsenic levels and 62% crossed acute toxicity thresholds. Detailed studies in Goini and Thulo Kunwar villages reported arsenic ranges of 104–1,702 µg/L and 4–972 µg/L respectively. Arsenic has also entered the food chain through crops such as onion leaves (0.55 mg/kg), cauliflower (0.33 mg/kg), and rice (0.18 mg/kg), adding dietary exposure. Clinically, 95.6% of patients showed melanosis, 57.8% keratosis, and 3.3% leucomelanosis, while severe conditions like bronchitis, gastroenteritis, neuropathy, gangrene, precancerous lesions, and cancers were also recorded. Therefore, comprehensive studies are urgently needed across the Terai districts to fully understand the scale and health impacts of arsenic exposure.

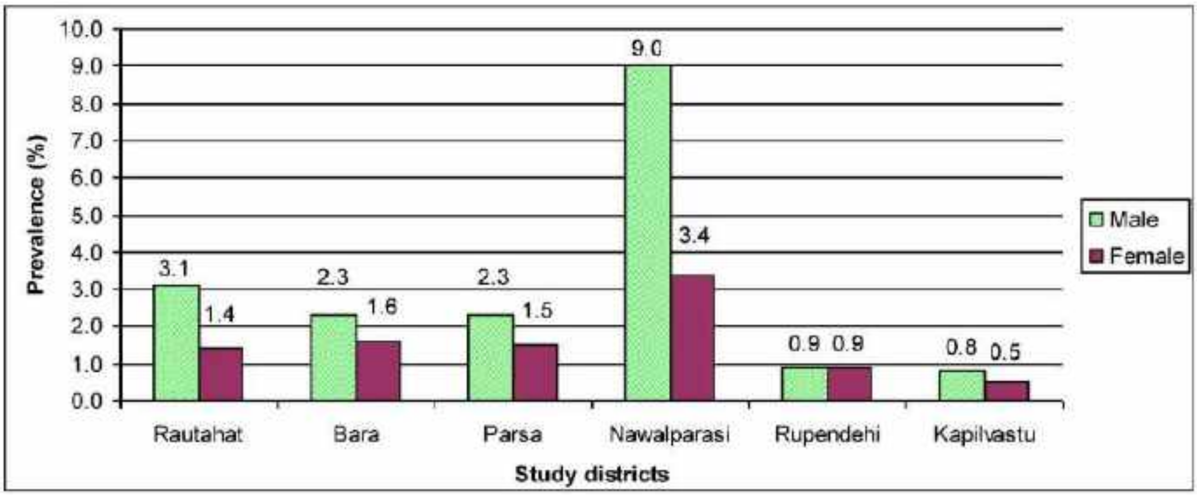

Figure 4: Prevalence of arsenicosis by sex (Maharjan, Shrestha, Ahmad, Watanabe, & Ohtsuka, 2006)

8.4 SOCIO-ECONOMICS STATUS OF ARSENICOSIS SYMPTOMS PATIENTS

Arsenicosis has become a serious challenge for affected communities, where factors like poverty, illiteracy, and farming occupation make people more vulnerable to the disease. Studies show that poorer, less educated, and agricultural workers are at higher risk, often facing both economic and social difficulties. For example, a case study in Santpur VDC, Rautahat district found an overall 15.3% prevalence of arsenicosis among risk households, with 84.21% showing melanosis and 15.79% keratosis. The disease was more common in males (22.8%), illiterate people (29.09%), the poor (17.5%), and especially farmers (51.72%) (Adhikari, 2005).Nearly half of the patients faced problems getting treatment, with women more affected due to long waiting times, lack of separate facilities, and discrimination. Financial hardship further worsened access, as many patients had to travel long distances, buy medicines themselves, or deal with shortages in hospitals. In short, arsenicosis not only threatens health but also deepens social and economic struggles for poor and marginalized groups.

9. MITIGATION APPROACHES

To reduce the risks of arsenic contamination, the National Sanitation Steering Committee (NSSC) along with DWSS, NGOs, research institutions, and international organizations have worked on identifying safe water sources, promoting arsenic removal technologies, improving health care, and raising awareness through communication campaigns. These efforts are divided into short-term and long-term approaches.

In the short term, household-level technologies were promoted, starting with the Three-Gagri Filter, which could remove up to 99% of arsenic but was soon abandoned due to problems like clogging and excess iron in treated water. It was replaced by the Arsenic Biosand Filter (ABF), later improved as the Kanchan Arsenic Filter (KAF). This filter uses layers of sand, gravel, and iron nails to trap arsenic, while also removing pathogens and suspended matter. Affordable and easy to use, costing only about NRs. 1,400–1,800 (US$20), each filter can treat 10–15 liters per hour with 87–100% efficiency, making it one of the most practical short-term solutions for rural households.

For long-term solutions, more sustainable water sources have been explored. These include deep tube wells that access safer aquifers, rainwater harvesting systems already serving around 47,000 people, and the use of deep boreholes originally built for irrigation. Other approaches include the rehabilitation of dug wells, tapping into safe springs and surface sources in hilly areas, and identifying arsenic-safe private wells through mapping and monitoring. While these methods may require higher initial investment, they are more reliable and sustainable for the future, ensuring safer water supply and reducing dependency on contaminated shallow aquifers.

10. CONCLUSION

Arsenic contamination in Nepal's groundwater, especially in the Terai region, has emerged as a major public health crisis. Blanket testing of over 737,000 samples across 25 districts showed that while nearly 90% were safe, about 7.9% contained 10–50 µg/L and 2.3% exceeded 50 µg/L, far above the WHO guideline of 10 µg/L. Chronic exposure has already led to widespread health impacts, with patients suffering from melanosis, keratosis, leucomelanosis, neuropathy, and cancers, while the poor, illiterate, and farming communities remain most vulnerable due to their dependence on shallow wells and limited access to healthcare. Short-term mitigation efforts such as the Kanchan Arsenic Filter (ABF/KAF) have proven affordable and effective, removing up to 100% arsenic at the household level, whereas long-term solutions like deep tube wells, rainwater harvesting, rehabilitation of dug wells, and identification of safe aquifers are vital for sustainable safe water supply. To control this crisis, Nepal urgently needs a national strategy that ensures regular monitoring, awareness campaigns, safe water access, and improved healthcare facilities, supported by strong collaboration between government, NGOs, and local communities.

11. ACKNOWLEDGEMENT

I sincerely thank the Department of Geology, Tri-Chandra Multiple Campus, for providing a valuable platform that helps students grow in the field of research. I am also grateful to the reviewer and my friends for their direct and indirect support during the preparation of this article.

ISSN: 3021-937X (Print)

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ISSN: 3021-937X (Print)

MELAMCHI FLOOD

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ABSTRACT

The Melamchi flood of June 2021 was a devastating natural disaster in Nepal, causing significant loss of life, property, and infrastructure. According to the findings, communities situated upstream in Helambu faced greater vulnerability from unexpected landslides and river damming, while those downstream gained advantages from advance warning communication. The flood inflicted extensive damage on infrastructure, including the Melamchi Drinking Water Project intake system, roads, bridges, and houses, resulting in considerable economic and social losses. This article emphasizes that enhancing early warning systems, monitoring rivers, and preparing communities is crucial for minimizing future risks. This article provides a concise overview of the flood event, its causes, impacts, and the response measures taken. The study aims to understand the disaster and suggest improved preparedness strategies.

Keywords: *Disaster, Vulnerability, Early warning, Risks*

1. BACKGROUND

The Melamchi flood happened in June 2021 and caused great damage in the Sindhupalchok district of Nepal. It showed how weak and risky mountain areas in the Himalayas can be. The Melamchi River starts high up in the Jugal Himal mountains. It flows through steep, fragile land with glaciers, narrow valleys, and unstable slopes. Because of this, the area often faces natural dangers like landslides and sudden floods, especially during the rainy monsoon season. In 2021, the monsoon brought very heavy and long-lasting rain. Some places got more than 100 millimeters of rain in one day. At the same time, warmer weather caused snow and glaciers to melt faster in the upper part of the river. This added even more water to the river. These weather conditions made the flooding more likely.

But the main cause of the flood was a huge landslide near a village called Melamchigaon. The landslide dropped a huge number of rocks and soil into the river, blocking it and making a natural dam. After some time, the water built up behind this dam and finally broke through suddenly. This released a fast and powerful flood of water, mud, and debris down the river. The land in this area is not very stable. The 2015 earthquake had already weakened the slopes and soil, making landslides more likely when it rained heavily. People's activities, like cutting down trees, changing the way land is used, and building roads and houses, also made the land less stable and increased the risk of flooding. The flood destroyed many bridges, roads, and important parts of the Melamchi Water Supply Project, which brings drinking water to Kathmandu.

2. OBJECTIVE

The major objectives of the study are:

- To analyze the causes and impacts of the Melamchi flood.
- To assess the response and relief efforts.
- To recommend future mitigation strategies.

3. METHODOLOGY

The methodologies used for the study are:

- The study used qualitative methods, including:
- Review of news reports, government and NGO documents.
- Satellite imagery analysis of the affected region.
- Interviews and testimonies from locals and officials.

4. ASPECTS OF THE MELAMCHI DISASTER

4.1 TRIGGERS OF THE MELAMCHI DISASTER

Melamchi disaster was triggered by multiple factors which occurred in various locations along the Melamchi River. The Melamchi flood was triggered by heavy rainfall, landslides and sudden debris flow (mud, sand, rocks, trees) in the river. Some major factors were weather conditions, high-altitude glacial environments, the formation of a new landslide at Melamchigaon, river damming, outburst floods, riverbank erosion and debris deposition.

4.2 WEATHER CONDITION

Both the Melamchi and Indrawati basins started receiving rainfall from 9 June, as recorded by the Department of Hydrology and Meteorology (DHM) in Sermathang, at an elevation of 2625 meters above sea level. According to the DHM report on pre-monsoon rainfall monitoring, the daily accumulated rainfall from March to May was 129% above normal, which shows that the watershed had experienced significant precedent precipitation.

4.3 LANDSLIDE

Prolonged and heavy rainfall in the Helambu and Melamchi-triggered region caused multiple landslides in the fragile Himalayan slopes. Because of this soil, rocks and trees slipped down as landslides which entered the Melamchi river.

Figure 1: About 100m from upstream from Gyalthum Bazar, an ancient active landslide was seen with sediment deposition

4.4 RIVER DAMMING

Landslides fell directly into the river channel in several locations, causing temporary blockages of the rivers, which acted as natural dams behind which large amounts of water and debris accumulated. Such river damming is naturally unstable because the debris is loose and cannot resist the increasing water pressure. When these natural dams ruptured. Suddenly, they emitted flash floods and debris flows with massive energy.

4.5 RIVERBANK EROSION AND DEBRIS DEPOSITION

The Melamchi watershed begins with the Jugal Himal glaciers and flows through a steep, narrow and rocky V-shaped valley. Numerous alluvial terraces and deposits from both recent and ancient landslides can be found in the river valley. After Bremthang and a few kilometres (km) below the fresh landslides at Melamchigaon, the rivers exhibit young features, with considerable force eroding their beds and banks. The fast-flowing water, heavily laden with debris from glaciers, fans, talus and lake deposits eroded the channel and riverbanks, resulting in numerous collapses and landslides. Sediment deposition begins a few km below Nakotegaun, as the river widens and becomes less steep. Large amounts of sediment are deposited downstream as the slopes decline.

Upstream of the Melamchi Bazaar, the river valley's sediment fills are larger. Additionally, a greater percentage of coarse and larger boulders are deposited above the Chanaute Bazar, Gyalthum Bazar, and Melamchi Bazar, while finer sediments, including sand and silt, as well as gravel and pebble-sized sediments, are deposited more downstream, in a region that is more unstable.

4.6 RISK ASPECT

The floods had a negative effect on extensive regions, impacting human settlements, farmland, river-based livelihoods and essential infrastructure like roads, bridges, hydropower plants and electric poles. This extraordinary flood event brought large amounts of debris from upstream, which were subsequently left in downstream locations, reaching as far as Dolalghat, located about 54 km from Melamchigaon.

Figure 2: About 500m upstream from Chanute Bazar on the left bank of Melamchi Khola, sediment was deposited (debris)

According to the initial report of the National Disaster Risk Reduction and Management Authority (NDRRMA), 5 people have been confirmed dead, 20 people reported missing and 6 injured during the floods. The persistent floods over 3-4 days resulted in 337 fully damaged

ISSN: 3021-937X (Print)

houses while displacing 525 families, as per the initial NDRRMA reports. The floods damaged many public infrastructures, including 13 suspension bridges, 7 motorable bridges and numerous road stretches in a number of locations above the Melamchi bazaar.

a

b

Figure 3: a. Melamchi river flow at the middle of Chanaute Bazaar

b. About 200 m upstream from Chanaute Bazaar, sediment was deposited on the left bank of Melamchi river

Among the public investments completely obliterated by the floods in the Melamchi bazaar were the bus terminal, suspension bridge, bridge, green city park and waste processing center. In fact, some wards in both Melamchi and Helambu municipalities are physically isolated from the outside due to the destruction of bridges and roads. Other areas are effectively cut off due to disrupted telecommunication, including internet and power outages.

Figure 4: Sediment deposited on the both bank of the Melamchi Khola (Melamchi Bazar)

The Melamchi water supply project was severely disrupted by the Melamchi flood, which particularly damaged headworks, temporary infrastructure, access roads, and buried intake areas in debris. The main tunnel is said to have remained structurally intact, primarily because its gate was closed, preventing it from coming into direct contact with flood waters and debris.

4.7 VULNERABILITY

Observation with both upstream and downstream communities revealed that prior to the significant floods on the evening of June 15, residents from the Helambu area reached out to downstream communities, including those in Melamchigaon. Furthermore, communities situated near the river experienced a greater risk compared to others due to their close vicinity to the disaster zone. These communications have suffered the loss of various sources of income, including small businesses, and have lost their sole homes and farmlands and are now confronted with the challenging task of meeting their essential needs for food, shelter and clothing in the future.

Figure 5: Water supply intake gate was disrupted by the Melamchi Flood

Those communities who are involved in fishing are particularly vulnerable due to their reliance on the river for their livelihoods. Floods destroyed extensive areas of productive khet land that were ideal for rice cultivation.

Lastly, some schools were damaged by the Melamchi flood, and children find themselves in a precarious situation regarding their education, as school buildings are in poor condition, which is likely to disrupt their learning in the near future.

5. LESSONS LEARNED

The following lessons were learned by the disaster:

- **Need for Multi-Hazard Risk Management**: The Melamchi flood was not just about rain but its combination with landslides, river blockage, and sediment loading. Risk assessments must include cascading hazards (e.g., landslide + flood).
- **Early Warning and Community Involvement**: Local communities upstream noticing signs (river blockages, unusual sediment, etc.) helped reduce losses. Formalizing early warning systems with community participation is essential.
- **Resilient Infrastructure**: Structures like headworks, bridges, and road networks that are in flood-prone zones need designs that withstand debris flow, sediment load, and dynamic river behaviour. Temporary camps, equipment storage, etc., must be placed with the risk of flooding in mind.

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6. RESULTS

The Melamchi flood of 2021 caused huge damage in many areas. More than 20 people died, including some foreigners, and several people went missing. This was reported by news sources like Khabarhub, Wikipedia, and Kathmandu Post. Many houses were destroyed or badly damaged, and many families lost their homes and had to leave the area (NIMJN, ICIMOD, Khabarhub). The flood also damaged a lot of farmlands. Large areas of fertile land (called 'khet' land) were covered by mud and sand or turned into riverbanks. This caused a huge loss to farmers, as thousands of ropani of land became useless (Nepal News, ICIMOD, NIMJN).

The flood also destroyed important infrastructure like bridges, roads, public buildings, and the Melamchi Water Supply Project. The water project's headworks (main structure) were buried in mud, making it hard to operate and send clean water (Khabarhub, Kathmandu Post, ICIMOD).

There was also a big economic loss. Fish farms (like trout farms) and local businesses were destroyed. One study said the total loss was around USD 436 million in Melamchi Municipality and USD 62 million in Helambu Rural Municipality (NepJol). The flood also affected the water supply to Kathmandu Valley. The water from the Melamchi Project became muddy and dirty, and the supply was stopped or delayed (Kathmandu Post, Nepal Press).

7. CONCLUSION

The Melamchi flood highlights Nepal's vulnerability to climate-induced disasters. A combination of extreme rainfall, loose geology, and lack of preparedness led to tragic outcomes. Better early warning systems, local capacity building, and sustainable land use planning are urgently needed.

8. ACKNOWLEDGEMENT

We thank the local communities of Melamchi, government agencies, NGOs, and media outlets who provided information and insights for this study.

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ISSN: 3021-937X (Print)

CLIMATE CHANGE AND GROUNDWATER SUSTAINABILITY IN THE HIMALAYAN TERAI INTERFACE OF NEPAL

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ABSTRACT

Climate change has emerged as one of the most pressing topics in South Asia and it grow faster than the global average 15°C (59°F) in Nepal. Our country Himalayan Terai Interface has weak mountain ecosystem and lowlands are heavily populated, where groundwater play critical role for drinking water, irrigation and economical purpose. Rising temperature brings uncertain rainfall, and glacial retreat which causes reducing groundwater recharge tends to projecting up to a 38% decline by 2050. Which gives a threat and alert on quantity and quality of groundwater resources. The impact of carelessness can cause water shortage, change in aquifer depletion and harmful elements present in water shift into disaster like droughts, arsenic contamination, floods and landslide. To solve these issues, government need to adopt right scientific hydro geological modeling, Hazard Assessment, and strong rights-based approach to water governance.

The article finds practical ways to improve groundwater sustainability and enhance vulnerability in the Himalayan-Terai area by merging grassroots leadership with scientific modeling. The results help Nepal and other vulnerable areas achieve Sustainable Development Goals (SDGs) 6 (Clean Water) and 13 (Climate Action). If Nepal adopts the right measures with commitment and discipline, within the next 30 years future generations will witness a model of climate change awareness and enjoy living in a healthier, disease-free environment with pride.

Keywords: *Climate change, Groundwater sustainability, Himalayan-Terai interface, Hydro geological modeling, Hazard assessment, Human right to water, Nepal*

1. BACKGROUND

In Nepal's Himalayan Teria interface, groundwater and climate change are crucial for sustainability and positive results for upcoming generations. Where groundwater works as lifeline for Nepalese people for water cycles, food systems, and human livehoods. Due to the weak hill slopes combine with dense plains, groundwater resources becoming insecure due to the rapid climate change and unorganized land use.

Groundwater supply and recharge are particularly vulnerable to the effects of climate change. Natural flow systems in the Terai aquifers have been disturbed by rising air temperatures and shifting monsoon patterns. Aquifer capacity has been reduced 2by a combination of decreased absorption, increased drought frequency, and declining river base flows. Experiments studies in Nepal project a continuous declining in groundwater levels and recharge rates under future warming scenarios, with water-stressed regions expected to face the greatest challenges (Shrestha, Pandey, & Babel).

The solution of groundwater and climate change should be conduct from the root level, where policy need to propose as effective and efficiently way so it help the millions of Nepalese.

ISSN: 3021-937X (Print)

Regular assessments, analysis, and improvement is need to overcome the problems. Technical support plays a vital role to fulfill the goal of success. Because of limited technical capacity and research gaps, solving the problem will be delayed. Climate change acts like a slow but destructive disease for nature, and while many countries are working to correct their past mistakes, the challenges continue to grow.

2. AIM

This article aims to see how climate change is affecting groundwater in Nepal's Himalayan Terai region. It also looks for simple ways to protect water and manage it better for the future.

3. OBJECTIVES

The major objectives of the study are:

- ❖ To find out how climate change is affecting groundwater in the Himalayan–Terai region of Nepal.
- ❖ To study the role of rainfall, temperature, and land use in groundwater changes.
- ❖ To see the problems people face due to less recharge and overuse of groundwater.
- ❖ To explore simple methods and local practices for protecting groundwater.
- ❖ To suggest better rules and plans for safe and fair water use in the future.

4. RESEARCH QUESTION

The study is signified by these research questions:

- ❖ How does climate change affect groundwater recharge and availability in the Himalayan Terai interface of Nepal?
- ❖ What role do rainfall, temperature, and land-use changes play in groundwater decline?
- ❖ What simple measures can help protect groundwater and make its use more sustainable?

5. MATERIAL AND METHODOLOGY

This article is based mainly on desk research. It collected information from secondary sources, including books, journal articles, reports, published papers, and online materials. The data was then carefully reviewed, analyzed, and arranged to build a clear and structured understanding of the topic.

6. RESULTS AND DISCUSSION

6.1 CAUSES

Groundwater stress, floods, and landslides in Nepal are all linked together. Rainfall has become irregular, with short heavy showers followed by long dry periods. This reduces the amount of water that can soak into the ground, while also raising the risk of floods. Rising temperatures make the problem worse by speeding up evaporation, drying springs, and putting pressure on underground water systems. Melting glaciers have reduced the steady flow of water into rivers and aquifers, creating long-term dangers. At the same time, unmanaged land use, rapid urban growth, and deforestation have disturbed natural recharge areas and increased surface runoff. In the Terai plains, heavy use of tube wells for farming and household needs is lowering groundwater levels and damaging aquifers. In the hilly regions, fragile slopes hit by intense rainfall often collapse, causing landslides that damage homes, roads, and rivers. On top of this, weak governance, poor monitoring, and limited technical knowledge mean that policies are not properly enforced and scientific research is not fully applied. As a result, communities remain more exposed to these hazards.

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6.2 EFFECT

6.2.1 MID-HILLS SPRING DECLINE

Communities and indigenous people from hilly are depends on river water that came from Himalayan. In the mid-hills of Nepal, springs are rapidly declining, with nearly 78% showing reduced discharge and about 20% having dried up completely, leading to water scarcity, reduced agricultural productivity, and migration in search of water. Local government leaders attribute this decline to irregular rainfall, infrastructure development, and forest changes, underscoring the urgent need for conservation efforts (Thapa, Bhattarai, Dahal, Tiwari, & Jacobsen).

Plate 1: Daily water collection in Nepal's mid-hills showing the impact of declining springs. Source: (https://kathmandupost.com/climate-environment/2019/11/29/once-gushing-with-water-nepal-s-springs-are-rapidly-drying-up)

6.2.2 KATHMANDU VALLEY RECHARGE REDUCTION

In Nepal, climate change is already affecting groundwater recharge and availability. In the Kathmandu Valley, modeling shows that recharge will decrease further in the future, with reductions expected under both RCP4.5 and RCP8.5 scenarios (Shrestha, Pandey, & Babel). This decline is linked to irregular rainfall, higher evaporation, and rapid urban growth, all of which reduce natural infiltration. Similar problems are seen in the mid-hills, where many natural springs are drying due to weaker pre-monsoon rainfall and rising temperatures (Thapa, Bhattarai, Dahal, Tiwari, & Jacobsen). People in both rural and urban areas are facing greater water stress due to these changes. Still, much of the available information comes from broad projections rather than detailed Nepal-specific studies, which estimate recharge losses of about 3–50 mm per year under RCP4.5 and 19–102 mm per year under RCP8.5.

Particularly in the Himalayan Terai interface, is highly sensitive to both climatic and human pressures. Climate change has altered rainfall intensity, seasonal recharge, and spring discharge patterns, directly affecting groundwater sustainability. (Shrestha, Shakya, Mishra, & Maharjan)

ISSN: 3021-937X (Print)

Emphasizes that in the Kathmandu Valley, declining recharge combined with over-extraction is leading to falling water tables, highlighting a broader national trend. Overall, the evidence from Nepal highlights a clear risk: if emissions remain high, groundwater recharge will continue to shrink, forcing communities to rely more on deep wells and creating new challenges for water security.

6.2.3 TERAI PLAINS DROUGHT AND DEPLETION

The Terai plains of Nepal, known as the nation's main food belt, are under increasing stress from drought and falling groundwater levels shown in image 2. The monsoon has become unpredictable, with sudden heavy rainfalls followed by long dry spells. This pattern makes it harder for water to soak into the ground and refill natural sources, while forests and natural recharge zones are being damaged at the same time.

Plate 2: Drought-induced soil desiccation and surface cracking in the Terai plains, Nepal. Source: https://kathmandupost.com/columns/2024/06/14/drought-land-and-livelihood)

At the same time, farmers and towns rely heavily on tube wells for crops and household use, causing rapid over-pumping. As a result, water tables are sinking, agriculture is at risk, and drinking water sources are becoming more uncertain. Without stronger laws, better planning, and active recharge measures, the Terai faces a serious water crisis (Mishra, Rauniyar, Jha, & Panthi).

6.2.4 RECENT INCIDENT IN NEPAL

6.2.4.1 2021 MELAMCHI FLOOD AND LANDSLIDE DISASTER

The 2021 Melamchi flood and landslide shows how heavy rain and unstable slopes can create big problems in Nepal's hills. When strong monsoon rain caused landslides, the debris blocked the Melamchi River and made a temporary dam. After the dam broke, a sudden flood rushed downstream carrying mud, rocks, and trees. This destroyed bridges, roads, and power lines, leaving people cut off from transport and electricity. About 260 houses were destroy and nearly 600 people had to cut off their shelter. Sadly, at least 18 Nepali peoples and three foreigners died, while others were hurt or went missing.

a b

Plate 3: Sediment deposition in the a. upstream part about 1 km upstream from Chanaute Bazaar and b. downstream part (Melamchi Bazaar) of the watershed). Source: (https://www.icimod.org/article/the-melamchi-flood-disaster/)

This disaster shows how people living in river valleys are at high risk. When rain, weak slopes, and settlements come together, the damage can be very serious. The Melamchi disaster highlights Nepal's urgent need for better early warning systems, stronger infrastructure, and effective water management laws to reduce risks during such events.

6.3 LESSONS FROM THE 2024 MONSOON

In September 2024, continuous heavy rain created a serious emergency in Nepal, affecting both

Plate 4: Urban flooding in Nepal following monsoon rainfall. Source:https://kathmandupost.com/national/2024/09/28/devastating-floods-and-landslides-claim-at-least-50-lives-across-country

the Terai plains and the nearby hill districts. In the Terai, rivers overflowed, flooding settlements, destroying farmlands, and forcing many families to leave their homes. Farmers lost crops close to harvest time, made them difficult. In the hill areas, the same rainfall loosened slopes, leading to multiple landslides that blocked highways, damaged houses, and cut off

ISSN: 3021-937X (Print)

communities from transport and supplies. Together, these hazards caused widespread damage, with more than 148 deaths reported and many others injured or missing. Thousands of people were displaced, and shortages of food, clean water, and medicines made recovery even more difficult.

7. PREVENTION AND CONTROL MEASURE

To reduce the risks of climate change on groundwater in Nepal's Himalayan–Terai interface, both technical measures and governance reforms are required. Climate change has lowered natural recharge while groundwater demand continues to rise. Article from the Jhiku Khola Watershed shows that hydrogeological studies and GIS mapping can help identify recharge zones and guide sustainable use, which is also useful for the Terai region (Timalsina, Upadhyaya, Gajurel, Shakya, & Pandey, 2024).

Modern tools such as monitoring wells, pumping tests, remote sensing, and GIS should be applied to track recharge, water quality, and extraction levels. These technologies can give early warnings of falling water tables and support recharge projects like ponds, pits, and managed aquifers. Skilled manpower is equally important. Nepal needs more trained hydrogeologists, engineers, and local technicians to operate equipment, analyze data, and support communities. Strengthening technical capacity at municipal and provincial levels will make groundwater management more effective.

Legal reforms must also regulate groundwater pumping, safeguard recharge areas, and control pollution. Linking policies with climate adaptation will improve their effectiveness. Finally, rights-based water governance should involve communities in decision-making and ensure coordinated efforts across all levels of government.

8. CONCLUSION

Climate change is putting serious pressure on groundwater in Nepal's Himalayan–Terai interface. Irregular rainfall, rising temperatures, and rapid land-use change are reducing recharge while demand continues to grow, creating risks of scarcity and hazards. Evidence from the mid-hills, Kathmandu Valley, and Terai shows that springs are drying, water tables are falling, and communities are facing both droughts and floods. Events such as the 2021 Melamchi flood and the 2024 Terai floods further demonstrate how groundwater challenges are linked with landslides and river overflows.

To respond, Nepal must strengthen technical capacity, enforce groundwater laws, and adopt rights-based water governance that involves local communities. Modern monitoring tools, skilled manpower, and community engagement are essential for managing recharge and preventing over-extraction. With timely reforms and sustainable practices, Nepal can secure its groundwater resources, reduce climate risks, and make progress toward SDG 6 (Clean Water) and SDG 13 (Climate Action).

9. ACKNOWLEDGEMENT

I would like to express my sincere gratitude to the Department of Geology for organizing Geoworld magazine and giving me the opportunity to write on this important topic. I am also thankful to my friends and the editorial board for their invaluable guidance and support throughout the preparation of this article. Special thanks go to all readers, whose interest and engagement inspire and motivate this work.

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ISSN: 3021-937X (Print)

DEVELOPMENT AND CHALLENGES OF THE GAUTAM BUDDHA (SISNE KHOLA) SMALL HYDROPOWER PROJECT IN NEPAL: A CASE STUDY OF PRIVATE SECTOR HYDROPOWER

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ABSTRACT

The Gautam Buddha Hydropower Project, also known as the Sisne Khola Small Hydropower Project, is a 750-kW run-of-river scheme located in Palpa district. The intake is at Marek Gaun and the powerhouse at Bhote Gaun. With a net head of 504.28 m and an annual generation of 4.597 GWh, the project faced delays and cost overruns during the COVID-19 pandemic but remains a key example of private investment contributing to Nepal's clean energy goals.

Keywords: *Hydropower, Powerhouse, Pandemic, Goals*

1. BACKGROUND

Nepal is a country with immense hydropower potential due to its steep rivers and abundant water resources. Despite having a total potential of over 80,000 MW, only a small fraction has been developed so far, making hydropower a crucial sector for meeting the growing energy demand. The private sector has played an increasingly significant role in harnessing this potential, investing in small- and medium-sized projects to support the national grid and reduce dependency on imported energy. However, the sector faces challenges such as regulatory delays, financial constraints, and market uncertainties.

2. LITERATURE REVIEW AND THEORETICAL FRAMEWORK

Nepal has been heavily studied on the development of its hydropower sector, especially in the form of privately funded investments, but there are still major research gaps on how it is resilient to systemic shocks. The potential of the sector has been determined in the previous research (Shrestha & Sharma, 2025), and the overall policy environment has been described (Sharma et al., 2025). The importance of the Private Power Producers Association, Nepal (IPPAN) in lobbying policies that are friendly to investors is emphasized by research by Basnet S. (2025), and the studies on financial models tend to concentrate on large-scale public-private partnerships (PPP) instead of small-to-middle enterprises (SMEs) such as the Sisne Khola project (Adjikary & Aryal, 2025).

The regulatory maze that incorporates the Electricity Act, 2049 and the Hydropower Development Policy, 2058 has been discussed as having good intentions but has been criticized as a slow mover (Shrestha & Sharma (n.d.)). Nevertheless, there is a fundamental missing linkage in the application of solid theoretical prism to such issues. This paper uses Institutional Theory (North, 1990) to examine how formal (laws, policies) and informal institutions (bureaucratic culture, risk aversion in banks) generate transaction costs and uncertainties to the private developers. Moreover, we apply a Stakeholder Analysis framework to assess the conflicting interests and power relations among developers, Nepal Electricity Authority (NEA), Nepal Rastra Bank (NRB) and local communities, especially in the case of a crisis such as the COVID-19 pandemic Nepali Times (2020, July 15). This integrated methodology can enable a

ISSN: 3021-937X (Print)

more in-depth, systematic study of the limitations of the private sector, rather than just a list of issues.

3. METHODOLOGY

The research design in this study is a qualitative case study research design to provide a detailed contextual analysis of the Gautam Buddha (Sisne Khola) Hydropower Project. The main goal is to comprehend how exogenous shocks affect the development path of the project and to generalize the results on the institutional and financial problems of the private hydropower sector in Nepal.

Figure 1: Dam at Marek Gau

Figure 2: Sub Station

The data was collected in two stages. Primary data was collected by conducting a thorough site visit to the intake (Marek Gaun) and powerhouse (Bhote Gaun) sites, which allowed observing civil works and electro-mechanical installation directly. The secondary data was widely obtained through project documents (feasibility study, financial summaries, progress reports), official publications of NEA, annual reports and directives of NRB (especially on refinancing facilities) and national policies (Hydropower Development Policy 2058, NRB Unified Directives 2079).

Thematic analysis was used in data analysis. Project documents and interview transcripts were coded in a systematic manner to detect common themes and patterns regarding financial constraints, regulatory hurdles and external risks. The analysis of these themes was then made under the two theoretical perspectives of Institutional Theory and Stakeholder Analysis to provide the underlying reasons behind the identified challenges and interactions among various actors.

This is limited to one project, which can be analyzed in depth, but generalized to other similar small-scale private projects in Nepal. One of the main limitations was the impossibility to interview officials of NEA PPA division or representatives of the local community because of the access restrictions, which might have left out the valuable views on the market risk and social acceptance.

4. TECHNICAL OVERVIEW

The Gautam Buddha Hydropower Project, also known as the Sisne Khola Small Hydropower Project, is in the Palpa district of Lumbini Zone, Western Nepal. The intake is situated at Marek Gaun, while the powerhouse is located at Bhote Gaun under the former Dobhan VDC. The project is a run-of-river type hydropower scheme with an installed capacity of 750 kW, designed to generate 4.597 GWh of electricity annually. The project utilizes the Sisne Khola river, with a gross head of 515 meters and a net head of 504.28 meters.

The hydrology of the site shows a catchment area of 13 km² with a design discharge of 183 liters per second and a minimum dry season monthly flow of 60 liters per second. The project has been designed to withstand a 100-year flood discharge of 100 m³/s, ensuring safety and sustainability of operation.

The main civil structures include overflow-type headwork with a side intake and trash rack, a gravel trap measuring 7.5 m by 2 m by 2.1 m, and a settling basin of 30 m by 2 m by 2.1 m. The penstock is made of mild steel and runs approximately 3,070 meters from the intake to the powerhouse. The surface-type powerhouse has dimensions of 7.5 m by 7.5 m with an additional section of 4.5 m, and the tailrace is a rectangular stone masonry structure of 5 meters length with a slope of 1:30.

The electro-mechanical components consist of a single Pelton turbine with a rated capacity of 770 kW and a speed of 1,500 RPM, coupled with a synchronous generator rated at 1,000 kVA, 400 V, and 50 Hz frequency with a 0.80 power factor. The turbine is controlled by an electro-hydraulic governor, capable of maintaining speed with 0.5% accuracy during drops of 0–10%. Power is stepped up using a 1,000 kVA transformer with a voltage ratio of 400 V/33 kV.

Together, these technical features ensure reliable generation and delivery of electricity to the national grid while demonstrating a well-planned small-scale hydropower project in Nepal.

5. ANALYSIS AND DISCUSSION

The Sisne Khola project is an example of a sector that is between its potentials and a fragile ecosystem where external shocks reveal the underlying institutional and financial weaknesses.

5.1 THE IMPLEMENTATION GAP IN HYDROPOWER POLICY

The policy framework in Nepal seems to be favorable on paper. The Hydropower Development Policy, 2058, is incentive-based and the Nepal Rastra Bank (NRB) has required banks to set aside 15 percent of their lending towards the energy sector (NRB Unified Directive, 2079). Nevertheless, the developer experienced serious delays in obtaining the Department of Electricity Development (DOED) license, the Ministry of Forests and Environment (regarding EIA) license, and local government licenses to purchase the land. This disjuncture between the official regulations and the way they are enforced, which is one of the main principles of the Institutional Theory, generates high transaction costs. This institutional rigidity was heightened during the pandemic. Nepal also did not have a well-organized response to the emergency, unlike India that issued force majeure notices to infrastructure projects, so developers such as Sisne Khola could not have expedited processes or relief, which directly led to project time and cost overruns.

5.2 FINANCIAL ARCHITECTURE: HIGH-COST DEBT AND ADVERSE LENDING

The financial model of the project is representative of a high risk, high-cost debt model typical of Nepal. Although NRB provides a 3% refinancing facility on projects of less than 10 MW, commercial banks continue to lend at an effective interest rate of 10-12% because they are perceived to be risky (Khanal, 2021). These changes caused by the pandemic created a vicious circle, as the lack of revenue caused the inability to service the debt, which, in turn, made the banks more conservative and unwilling to reorganize loans without strict collateral. This is the conflict between the stakeholders, i.e. the flexibility required by the developer and the fiduciary duty of the bank which brought the project almost to the halt. The directive issued by NRB that made it possible to capitalize interest was partially a relief, but that banks can exercise discretion in its implementation represents a fatal flaw in financial management during the crisis period.

The revenue model of the project will solely rely on Power purchase Agreement (PPA) with NEA, which is the only bulk purchaser. The pandemic resulted in a temporary decline in the national energy demand (NEA Annual Report, 2077/78), which made NEA postpone the signing of new PPAs. This was a move that was logical in the operational perspective of NEA, but it shifted the massive market risk to the private developers. The lack of a liquid energy market or any clear compensation provisions in PPAs in the event of a force majeure situation meant that the Sisne Khola project was left with vague revenue forecasts which further undermined the confidence of the bankers. This highlights a core market failure and the huge power disparity between state-owned monopoly and the individual developers.

ISSN: 3021-937X (Print)

5.3 GOVERNMENT INFLUENCE AND ROLE

The Nepal government is very instrumental in influencing the private hydropower industry either positively or negatively. On the negative side, there are delays in environmental clearances, water use permits and land acquisition approvals which tend to delay the implementation of a project. The COVID-19 pandemic aggravated the situation with lockdowns and the absence of emergency relief measures, and developers had few options to continue the progress. These inflexibilities underscore the difficulties that the private developers go through when trying to navigate through the complicated regulatory processes that may add to the cost and uncertainty among the investors.

On the good side, the government has developed several policy frameworks to assist in the development of hydropower. Tax breaks, waiver of duties, and the policy of public-private partnerships are the incentives offered by the Hydropower Development Policy, 2058, and other laws. Low-interest loans are provided to small-to-medium hydropower projects by special refinance facilities of Nepal Rastra Bank. These policies promote individual investment and assist in fortifying the national power supply.

The government can also be proactive in terms of approvals being faster, providing crisis relief in case of an emergency, and enhancing the coordination of various agencies. The viability of the private projects can be further improved by stronger institutional support, clear PPA regulations, and opportunities of cross-border electricity trade.

5.4 UPLIFTING THE PRIVATE SECTOR: POSSIBLE SOLUTIONS

The problems of hydropower projects in Nepal by the private sector like the Sisne Khola project indicate that the sector requires specific solutions to empower it. The solution of financial, regulatory, market and institutional challenges can establish a more favorable environment of private developers and enhance the general energy provision of the nation.

5.5 FINANCIAL SUPPORT

Provision of financial aid to the private developers is one of the most significant steps. Projects can be restructured by loan restructuring and capitalizing of interest to ensure that they do not suffer due to delays but can repay their loans over time without pressure. Banks are also able to provide reduced interest rates or loan periods, especially on small-to-medium hydropower projects. The perceived risk among commercial banks can be mitigated through government-sponsored guarantees, which will prompt the banks to finance on time. The Nepal Rastra Bank should increase its refinance facilities and make them more accessible so that the private developers have an unending supply of financial resources even in times of crisis.

5.6 POLICY REFORMS

Predictable and stable policies are essential in attracting and retaining private investment. Approval delays on environmental, land and water use permits can be greatly minimized by streamlining the process of approvals. Implementing single-window clearance would make the processes easier and timesaving to the developers. Defined rules of compensation in the event of termination or delay can also be used to reduce uncertainty and motivate banks to lend with less fear of making losses, through clear and uniform Power Purchase Agreements (PPAs). The sector would also be helped by strengthening the role of the Electricity Regulatory Commission (ERC) in the monitoring of fair tariffs and enforcement of contracts.

5.7 MARKET DEVELOPMENT

Hydropower projects can be more viable with the improvement of the market conditions. The market of Nepal hydropower can be increased through encouraging cross-border electricity trade with the neighboring countries and open new sources of revenue to the developers in the private sector. The creation of storage systems and small-scale grid balancing systems can assist in using the excess electricity productively and minimize the effect of seasonal variability in river flows.

5.8 INSTITUTIONAL STRENGTHENING

There should be improved coordination between government agencies, NEA and the private developers. A special support office to hydropower projects might help in regulatory compliance, technical advice, and communication with stakeholders. The capacity building of the local communities in terms of employment and maintenance of hydropower facilities will help to increase social acceptance and minimize the challenges of operation.

5.9 CRISIS PREPAREDNESS

Lastly, there is the need to have contingency plans in case of an emergency like pandemics, natural disasters or financial shock. This may encompass emergency funding arrangements, expedited approval procedures and reserve financing of essential infrastructure. The presence of such measures would ensure the safety of the private projects and continuity of electricity production in case of unforeseen circumstances.

6. CONCLUSION

The Sisne Khola (Gautam Buddha) Hydropower Project is an example of the opportunities and the obstacles of hydropower development in the Nepalese private sector. The project is technically well-designed, having a strong run-of-river system, effective turbines, and strong civil structures. Nevertheless, the COVID-19 pandemic, financial instability, regulatory delays, and market uncertainty were also external factors that had a strong impact on its progress. Such difficulties are not specific to this project and are representative of larger problems encountered by most of the private developers in the country.

The government policies, though providing incentives and support, in most cases fail to deliver in times of crisis and cause delays and extra expenses to the private developers. The financial risk is also contributed by banking regulations, interest rates and PPA uncertainties. To enhance the involvement of the private sector, a conducive environment should be offered by means of restructuring loans, consistent policies, simplified approvals, market growth and enhanced institutional coordination. Contingency planning and crisis preparedness are also essential to reduce unforeseen interruptions.

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ISSN: 3021-937X (Print)

A COMPARATIVE STUDY OF CAVES IN POKHARA VALLEY

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ABSTRACT

The Intermountain Pokhara Valley is the second largest valley within the Lesser Himalaya of Nepal, elongated NW-SE direction. Karst system determines the ground behaviors of the valley; extensive sinkholes, underground drainage, and limestone cave systems. Among these, Gupteshwor, Mahendra, Bat, and Birendra caves are particularly significant for their geomorphological, mineralogical, and ecological features. This study presents a comparative analysis of these caves, drawing on both field observations and a review of published literature.

Gupteshwor Cave, developed within the Pokhara Formation, is distinguished by an active underground stream and diverse speleothems, including helictites. Mahendra Cave, located in the Ghachowk Formation, exhibits well-developed stalactites, stalagmites, and flowstones (Regmi, 2013). Bat Cave, also within the Ghachowk Formation, is notable for its narrow passages, large bat colonies, and guano-altered mineral deposits. Birendra Cave, formed in the Ghachowk Formation, remains relatively undisturbed and hosts columns, stalagmites, and irregular texture. All four caves are developed primarily in limestone and composed mainly of calcite and quartz. Beyond their geological importance, these caves provide significant opportunities for geo-tourism. Their proper management can raise awareness of Nepal's unique karst heritage while also contributing to the local and national economy.

Keywords: *Debris flow, Karst geology, Mineral, Cave, Geo-tourism*

1. BACKGROUND

Pokhara Valley, located in west-central Nepal, Lesser Himalaya, rests on the ancient Kuncha Formation, one of the oldest rock units in the country. This basement is mainly composed of metamorphic rocks and is overlain by riverine and Quaternary sediments, creating a complex and diverse geological setting. Valley filled sediments formed probably due to major episodes of debris flow events that occurred along the 'Paleoseti River' originating from Annapurna regions. There are several researchers researching about origin and formation of Pokhara valley (Hagen, 1969, Gurung, 1970 and Yamanaka et al. 1982). Different researchers classified these valley field sediments from four formations to seven formations. The variety of rock types across the valley has strongly influenced its landscape development and geological characteristics.

Landforms developed in soluble rocks such as limestone, dolomite, and gypsum through dissolution by acidic water are Karst landscapes. Such landscapes are globally recognized for features like sinkholes, underground drainage, dolines, and caves (Ford & Williams, 2007). Caves, in particular, provide insights into hydrogeological processes, mineral deposition, and ecosystem interactions. Pokhara Valley is one of the most well-developed karst regions of the country. The valley is underlain by carbonate-rich rocks and Quaternary sediments, producing a remarkable variety of karst features (Sapkota, N., & Paudel, L.P. (2019)). Several caves in this valley are not only of geological significance but also hold ecological, cultural, and touristic value.

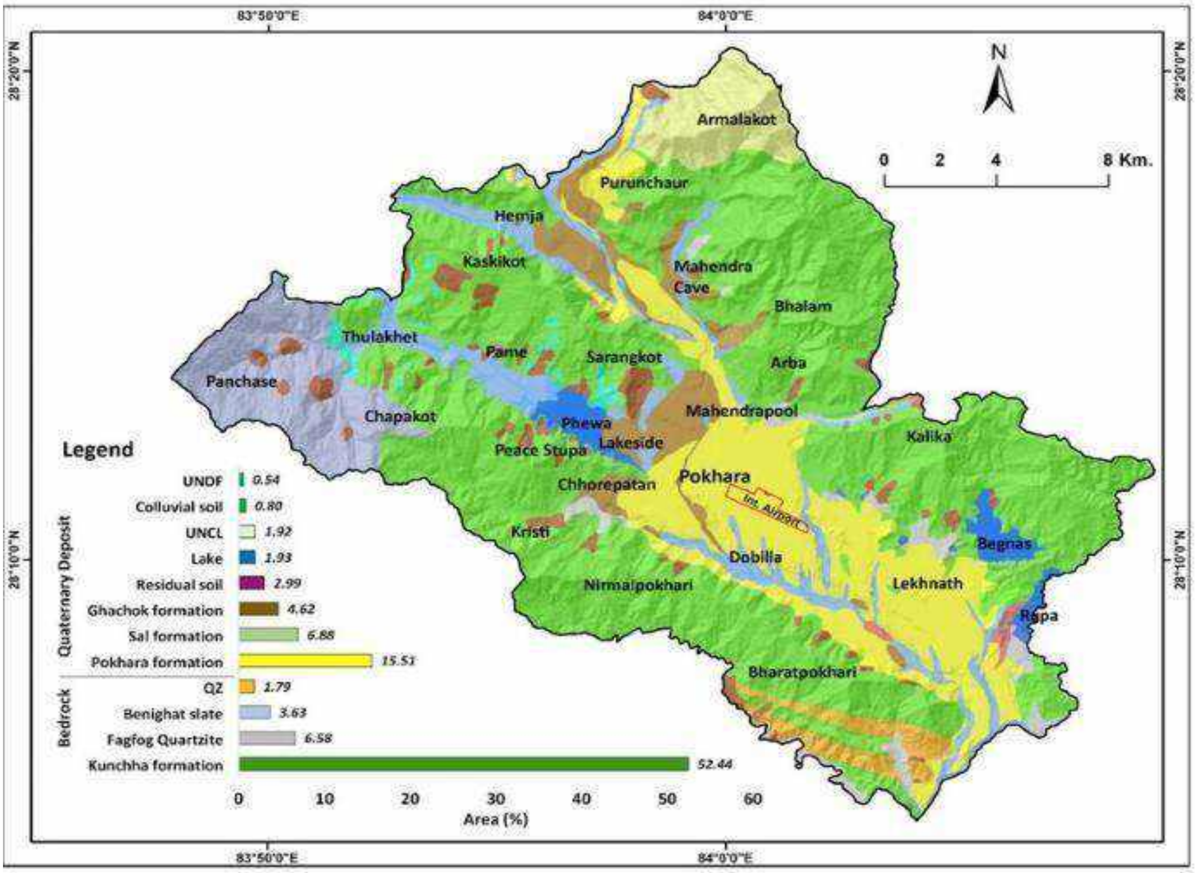

Figure 1: Geological and soil map of Pokhara Metropolitan city (DMG,1998)

The main carbonate rocks are found in Lesser Himalayan zone, local units such as Dhading Dolomite, Jhiku carbonate bed, Malekhu Limestone and Dhanpure Limestone equivalents. In Higher Himalaya, carbonate rock marble is found mainly in Formation-II and some section of formations III and I also (Upreti, B.N. (2001). Tibetan Tethys Himalayan rocks are mainly sedimentary sequence, carbonate rocks are found from Paleotethys to Neoththys sequence (Sherpa et al., 2024). Debris type of slides as well as rock fall and rock avalanches are the main problem in the valley which lies downhill side of slow cap mountains like Higher and Tibetan Tethys Himalaya. Within Lesser Himalaya, past big avalanches and debris flow filled the valley and tar of lesser Himalaya espically in the Midland group (Bhandari and Pokhrel, 2022) and similar type of debris flow and rock slides are main problem in Terai comes from Lesser Himalaya and Siwalik (Pokhrel et al. 2022).

2. AIM

The aim of this study is to understand the geological and geomorphological characteristics of different caves in Pokhara including and identifying their similarities and dissimilarities; in addition, Pokhara is a dream city for visitors, so geo-tourism of Pokhara valley is very important to know.

3. METHODOLOGY

This study is based primarily on field observations carried out in the Pokhara Valley, supported by relevant geological literature and reports from the Department of Mines and Geology

(DMG). Detailed notes were made on cave lithology, speleothems, mineral compositions, surface features, and the associated flora and fauna during site visits. Each cave was described individually, and a comparative summary was prepared in tabular form (Table 1). Photographs (Figure 2) are included to visually represent the karst features and cave environments.

4. RESULTS

4.1 GEOLOGICAL SETTING

The caves in Pokhara Valley are found within two major formations. Gupteshwor Cave lies in the Pokhara Formation, where cave passages have mainly developed inside carbonate-rich sediments. In this setting, layers of sand and silt are also present, and their leaching by groundwater has further supported the widening of voids, rather than the caves being restricted only to massive limestone beds. On the other hand, Mahendra cave, Chamero Gufa and Birendra Cave are developed in limestone beds interlayered with sandstone, siltstone, and mudstone of Ghachowk Formation. The removal of these finer sediments by groundwater, together with dissolution of carbonate, has strongly influenced their morphology.

Pokhara Valley is composed mainly of limestone and other carbonate-rich lithologies. Dissolution of these rocks by slightly acidic water has produced an extensive cave system along with sinkholes and underground streams.

4.2 CAVE DESCRIPTIONS

4.2.1 GUPTESHWOR CAVE

Gupteshwor Cave lies in the Pokhara Formation and is formed in calcareous conglomerates and sandy limestone. The conglomerate layers can hold and channel water, while the limestone gradually dissolves. Leaching of finer sediments has further shaped the cave, creating its underground stream and winding passages. The cave features a deep passage with an active stream. Well-developed stalactites, stalagmites, flowstones, and helictites decorate the interiors, with calcite and quartz as dominant minerals. Mosses grow in the moist, light-exposed zones near the entrance.

4.2.2 MAHENDRA CAVE

Mahendra Cave lies in the Ghachowk Formation, where thick limestone beds are interlayered with sandstone and siltstone. Dissolution of limestone, along with the removal of finer sediments, has widened voids and allowed seepage along bedding planes. Inside, the cave shows abundant stalactites and stalagmites, along with flowstone deposits. Surfaces vary from smooth to porous, and bat colonies are commonly found.

4.2.3 CHAMERO GUFA (BAT CAVE)

Chamero Gufa is also part of the Ghachowk Formation, developed in bedded limestone mixed with mudstone and siltstone. Narrow passages have formed along weaker layers, while leaching of finer materials has created irregular openings near the surface. The cave is narrow, dominated by large bat populations. Karst features are smaller with limited flowstones, and guano deposits have caused local variations in mineralogy. Lichens are seen near the entrances.

4.2.4 BIRENDRA CAVE

Birendra Cave is developed within the Ghachowk Formation limestone, which is interbedded with sandstone and siltstone. The dissolution of limestone, along with the removal of finer sediments, has formed relatively narrow yet stable passages, characterized by fewer fractures compared to nearby caves. Inside, the cave features stalactites, stalagmites, columns, and flowstones. The surfaces are rough and irregular, and the overall presence is lower compared to Chamero Gufa.

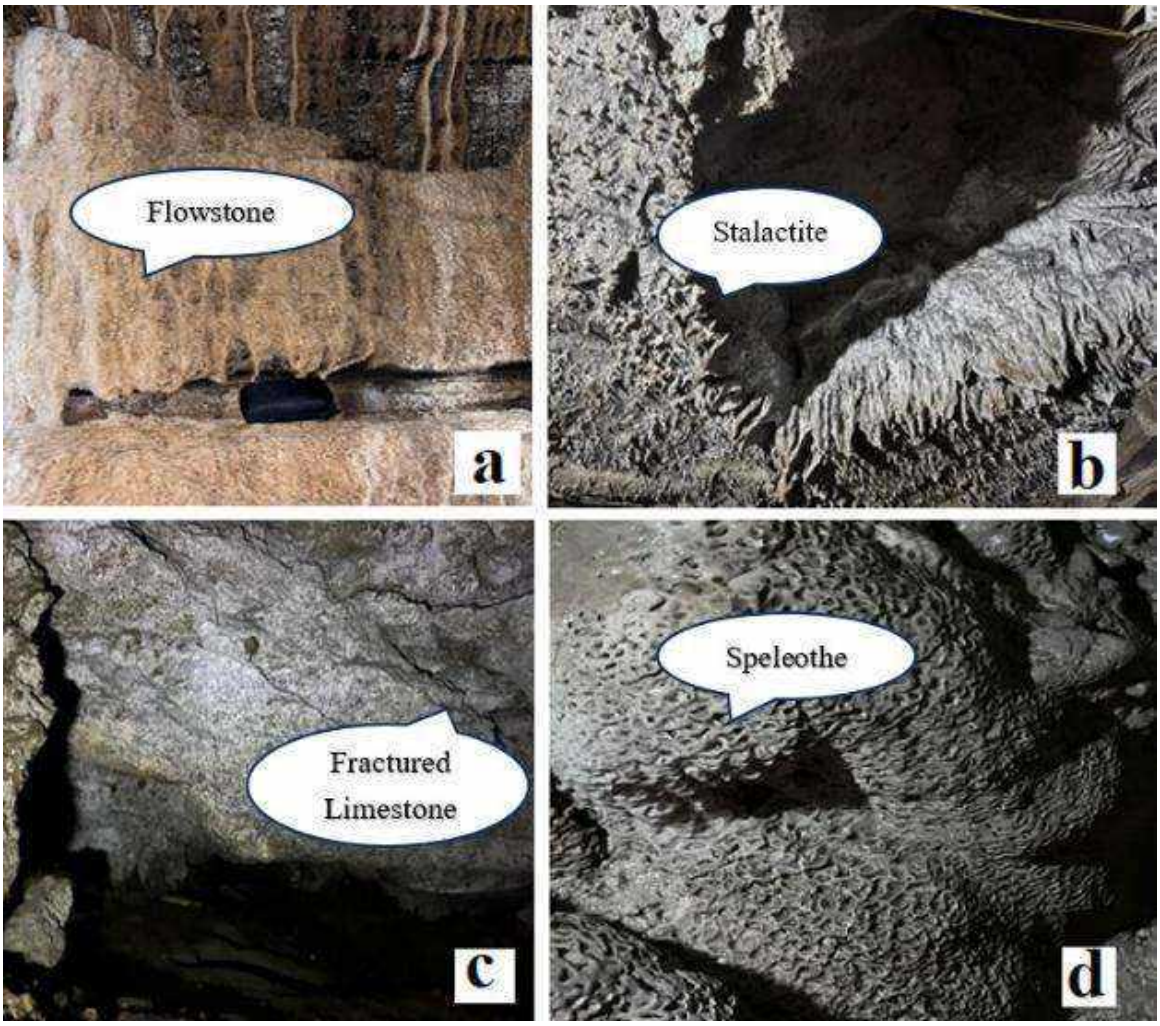

Figure 2: (a) Flowstone deposit in Gupteshwor Cave, b) Stalactite and stalagmite formation inside Mahendra Cave, c) Dissolution features and fractured limestone ceiling in Chamero Gufa, d) Speleothem texture inside Birendra Cave

5. DISCUSSION

All four caves in Pokhara Valley are developed within limestone formations but show distinct morphological and mineralogical traits. Gupteshwor Cave occurs in the Pokhara Formation, composed of calcareous conglomerates and sandy limestone, while Mahendra, Bat, and Birendra caves lie in the Ghachowk Formation, with limestone interbedded with sandstone and siltstone (DMG, 2024; Upreti, 2001). Comparable karst features have been reported in nearby regions such as Kusma, where carbonate rocks host diverse cave morphologies (Poudel et al., 2018: Sapkota and Poudel, 2019).

For example, Gupteshwor Cave contains a wide variety of speleothems including rare helictites, Mahendra Cave has extensive stalactites and is highly accessible to tourists, Bat Cave shows strong interaction between geological and biological processes, and Birendra Cave remains relatively undisturbed. These differences reflect the influence of local lithology and sediment interbeds on cave morphology and interior microclimates.

From a geo-tourism perspective, Gupteshwor and Mahendra caves attract more visitors, whereas Bat and Birendra caves are less modified. This highlights the need for sustainable conservation strategies that preserve both geological integrity and ecological value.

6. COMPARATIVE SUMMARY

Table 1: Comparative summary of geological, mineralogical, and ecological characteristics of major caves in Pokhara Valley.

Cave	Geological Formation	Dominant Rock	Karst Features	Mineral Content	Surface Texture	Ecological Notes
Gupteshwor	Pokhara Formation	Limestone	Stalactites, stalagmites, flowstones, helictites	Calcite, quartz	Smooth, porous, crystalline	Mosses in moist zones
Mahendra	Ghachowk Formation	Limestone	Stalactites, stalagmites, flowstones	Calcite, quartz	Smooth, porous, crystalline	Bats
Chamero (Bat)	Ghachowk Formation	Limestone	Smaller stalactites or stalagmites	Calcite, guano-altered deposits	Porous, crystalline	Large bat population, lichens
Birendra	Ghachowk Formation	Limestone	Stalactites, stalagmites, columns, flowstones	Calcite	Rough, irregular	Few bats

7. CONCLUSIONS

This study has following conclusions:

- The Pokhara Valley was shaped through episodic deposition of debris flows transported from the Annapurna region. These processes, repeated over time, gradually built up the valley floor and surrounding terrain. However, the valley remains highly dynamic and vulnerable to geological and hydrological changes.
- Climate change, particularly the rise in extreme rainfall events, poses significant threats to the valley. Over-precipitation can trigger floods, slope failures, and sediment deposition, further modify the valley's landscape and affect settlements, agriculture, and infrastructure.
- Another critical concern in the Pokhara Valley is the presence of sinkholes and land subsidence, which are directly related to karstic limestone formations in the region. Dissolution of carbonate rocks leads to the development of underground voids and cavities. When the overlying materials collapse into these voids, sinkholes and surface subsidence occur, creating hazards for local communities.

- The Pokhara Valley has strong geo-tourism potential due to its caves, sinkholes, and karst formations within the Pokhara and Ghachowk formations. Features like stalactites and stalagmites attract visitors, while scientific value adds to its significance.
- Based on these findings, detailed investigation of the subsurface geology is essential before planning or constructing any major infrastructure in the valley. Engineering solutions must be supported by scientific studies that identify zones of high risk. Furthermore, the government should prioritize investment in research focusing on sinkhole development, cave genesis, and karst-related hazards. Such proactive measures would contribute to sustainable development and risk reduction in the Pokhara Valley.

7. ACKNOWLEDGMENT

I would like to thank the Department of Geology, Tri-Chandra Multiple Campus and Editorial committee of Geo World Journal for this auspicious opportunity in my academic journey. Also, grateful to Prithvi Narayan Campus, Mr. Nawraj Sapkota, Geologist and, Mr. Chhabilal Pokhrel, Assistant Professor, my colleagues, seniors and to all the helping hands through this journey.

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GEOLOGY: UNDERSTANDING THE UNTOLD STORIES OF EARTH

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ABSTRACT
Imagine yourself standing on a great plain or rock mountain, gazing out over the country in front of you. Beneath your feet lies the tale to be written, penned over a span of billions of years and inscribed in the rocks and soil you are standing upon. That narrative is geology, the physical structure of the Earth, its history, and the forces that act upon it. For students who are eager to learn and occasionally need reminding where their feet are, geology has a valuable lesson: it teaches us that the earth beneath our feet has time, perseverance, and our connectivity with the world in store.

Keywords: *Geology, Structures, History*

1. A JOURNEY THROUGH TIME

Geology has been called the "science of time." Reading rocks, fossils, and landscapes, geologists unravel the tale of the Earth, from the initial fire to the present time. Have you ever stopped by the river and picked up a tiny rock and wondered where it came from? That small rock could have started life hundreds of millions of years ago as magma deep in the Earth, spewed out by a volcanic eruption, knocked about by wind and rain, and traveled along streams to reach your hand. Geologic time involves hundreds of millions of years, a period that is almost beyond human imagination. Yet, through studying layers of sedimentary rock, geologists have deciphered the history of the Earth, disclosing major events like mass extinctions, ice ages, and the assembling of continents. These layers of geology remind us in no uncertain terms that, while human history is of the greatest importance, it is but a moment in the long history of the Earth.

2. EARTH'S DYNAMIC PROCESSES

The planet can seem solid and motionless, yet it is full of movement. The tectonic plates, enormous sheets of the planet's crust, move inexorably, colliding to form mountains, cause earthquakes, and spout volcanoes. Rivers cut valleys, glaciers shape the landscape, and wind erodes the desert. Each minute crack in a rock and each dune wave bears witness to the vast forces at work.

These geological occurrences can serve as metaphors for our own existence. As the Earth's tectonic plates crash into each other to form mountains, pressure and stress we are exposed to can strengthen us and make us bulwarks. The active Earth teaches us to adapt and change according to whatever life brings before us.

3. A PRACTICAL AND PERSONAL CONNECTION

Geology is not merely a theoretical science, but it also has a concrete relationship with our day-to-day life. Minerals in the soil that you are standing on, the heat you use to warm your house, and the water you consume all get their roots from geological forces. Geologists play a critical role in learning how to obtain resources in a way that will last, minimizing the effect of nature's hazards, and mitigating climate change. For students, geology is a chance for them to learn

ISSN: 3021-937X (Print)

about the Earth in a more advanced level. A walk outside is an expedition. That odd rock or layered cliff becomes a cue to marvel and look closer.

4. GROUNDED AND INSPIRED

In this tech venture and era of social media, geology re-roots us on Earth. Geology keeps in mind that we belong to a larger narrative which pre-dated us by a long time and will continue when we are no longer present. Studying geology is a chance to look at the world differently and admire the elegance and sophistication of what lies beneath our feet. It makes us dig deeper, science and life. But above all, it reminds us that while our own lifetime is short, it is part of an epic story told by the Earth.

ISSN: 3021-937X (Print)

THE UNSEEN IMPACT OF MICRO-LANDSLIDES AND THEIR CUMULATIVE EFFECTS IN NEPAL

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ABSTRACT

Micro-landslides are small-scale slope failures that often go unnoticed, yet they collectively cause serious environmental and infrastructural problems in mountainous regions like Nepal. This paper discusses their characteristics, causes, and long-term impacts on rural livelihoods and ecosystems. Focusing on Sindhupalchowk district as an example, it highlights how repeated micro-failures can gradually lead to larger landslides. The 2021 Sindhupalchowk disaster, where 73 people lost their lives and over 120 houses were destroyed, demonstrates the cumulative effect of small slope instabilities. The paper also outlines mitigation strategies such as drainage management, bio-engineering, and community awareness programs. Overall, understanding and managing micro-landslides is essential to minimize future hazards and protect rural infrastructure in Nepal.

Keywords: *Micro-landslide, Infrastructural, Micro-failures, Slope instability*

1. INTRODUCTION

In Nepal micro-landslides are small slope failures usually less than a meter deep and since they are so small they hardly ever get reported. But if you look at their impact over the years it becomes clear how serious they really are. Each one by itself looks minor, however together they end up disturbing peoples' livelihoods, damaging roads, houses and other infrastructure and putting a long-lasting stress on the ecosystem.

Research done in recent years (NHESS, 2018; Springer, 2022; IJWRE, 2024) suggest that these frequent micro-landslides slowly weaken slopes, they deposit soil and debris into rivers and reservoirs, sometimes blocking water supply lines, and in the end create long term economic, social and environmental problems.

2. DEFINITION AND CHARACTERISTICS OF MICRO-LANDSLIDES

Micro-landslides are generally defined as small slope failures; they affect only the top few meters of soil or weathered rock. They are mostly triggered by heavy or continuous rainfall, road construction, poor surface drainage and also even micro seismic vibrations.

Usually, the process begins with slope compaction then small cracks appear, those cracks spread further and at the end the slope collapses. These kinds of slides are very common along rural road cuts, steep hillsides and cut slopes, with the most cases during the monsoon months in Nepal when rainfall is heavy and doesn't really stop.

3. HISTORICAL BACKGROUND AND FREQUENCY

Nepal has steep terrain and with heavy concentrated monsoon rainfall it creates the right condition for micro-landslides. These have been happening for centuries but in recent decades new factors have made them more frequent, things like the rapid expansion of rural roads, unplanned land use, poor surface water management, and the destabilization of slopes after the 2015 Gorkha earthquake (NHESS, 2018).

Bigger landslides always get more attention but micro-landslides are actually more common and since most of them don't get recorded, their overall effects are usually underestimated.

4. CUMULATIVE IMPACTS

When you look at them over a longer period of time, micro-landslides add up to cause serious problems. They bring soil into rivers, streams and reservoirs which lowers storage capacity and raises flood risk. Small repeated slope failures slowly weaken the ground, and this makes bigger landslides more likely in the future.

Figure 1: In the past year, 73 people have died due to floods and landslides in Sindhupalchowk destroying 127 houses. Source: The Kathmandu Post (2021)

Roads, bridges, embankments, drainage systems and rural transport lines are hit again and again which raises maintenance costs in the long run. The soil that gets deposited also blocks water supply lines, reduces water quality, affects irrigation and even hydropower projects.

Figure 2: Mudslides triggered by heavy downpours block Siddhartha Highway and Narayanghat- Mugling road section among others. Source: Setopati News (2021)

For local people these slides mean losing fertile land, broken irrigation channels, endless road repairs and sometimes even being forced to move, all of which bring not only economic but social and psychological stress too. Altogether these impacts weigh heavily on rural life, the economy and also the environment itself.

5. MITIGATION STRATEGIES

To control these problems some measures are used like soil retention methods, structural supports, drainage management, bio-engineering, better road construction and also awareness programs for communities. Retaining walls, breast walls, gabion boxes, check dams and similar structures are important to hold slopes and stop failures.

Drainage management is about diverting rainwater away from slopes and roads so water doesn't build up. In bio-engineering people plant trees with deep roots, grasses, vetiver, bamboo and other local plants that help stabilize soil. For road works gentler slope cuts, retaining walls and good drainage systems are effective.

Awareness raising is also important, so local trainings, workshops and campaigns through notice boards, radio or mobile messages should be done. Communities can have small monitoring teams for risky slopes and also do drills or role play to be ready for emergencies. On top of that, government policies and coordination with local authorities makes the risk reduction effort stronger.

6. CONCLUSION

Because of Nepal's terrain, climate and human activity, micro-landslides and other small-scale events have very big effects on infrastructure, environment, economy and people's daily lives. The long-term solution needs to include better drainage, safer road design, slope monitoring, plus community involvement to cut risks.

If we combine micro-landslide control, soil retention work and raising awareness in local people, then road safety will improve, infrastructure will last longer and the risks of natural hazards will go down in Nepal.

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ISSN: 3021-937X (Print)

A CASE STUDY ON THE IMPACTS OF IN-SITU PARAMETERS ON WATER QUALITY IN GROUNDWATER IN MADIPHAT, PALPA

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ABSTRACT

The assessment of groundwater quality was done by measuring the in-situ tests in four key parameters: PH, electrical conductivity (EC), dissolved oxygen (DO) and temperatures. The study was carried out randomly from eleven sampling shallow tubewells (G5H1-GH11) in Tinteaap, Kunsara, Beltari, Gorsat, Arkhale and Pokharathok of Madiphat villages, Palpa, Nepal. The measured value was compared against the WHO (1993), Nepal Drinking Water Quality Standards (NDWQS) (2005) and European Union (EU) (2005) guidelines respectively.

The results revealed the pH values ranging from 5.9 to 7.1 with only four samples showing the value in upper limits with alkaline conditions and the majority of sample showing the acidic tendencies according to the guidelines. The values of EC varied widely in dissolved ionic content from 1104 µs/cm to 2980 µs/cm. The moderately mineralized samples varied from 1104 µs/cm to 1350 µs/cm whereas the highly mineralized ionic content ranges from 2090 µs/cm to 2980 µs/cm exceeding NDWQS (<1500 µs/cm) guidelines. The DO level ranges from 4.5 mg/L to 7.87 mg/L with two of the sample have below the acceptable threshold 5mg/L. The temperature remained consistent 15.5°C to 16.5°C within the guideline limit <25°C. The overview of the results seems that the groundwater is largely suitable for drinking and irrigation purposes but spatial issues such as salinity, acidity, and low oxygen level in some of the samples may require proper water treatment, analysis, continuous monitoring and proper management strategies is suggested.

Keywords: *Groundwater quality, In-situ tests: pH, Electrical conductivity, Dissolved oxygen, Alkaline, Acidic, Threshold, Water treatment.*

1. INTRODUCTION

1.1 BACKGROUND

Madiphat is also known as the Madi valley which is one of the biggest agricultural flat terrains that lies in the watershed area of the Tinau Khola. The Tinau Khola fed as the major drainage pattern area with the tributaries such as Sukjhor (Khahare): lies in southern part of valley in Beltari, Khahare and Lalpati, Pande Khola, Maraha Khola, Mahjare and Naubise Khola: lies NE part of the valley, Chuhar and Tasing Khola: lies NW part of Gorsot areas and so on. It is an enclosed valley surrounded by the Mahabharat range. The spatial location of this valley lies between 27°48'N to 27°51'N and 83°33'E to 83°39'E. (Shrestha, 1983).

The valley is tectonically active valley. Groundwater is considered as the primary sources of drinking and irrigation purposes in rural areas, especially in Madiphat Palpa of Western Nepal. Although groundwater is used more and more for agriculture, industry, and drinking, overuse, climate change, and human activity are threatening its availability and quality (Abadi et al., 2024). In order to use groundwater effectively and save future generations from dealing with rising treatment costs or limited access, it is important that the quality of the resource is known and protected. Groundwater is susceptible to both natural and anthropogenic risks, and addressing them is essential to achieve the Sustainable Development Goals, even if adaptation is frequently difficult due to a lack of resources. (Lapworth et al., 2022). This article emphasizes the use of in-situ parameters for general study of the effects of parameters measured in the field immediately. Therefore, it is essential to understand the hydrogeochemical properties of groundwater in order to assess its quality and ascertain its suitability for a variety of uses. According to research, groundwater chemistry is significantly impacted by both natural and human factors (Ghimire et al., 2024). The article provides the assessment of water quality by the measurement of in-situ parameters and to find the impacts of the parameter in the health risk as well as major possible effects on agriculture and soil permeability respectively.

1.2 AIMS

The major aims of the study are as follows:

- To measure in-situ water quality parameters ramdomly (PH, EC, DO and temperature) in Tinteaap, Kunsara, Beltari, Gorsat, Arkhale and Pokharathok of Madiphat villages.
- To compare the measured values with WHO, NDWQS and EU water quality standards.
- To find out the impacts to groundwater and evluate its suitability for drinking and irrigation purposes.

1.3 OBJECTIVES

The objectives for this study include:

- To accesses the impacts of the in-situ water quality parameters (PH, EC, DO and Temperature) on groundwater in Madiphat's Village.
- To highlights the possibility of health and environmental risks associated with poor groundwater quality.
- To learn to handle in-situ parameters probe and to bring curiosity in water quality parameters that may prevail in the groundwater of the study area.
- To provide suggestions for sustainable groundwater uses through continuous monitoring and safely maintenance of tubewells.

1.4 RESEARCH QUESTIONS

The following research questions signify the study.

- What is the present status of PH, electrical conductivity, and dissolved oxygen and temperature values in the groundwater sources of Madiphat, Palpa?
- How do these in-situ parameters compare with guideline set by WHO (1993), NDWQS (2005) and the EU (1998)?
- Which locations groundwater shows deviations from the standards and what might be the reasons behind the variations in the values?
- What are the possible risks that may arise for health and agricultural sectors due to acidic PH, low oxygen levels and high salinity (EC) in some wells?
- In what ways does the findings of these surveys would be helpful to develop local strategies for sustainable groundwater management in Madiphat's villages?

2. MATERIALS AND METHODS

The study was conducted in two major phases i.e., desk study and field survey. The desk study of groundwater quality was done by going to detailed literatures, journals, scientific articles, geological and hydrogeological maps, google maps, MAPS.me, QGis and so on. The major data for the article was obtained from individual hydrogeological well inventory survey. Thus, water sample was collected randomly from different valleges of Madiphat area, Palpa.

Thus, the methods applied during field survey was direct questionnaire to the local people, water sample collection giving emphasis on the proper procedure and guidelines of water quality sample collection. The in-situ parameters like PH, EC, DO and temperature using the portable instruments.

3. STUDY AREA

Madiphat lies in mid hills which is the madi valley of Palpa district. The field survey as well as local reports shows seasonal water shortages and Pump failures affecting the local communities of the area indicating the need to understand the groundwater quality and sources differences.

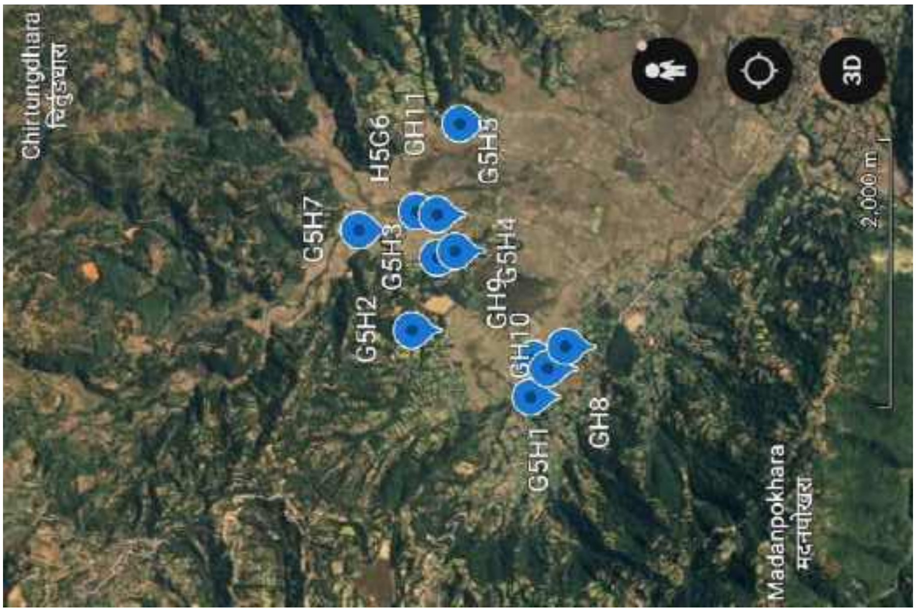

Figure 1: Location of sampling area

4. RESULTS

The groundwater samples showed noticeable variation in quality across different location in Madiphat's villages. The value of the EC varies 1104 µs/cm to 2980 µs/cm fluctuating from lower mineralization to higher mineralization exceeding the standard limits. The higher mineralization ionic content was seen in location GH8 to GH11 highlighting the higher salinity as shown in cu. The dissolved concentration ranges from 4.5 to 8.4 mg/L reflecting low oxygen availability. The majority of sample shows acidity with PH less than 6.5 making the water acidic which is non- complient with WHO, NDWQS and EU guidelines. Water temperature of all the location was constant between 15.5 °C to 16.4 °C, which is safe.

5. DISCUSSION

The site-oriented concerns are highlighted by the findings of our study. The majority of samples representing acidic nature would result into corrosion and may enhance the solubility of metals like iron which may lead to health-related risks. The sample from the four sample of Arkhale and Pokhrathok villages of Madiphat exceeded NDWQS and WHO guidelines which is raising

ISSN: 3021-937X (Print)

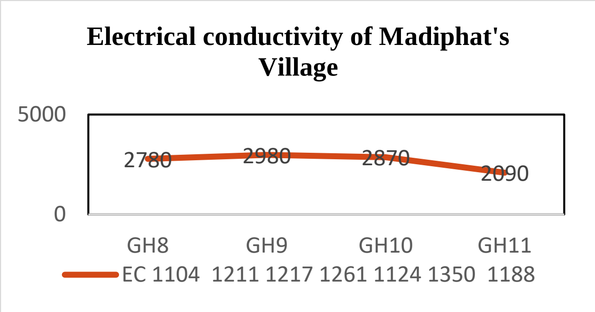

Figure 2: Electrical conductivity curve of Madiphat

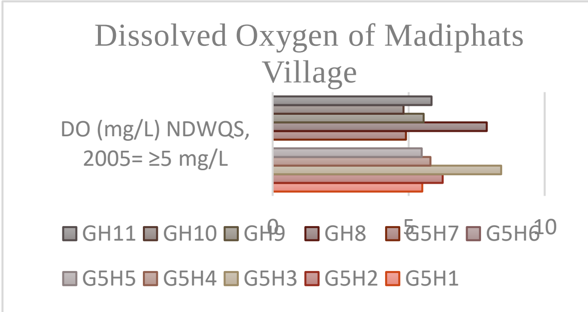

Figure 3: Bar diagram of DO of Madiphat

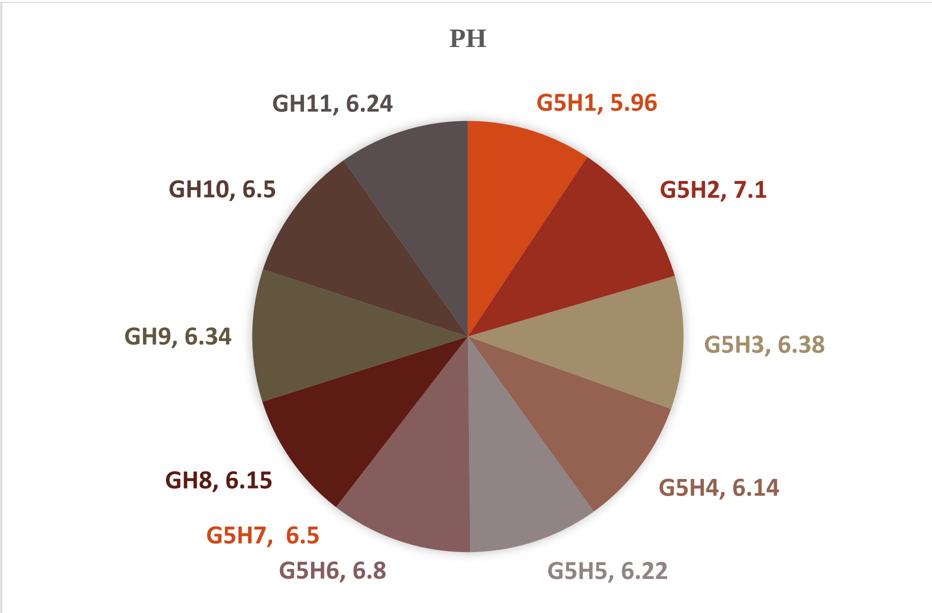

Figure 4: pH values of Madiphat sampling area

concerns for irrigation as high salinity may affect the crop productivity and soil permeability. The reduction of DO in the three wells with sample no G5H6, G5H6 and GH10 indicates the organic contamination or inadequate recharge. As, the temperature of overall location is stable which suggests that the sub-surface is unaffected by the surface fluctuations which is a positive indicator. The overall results provides that the groundwater is safe but requires continuous monitoring for sustainable groundwater use.

Table 1: Detailed summary of in-situ groundwater parameters

S. N	Spot	Coordinates	Village	EC (µs/cm)	DO (mg/L)	Temperature (°C)	pH
1	G5H1	27°49'48.08"N 83°33'50.43"E	Tinteaap	1104	5.5	15.5	5.96
2	G5H2	27°50'16.27"N 83°34'08.29"E	Kunsara-7	1211	6.25	16.5	7.1
3	G5H3	27°50'10.11"N 83°34'27.76"E	Gorsat	1217	8.4	16.2	6.38

4	G5H4	27°50'05.96"N 83°34'29.53"E	Beltari	1261	5.8	15.4	6.14
5	G5H5	27°50'10.52"N 83°34'39.34"E	Beltari	1124	5.48	16.3	6.22
6	G5H6	27°50'15"N 83°34'40"E	Beltari	1350	4.5	15.5	6.8
7	G5H7	27°50'28.82"N 83°34'35.12"E	Beltari	1188	4.9	15.5	6.9
8	GH8	27°49'43.69"N 83°33'57.64"E	Arkhale	2780	7.87	16.4	6.15
9	GH9	27°49'47.64"N 83°34'00.5"E	Arkhale	2980	5.55	16.4	6.34
10	GH10	27°49'39.9"N 83°34'03.82"E	Arkhale	2870	4.81	16.3	6.5
11	GH11	27°50'04.89"N 83°35'03.67"E	Pokharathok	2090	5.84	16.4	6.24
Drinking water standards		WHO Standards 1993		Preferably < 1500 µs/cm (linked to TDS <1000 mg/L	No health based guidline	Desirable <25°C	6.5-8.5
Nepal (NDWQS,2005)				<1500 µs/cm (Mandatory)	≥5 mg/L (Guideline)	< 25°C	6.5-8.5
EU standard, 1998				2500 µs/cm (at 20°C) Parametric value	Not included	Not included	6.5-9.5

6. CONCLUSION

The groundwater in Madiphat is suitable for use as the water quality meets WHO, EU and NDWQS guidelines. However, few samples have acidic PH, high salinity and low DO levels in few wells may affects human health and irrigation efficiently. The monitoring of groundwater continuously, improving well design, PH neutralization, etc can be recommended to ensure sustainable and safe groundwater. The various community-based awareness campaign can be carried out for the groundwater management strategies.

7. ACKNOWLEDGEMENT

I would like to express my sincere appreciation for the Editorial committee of the Geo-world, Article reviewer and the Department of Geology, Tri-Chandra Multiple Campus of Tribhuvan University to have in-depth knowledge on water quality parameter and share my ideas for publishing this article. I would like to express my gratitude to ground no 4 team members and group no 5 team members for helping me to collect as well as provide the data on my interests of choice.

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ISSN: 3021-937X (Print)

FLASH FLOOD: GENESIS AND CONSEQUENCES

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ABSTRACT

Flash floods are sudden and highly destructive natural disasters characterized by the rapid discharge of sediment-laden water in normally dry areas. Unlike regular floods, they develop within a few hours of heavy rainfall or triggering events such as dam failures, cloudbursts, or glacial lake outbursts, giving little time for warning and evacuation. The genesis of flash floods is influenced by meteorological factors (intense rainfall, cloudbursts), physiographic and geological factors (steep slopes, impermeable rocks, saturated soils), and anthropogenic factors (urbanization, deforestation, land degradation, dam or levee failures, and glacial lake outbursts). Their impacts include loss of life and property, damage to infrastructure, soil erosion, water contamination, and significant economic losses. Nepal, with its steep Himalayan terrain and glacial lakes, is particularly vulnerable, as evidenced by recent flash floods in Thame (2024), Rasuwagadhi (2025), and Tilgau, Humla (2025), which caused widespread destruction and displacement. This article synthesizes information from secondary sources to highlight the causes, consequences, and recent occurrences of flash floods, emphasizing the need for awareness, preparedness, and preventive measures to mitigate their devastating effects.

Keywords: *Flash floods, Genesis of flash floods, Consequences*

1. INTRODUCTION

Flash floods are such natural disasters, which are both sudden and disastrous. They can be characterized as the rapid discharge of huge amounts of sediment-laden water in normally dry areas. Unlike regular floods that develop gradually over time, flash floods occur within a short time frame typically less than six hours after heavy rainfall or other triggering events such as dam or levee failure (National Weather Service [NWS], 2022).

The flash floods, in comparison to regular floods, are highly unpredictable and pretty fast. The lead time in case of a flash flood is very low. As a result, the general public in the lowland or downstream areas has very little time to react, or they may not get time at all if the incident occurs at night. Whereas regular floods give more time for people to get prepared and evacuate to a safe place.

The primary causes of flash floods include intense rainfall, rapid snowmelt, the sudden release of water from upstream barriers, cloudbursts, and steep topography. Urbanization, deforestation, poor drainage systems, and disruption of the natural flow channel of rivers have further increased the vulnerability of both rural and urban areas to these events (Smith & Ward, 2020). In many parts of the world, particularly those prone to extreme weather patterns, flash floods are becoming more frequent and intense, driven in part by the effects of climate change (IPCC, 2021).

2. OBJECTIVES

The major objectives of this research are:

1. To give a brief introduction about the flash flood and the factors that trigger it.
2. To spread awareness about the consequences resulting from the flash flood and the necessary preventive measures that can be adopted to reduce its effects.

3. METHODOLOGY

All the information regarding this article has been derived from secondary sources like research papers, online news websites, and geological articles. The information and the data have been arranged and described systematically.

4. GENESIS OF FLASH FLOOD

There are numerous factors responsible for the genesis of flash floods, which may act singly or in groups. The probability of flash floods is high when there is heavy precipitation, sudden release of a huge amount of water by the breaking of a dam, reservoir, or even a glacier lake. The narrow size of a discharge channel of a river or stream aids in the velocity of the flash flood. All these factors are elaborated below under different categories.

4.1 METEOROLOGICAL FACTORS

The meteorological factors include:

- **Heavy or prolonged rainfall**: When an area receives high precipitation, especially during the monsoon, the water volume in the rivers/streams increases to a very high amount, which cannot be absorbed and discharged sufficiently, and flooding occurs.
- **Cloudbursts**: The cloudbursts can be defined as the heavy rainfall that occurs suddenly and over a small area (often in mountains) that drops so much water in a short time that the rivers cannot contain it within their natural channel, and it often leads to instant flooding.

4.2 PHYSIOGRAPHIC AND GEOLOGICAL FACTORS

The physiographic and geological factors include:

- **Steep slopes and mountainous terrain**: The mountainous terrains generally have a high slope gradient, which makes their slopes very steep, and these steep slopes accelerate the runoff speed of water, aiding in the flash flooding.
- **Impermeable rocks and soils**: Rocks like granite, shale, as well as clay-rich soil, have lower porosity, which means less water will enter the ground and more water will flow as surface runoff. This will contribute to the overall volume and speed of the flash flood.
- **Saturated soil conditions**: When the ground is already saturated with water either due to previous rainfall or inflow from rivers and streams the additional rainfall quickly turns into runoff, ultimately leading to a flash flood.

4.3 ANTHROPOGENIC FACTORS

The anthropogenic factors include:

- **Urbanization**: Since the beginning of human civilization, people have been residing near riverbanks, as it provided easier access to food from rivers and facilitated crop cultivation. Over time, more and more people began settling near riverbanks, specifically occupying the river's flow area, which narrowed its width and increased flow velocity. Furthermore, the pavements and roads they constructed are impermeable, leading to greater surface runoff. All these factors ultimately add to the power of flash floods.

- **Deforestation and land degradation**: Deforestation and land degradation reduce the land's ability to absorb and regulate rainwater. The removal of vegetation decreases interception and root binding, while degraded or compacted soils become less permeable. As a result, rainfall quickly turns into surface runoff, increasing the volume and speed of water entering rivers. This rapid flow significantly raises the likelihood of flash floods.
- **Dam failures**: Dam failures can cause sudden and uncontrolled release of large volumes of water. When a dam breaks, the stored water rushes downstream with great force, often overwhelming natural channels. This sudden surge increases flow velocity and discharge, leading to devastating flash floods. Such failures are often triggered by poor maintenance, structural weakness, earthquakes, or extreme rainfall.
- **Glacial Lake Outburst Floods (GLOFs)**: Glacial Lake Outburst Floods (GLOFs) occur when a moraine or ice dam holding a glacial lake suddenly fails. This releases a massive volume of water downstream within a short time, often accompanied by debris and sediments. Such outbursts are usually triggered by ice or rock avalanches, earthquakes, or melting due to rising temperatures. The sudden surge of water can cause destructive flash floods in downstream valleys.

5. CONSEQUENCES OF FLASH FLOOD

Flash floods are one of the quickest and most devastating natural disasters. They cause huge losses in a matter of time. The many effects that a flash flood causes are given below.

- **Loss of life and property:** Flash floods arrive with little to no warning, sweeping away people, animals, houses, and vehicles. The suddenness leaves very little time for evacuation, making them one of the deadliest types of floods. Families often lose their homes and belongings within minutes. Flash floods that occur at night cause even more damage than those that occur during the day.
- **Damage to infrastructure:** Roads, bridges, dams, and communication lines are often destroyed or blocked by floodwaters and debris. This not only isolates communities but also makes rescue and relief operations very difficult. The repair and reconstruction of such infrastructure take a long time and costs a huge number of resources.
- **Soil erosion and land degradation:** The strong current of water erodes fertile topsoil, deposits sand and boulders on agricultural land, and sometimes changes the natural course of rivers. This makes farmlands unfit for cultivation and reduces agricultural productivity in the long term.
- **Water contamination and health risks:** Floodwaters usually get mixed with sewage, solid waste, and harmful chemicals, polluting drinking water sources. This contamination creates favorable conditions for outbreaks of waterborne diseases such as cholera, diarrhea, and typhoid, putting public health at serious risk.
- **Economic losses:** Agriculture, local markets, industries, and transportation systems face heavy losses due to flash floods. Many families lose their sources of income, and the overall economy of the affected region suffers. Recovery requires both time and financial resources, which is often a big challenge for developing countries.

6. RECENT FLASH FLOODS IN NEPAL

Nepal, being a Himalayan country, has extreme geology and topography, which makes it prone to flash floods. The recent flash floods in Nepal were:

6.1 THAME, SOLUKHUMBU – AUGUST 16, 2024

Thame village in the Khumbu region of Nepal was struck by a devastating flash flood caused by the outburst of two glacial lakes; Thyanbo and Dig Tsho. The flood inundated the Thame River with mud, gravel, and boulders, destroying approximately 20 houses, an elementary school, and a health clinic. Around 135 residents were displaced, including 40 children. The flood occurred suddenly, and most residents had already left for Kathmandu or were at the weekly marketplace in Namche. The school was closed for the day, so no students were hurt. Search and rescue operations were conducted by the Nepali Army and Nepal Police.

6.2 RASUWAGADHI, RASUWA – JULY 8, 2025

A catastrophic flash flood occurred at the Rasuwagadhi border crossing point between Nepal and China, caused by the sudden drainage of a supraglacial lake formed atop a glacier in Tibet. The floodwaters surged into the Bhote Koshi River, sweeping away the Friendship Bridge, inundating roads, and causing severe infrastructural damage. At least nine people were killed, and over two dozen went missing. The Rasuwagadhi hydropower plant, a critical electricity provider for the region, was also damaged. Rescue operations successfully airlifted over 150 people to Kathmandu.

6.3 TILGAU, HUMLA – MAY 14, 2025

A glacial lake outburst flood struck Tilgau in Namkha Rural Municipality-6, Humla district, Nepal. The flood, caused by the outburst of two glacial lakes, destroyed 18 houses and washed away five bridges. The affected families were relocated to safer sites, and relief materials, including food and other essential supplies, were dispatched by the District Disaster Management Committee.

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ISSN: 3021-937X (Print)

SEISMITES IN THE KATHMANDU BASIN AND SEISMIC HAZARD IN CENTRAL HIMALAYA

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ABSTRACT
Kathmandu valley is a sedimentary basin having lacustrine and alluvial sediments which are fertile, thick and loosely deposited. This paper aims to show the deformation of the sediments overtime in the valley worsening the seismic hazard. With high proportion of silt there is development of soft sediment deformational structure and sand proportion is passively deformed. Well sorted sand level generates fluid pressure if it is compacted beneath silty cap leading fluidization and dike development. These sediments are analysed in six places of Kathmandu valley. Due to the development of seismites horizontal sharing occurs. By keeping the reference of 1883 earthquake which form 30cm soft sediment deformation the study is done. Kathmandu overlies a fault asperity that laterally bounds the extent of mega-thrust earthquake ruptures, with historical evidence documenting two catastrophic events—one to the east around ~1100 CE and another to the west in 1255 CE.

Keywords: *MHT, Basin, Deformational, Seismites, Catastrophic*

1. BACKGROUND

The Himalaya is characterized by under-thrusting of the Indian lithosphere along the Main Himalayan Thrust (Zhao et al., 1993). Most of the earthquakes occurs at MHT (Avouac, 2003) but some of the earthquake occurs out of sequence (Kaneda et al., 2008; Mugnier et al., 2005). Multiple observation shows the occurrence of mega-earthquakes along the MHT, (greater than magnitude ~8.1 events recorded historically).

- Seismic moment summation for the Himalayan arc suggests that the frequency of great earthquakes in the past three centuries is too low to account for the convergence between South Tibet and India (Bilham et al., 2001).
- Paleoseismic trenching along the front belt indicates ruptures with displacements exceeding 10 m (Kumar et al., 2006; Lavé et al., 2005).
- Historical records further support these findings seismicity underlines seismic gaps (. Seeber and Armbruster, 1981).

To improve the seismic hazard estimation, researcher have performed an extensive survey of the soft-sediment deformation and dikes preserved in the Plio–Pleistocene fluvio-lacustrine sediments of the Kathmandu Valley. Nepal has a long history of destructive earthquakes. At least ten major earthquakes (Chitrakar and Pandey 1986) were recorded in the historical archives since the 13th century. The oldest event badly damaged Kathmandu in 1255 AD and the associated intensity reached at least X (Rana et al., 2007). One third of the Kathmandu population (several thousands of people), including King Abhaya Malla, was killed (Rana et al., 2007; Shava et al, 1992).

2. AIM

The main aim of this paper is to show how the soft, sand, silt are affecting the basin geometry.

3. OBJECTIVES

The major objectives of the study are:

- To understand how the paleo sediments are triggering the hazard.
- To know the Geological setting of the seismites of the Kathmandu basin.

4. RESEARCH QUESTIONS

The followings research questions are considered in this research:

1. How the basin geometry induces a site effect that magnifies the intensity of the earthquake damage?
2. How the Sediment and soft-sediment cause deformation in the Kathmandu basin??

5. MATERIAL AND METHOD

This research study is based on secondary data with only desk study of research paper.

6. RESULT AND DISCUSSION

6.1 THE KATHMANDU BASIN

The catchment of this basin (Figure1) is ~30 km in east–west direction and ~25 km in north–south direction and its outlet is through the Bagmati River. This basin is filled with a very thick (500–600 m) sequence of fluvio-lacustrine sediments (Moribayashi and Maruo, 1980) which is bounded southwards by a tectonic ridge developed above the MBT.

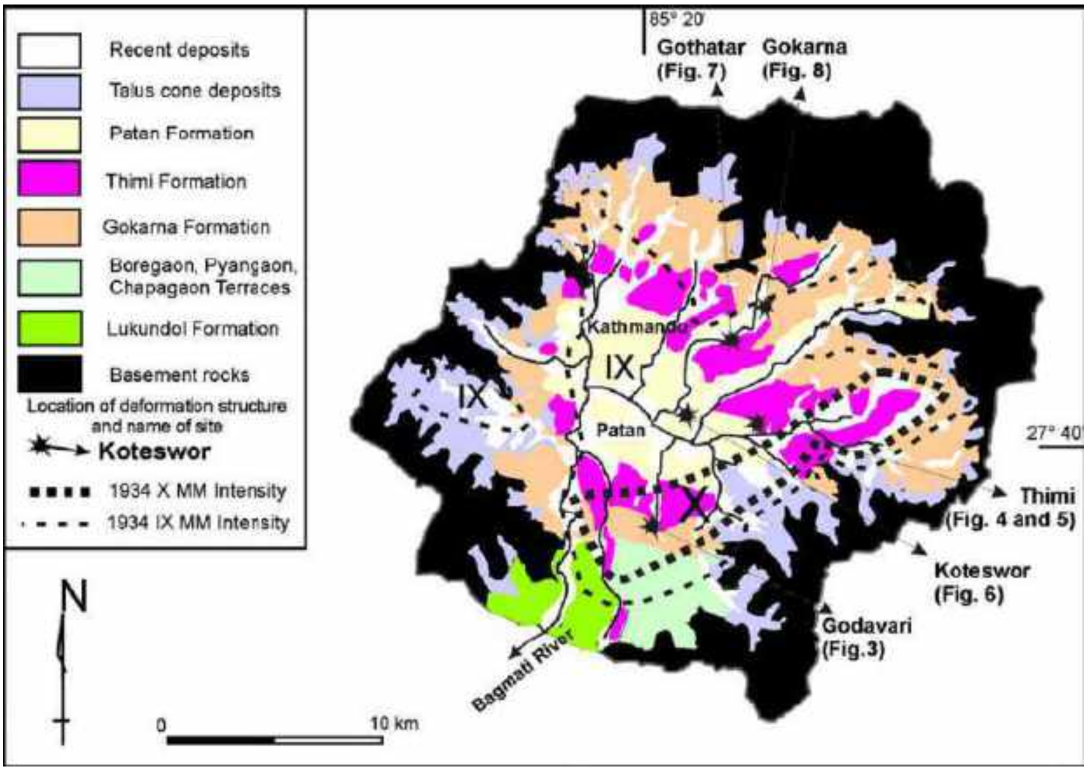

Figure 1: Geological map (adapted from Yoshida and Gautam, 1988) of Kathmandu hydrological catchment with location of paleo-seismites

6.2 SOFT-SEDIMENT DEFORMATION IN THE KATHMANDU BASIN

By analyzing the fresh out crops there are Two types of structures occurred in the sediments of the Kathmandu basin a) dikes b) soft sediments. Dikes were fed by liquefied sands (Obermeier, 1996) and formed sub aerial cones when they reached the surface and soft sediments affected the top of the sedimentary pile and completely de-organized the initial tabular attitude of sediments, leading to ball-and-pillow, flame and folded structures which lead in the mobilization of sediment which trigger earthquake (Obermeier et al., 2002).

6.2.1 SEDIMENT DEFORMATION IN GODAWARI SITE

This place is situated in the southernmost part of valley (figure 1). Study of four dikes having silty and sandy layer along with soft sediment deformation are done. Orientation of the dikes strikes N 355°E to N 10°E, perpendicular to the N 100°E paleo-shore line (Yoshida and Gautam, 1988) and 20° apart from the mean paleo-flow direction.The cross-cutting relations between dikes and host sediments allow establishing a relative timing of deformation forming the folding structure of dike. All the deformation occurs simultaneously.

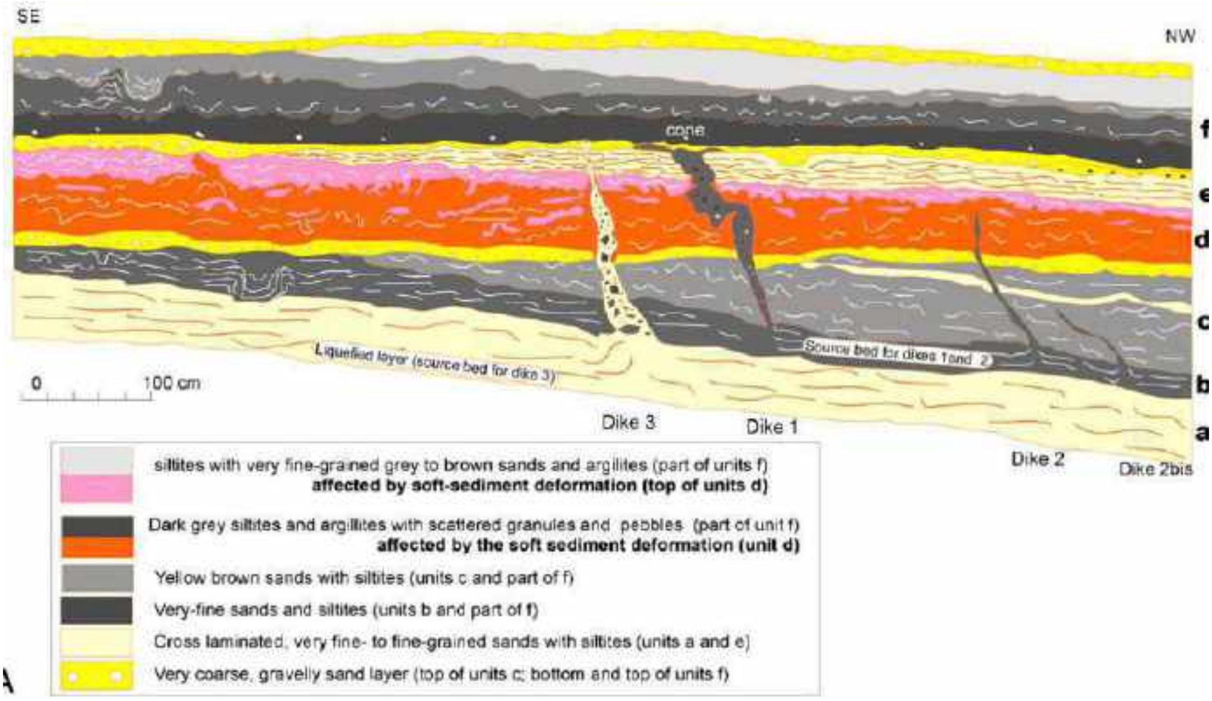

Figure 2: Dikes and soft-sediment deformation at Godawari; (a) to (f) refer to different Mugnier et al (2011)

Granulometric analysis of the sediments shows that the dike is not homogenous, the proportion of sand is high as infilling material and the sediment deformation is due to large amount of silt. The contrast between granulometry of the dike and the host sediment is weaky due to assimilation of host material within the dike and to very little u-section transport of the source material.

6.2.2 SOFT-SEDIMENT DEFORMATION AT THIMI SITE

Thimi is located at south east part of the valley, where deformation of soft sediment and the study of collected big wood pieces and charcoals don't give proper stratigraphic order which makes it impossible to estimate the recurrence of the seismites and suggests that most of the delta front sediments are reworked from older sediments deposited in a more extended lake. Study of single ball and pillow structure suggest that the pillow is separated by thin layer of silty materials. Then unconformity found here are folded which suggest gently shaking. Deformation of sediments create a gap and other elements like sand silt is filled within it.

6.2.3 MEGA SOFT-SEDIMENT DEFORMATION AT KOTESWOR

The Koteswor site was located in the prodelta sediment of the Patan formation (Sakai et al., 2001). The soft-sediment deformation level is the thickest (70 to 90 cm) among the observed one in the Kathmandu valley. The underlying undeformed layers are composed of very fine-grained sand cross-laminated ripples. The deformed zone is composed of elutriated particles having ball and pillow zone composed of sandy silt less than 7% of clay which is intensely folded and the ball-and-pillow structures are composed of thinly laminated sand with less than 20% of silt and clay (Gajurel et al., 2000),), lower zone which is moderately folded with continuous sandy layers embedded in deformed sandy silt.

6.2.4 SOFT-SEDIMENT DEFORMATION AFFECTING THE RECENT DEPOSITS OF THE BAGMATI RIVER

Soft deformation is observed at Gokarna and Gothatar site due to extraction most of the part is not visible.

6.2.4.1 THE GOTHATAR SITE

In the left bank of Bagmati river of Gothatar two types of structure are found. Three sand dikes cut through a succession of undeformed layers which tip upward in undeformed layers and are connected to the underneath coarse sand layer. Partly liquefied source preserved sedimentary features which indicate a channel and point bar depositional environment leading to a high porosity of sediments. The upper part of the outcrop contains soft-sediment deformation containing sandy lens which affect thick silty unit. The granulometric similarity between undeformed and deformed layers suggests that the base of the deformed level is not controlled by granulometry.

6.2.4.2 THE GOKARNA SITE

The soft-sediment deformation consists of flame structures within silty layers and contorted sandy layer. The thickness of the soft-sediment deformation level is 35–40 cm where sand injections are incorporated at its base, but is only 30–35 cm where deformed silty layers lie above undeformed silty layers. The interface between silt and sand levels is folded, but sand injections locally occurred within silt. The soft-sediment deformation is covered by a 30 cm thick very young soil where no horizon has yet developed.

7. DISCUSSION

The following points are taken as discussion:

- The observed ball-and-pillows (Koteswor and Thimi sites) are characterized by the same granulometric contrast between the sandy pillows and the silty matrix, although their thickness and geometry are quite different.
- The soft-sediment deformation level at Thimi reflects strong fluidization of silt layers.
- 1883 earthquake cause flood in Bagmati river so the soft sediments were covered by flooded sediments.
- The development of soft sediment deformation in Koteswor site is due to seismic waves inducing alternate shearing between planes parallel to the earth surface. Such a shearing could be related to the Love waves or horizontal component of the Rayleigh waves (Heifetz et al., 2005; Rodriguez-Pascua et al., 2003).
- Geomorphologic and seismologic contexts are favorable for the development of seismites in Kathmandu valley.

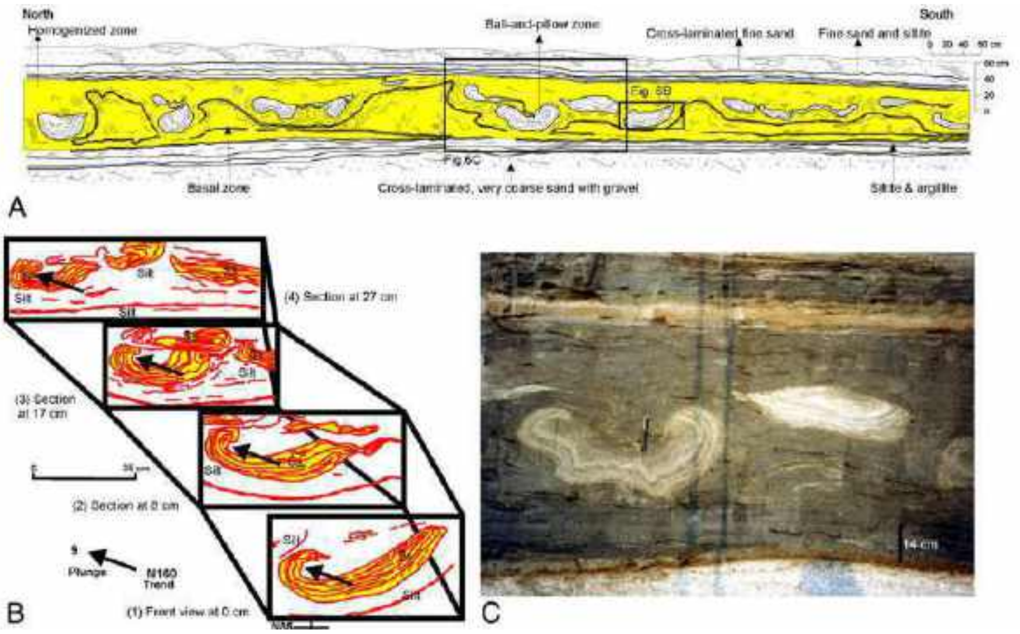

Figure 3: A) Cross section of the Koteswor seismite zone (from Gajurel et al., 2000); B) serial cross-sections of a ball-and-pillow structure c)) photographs of ball-and-pillows source Technophysics 2011)

8. CONCLUSION

This article shows that geomorphologic and seismologic contexts are favorable for the development of seismites which is mainly controlled by the fluidization of silty levels during earthquake shaking in Kathmandu valley. The soft sediments deformation features are linked to earthquakes. Due to the peculiar location of the valley, successive mega-earthquakes could affect the city in a short time interval. Structural studies suggest that waves inducing shearing between planes parallel to the surface are a major cause for soft-sediment deformation. Structural framework and paleo-seismologic studies suggest that Kathmandu is at the transition between 2 seismotectonic segments of Himalaya and could be badly affected by earthquakes respectively located at the east and at the west of the city.

9. ACKNOWLEDGEMENT

I would like to express my sincere gratitude to Tri-Chandra College's Geology Department for providing me with a solid educational foundation. The knowledge and skills I acquired during my time at the college have been invaluable in shaping my academic journey.

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ISSN: 3021-937X (Print)

LANDSLIDE SUSCEPTIBILITY AND GEOLOGICAL CONTROL ALONG THE DAUNNE ROAD SECTION, NARAYANGHAT–BUTWAL HIGHWAY

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ABSTRACT

The Daunne road section along the Narayanghat–Butwal highway is one of the most landslide prone road sections in Nepal. Located in the Siwalik (Churia) range, this area mainly consists of sandstone, mudstone, siltstone and conglomerates that weather easily and lose stability under the impact of heavy rainfall. This paper looks into the Geological controls, slope profile and anthropogenic factors controlling recurrent landslides along Daunne Road. Field observations, literature review and secondary data suggest that slope cutting, drainage issues and the lithological weakness of the Siwalik rocks are the primary causes. Landslides along this corridor lead to traffic disruption, economic loss and loss of lives. Effective slope stabilization measures like bio-engineering, effective and proper drainage and use of retaining structures are recommended for long term and sustainable road operation.

Keywords: *Daunne Road, Landslide, Siwalik, Highway Engineering*

1. INTRODUCTION

Daunne Road is an important part of the Narayanghat–Butwal highway in central Nepal. It connects the eastern and western regions of the country. This route holds significant economic and strategic value but it often faces road blockages from landslides. In the fiscal year 2023/24, the Daunne section was blocked more than 60 times showing how vulnerable it is. This study aims to examine the geological and geomorphological factors that cause slope instability along Daunne Road and to suggest ways to reduce these risks.

2. AIM

The aim of this study is to analyze the geological and geomorphological factors contributing to slope instability along Daunne Road and to recommend mitigation strategies.

3. OBJECTIVE

The major objectives of the study are:

1. To identify the lithological and structural controls influencing landslide occurrence.
2. To analyze geomorphological and hydrological factors affecting slope stability.
3. To document types and impacts of landslides along Daunne Road.
4. To recommend sustainable mitigation measures.

4. RESEARCH QUESTIONS

The following research questions signify the research:

1. What geological and geomorphological factors make the Daunne section highly susceptible to landslides?
2. How do anthropogenic activities exacerbate slope instability?
3. Which mitigation measures are most effective for this corridor?

5. METHODOLOGY

This study is based on field observations, literature review and secondary data from government reports and news sources. Geological mapping, slope characterization and review of previous engineering geology studies in the Siwalik region were undertaken. Case records of landslides were compiled to assess frequency and impacts.

6. RESULTS

The Daunne area is located in the Siwalik (Churia) hills, a region made up of loosely packed sedimentary rocks. The rock types mainly include layers of sandstone, mudstone, siltstone and conglomerates. These rocks are highly weathered and can break apart easily. Structural features like steeply dipping bedding planes, fractures and joints weaken slope stability even more. The area is also prone to earthquakes which increases the potential for hazards.

Figure 1: Photographs showing active landslide along Daunne road section.

6.1 GEOMORPHOLOGY AND SLOPE CHARACTERISTICS

Daunne has steep slopes, narrow ridges, and broken valleys. Road construction has involved a lot of slopes cutting, often at angles that go beyond natural stability limits. The drainage pattern is dendritic, with seasonal streams that grow stronger during the monsoon causing slope failures. Weathering of mudstone layers and undercutting of sandstone beds speed up mass wasting processes.

6.2 TYPES OF LANDSLIDES OBSERVED

Several types of slope failures have been reported along Daunne Road.

- **Rockfalls**: They are common along steep road cuts especially where sandstone layers are cracked.
- **Debris flows**: They are triggered by heavy rain and carry mud, boulders and vegetation.
- **Rotational or slump slides**: They happen in thick layers of weathered mudstone.
- **Shallow soil slips**: They are frequent on slopes that have been deforested and in cuttings.

6.3 CAUSES OF LANDSLIDES

The main causes of landslides in the Daunne area include:

- **Lithology**: Weak Siwalik rocks that break down easily with weathering.
- **Rainfall**: Monsoon rains soak the slopes and cause mass movements.
- **Human Activities**: Road widening, heavy loads on slopes and cutting down trees.
- **Seismic Activity**: Regional earthquakes make already weak slopes less stable.

ISSN: 3021-937X (Print)

6.4 CASE RECORDS AND IMPACTS

According to recent reports, the Daunne section was blocked 63 times in a single year MyRepublica (2024, July 12). Traffic was halted for several hours to days. Landslides cause direct losses for transporters, traders and local communities. Long traffic jams increase fuel consumption, accidents, and economic disruption. The overall impact emphasizes the urgent need for geological input in road construction and maintenance.

6.5 MITIGATION MEASURES

Current stabilization measures include gabion retaining walls, slope trimming and temporary drainage channels. However, these often fall short. Recommended measures include:

- Bio-engineering techniques, such as planting deep-rooted vegetation. Some of the Popular plants species of Nepal used in soil engineering are Amiso (*Thysanolaena maxima*), Chilaune (*Schima wallichi) etc.*
- Proper surface and subsurface drainage systems to reduce water infiltration.
- Retaining and check walls in critical sections.
- Monitoring and early warning systems to inform travelers about road blockages.
- Geological feasibility studies before any further road expansion.

7. DISCUSSION

The frequent landslides along Daunne Road result from weak Siwalik geology and poor engineering practices. While structural and bio-engineering methods can offer temporary relief but the lasting solutions need to involve geological insights in road planning. Studies of other Siwalik Road sections, like Hetauda and Narayanghat reveal similar problems. This indicates that a regional strategy for road safety is essential**.**

8. CONCLUSION

The Daunne section of the Narayanghat-Butwal highway shows the difficulties of building infrastructure in unstable Siwalik terrain. Weak rock formations, heavy rain and various human activity make the area prone to landslides as shown in figure 1 and figure 2. Using geological knowledge in road design, applying bio-engineering methods and ensuring ongoing monitoring can lower risks and support the sustainable use of this important highway.

9. ACKNOWLEDGEMENT

I would like to express my heartfelt thanks to the Department of Geology, Ghantaghar-Kathmandu, for providing me the opportunity to be the part of the 'Geo-World Journal' and I would also thank my friends and editorial team for their valuable suggestion and unwavering support throughout the publication process.

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ISSN: 3021-937X (Print)

SIDDHABABA ROAD TUNNEL: A PATHWAY FOR ROCKFALL PROBLEM IN THE PALPA DISTRICT, NEPAL

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ABSTRACT

Nepal is a mountainous country, and for road safety, tunnels are generally more reliable than surface roads. The under-construction Siddhababa Road Tunnel, located along the Siddhartha Highway in Palpa District, western Nepal, is one such example. The Siddhababa area frequently experiences rockfalls and debris flows, especially during the monsoon season. Geologically, the area belongs to the Siwalik Zone of the Nepal Himalaya and is composed of alternating layers of mudstone, sandstone, and siltstone.The main challenges in this region include landslides, rockfalls, debris flows, alternating weak lithology, unfavorable highway alignment, the orientation of bedding planes, and the presence of groundwater within slopes, all of which become severe during the rainy season. To address these issues, the Siddhababa Highway project is constructing a 1,089 m tunnel between the main Siddhababa Temple area and the Ramapithecus Park area.

However, the primary concern is why the tunnel length is so short. The most problematic section of the highway is about 2.3 km long, stretching from ChidiyaKhola to near Dobhan. For a permanent solution to the hazards of the entire Siddhababa section, the tunnel should extend across this length. The current tunnel only ensures safety within its limited section, while the remaining portions will be protected with rock nets, rock sheds, and slope protection measures, which are effective only during the dry season and less reliable during heavy rainfall. Since Nepal is still relatively new in the field of tunnel construction, such short-term solutions may create greater financial burdens in the future compared to making a one-time investment in a longer, properly designed tunnel.

Keywords: *Road tunnel, Rock-fall, Slope stability, Siddhartha Highway, Kuhire Bhir*

1. INTRODUCTION

The Siddhababa Tunnel is located along the Siddhartha Highway, linking the Terai and Hilli regions of western Nepal. It is approximately 1,089 m long and is being constructed to bypass the hazardous rockfall- and landslide-prone Siddhababa Kuhire Bhir. Geologically, the area belongs to the fragile Siwalik zone, which is composed of weak sedimentary rocks such as sandstone, shale, and mudstone. These rocks are easily fractured and prone to sliding, especially during heavy rainfall. By creating a direct underground passage, the tunnel provides a safer and more reliable route through this geologically unstable terrain.

The Tinau Khola constitutes the main drainage system of the area, supplemented by its tributaries, Chidiya Khola and the Siddhababa Waterfall, which play an important role in the local hydrological network. The study area is situated between the Himalayan Frontal Thrust (HFT) in the south and the Central Churia Thrust (CCT) in the north. Numerous landslides, ranging from relict and inactive scars to actively evolving failures, are distributed along the HFT zone. There are several geologists studied in the past of Tinau River section.

ISSN: 3021-937X (Print)

Tokuoka et al. (1986, 1990) conducted a detailed geological study that classified the Siwalik sequence of west-central Nepal into the Arung Khola, Binai Khola, Chitwan, and Deurali formations. The present study area is confined to the upper part of the Arung Khola Formation and the lower to middle parts of the Binai Khola Formation. The rockfall problems along the Tinau Khola section (Pokhrel, 2017; Pokhrel et al., 2022) arise from the contrasting behaviors of sandstone and mudstone when exposed to water, the orientation of the road relative to bedding planes, unstable road cuts, and the proximity to major geological structures such as the Main Central Thrust and the Central Churia Thrust. Mudstone readily disintegrates upon contact with water, allowing infiltration along the inclined beds, while sandstone remains comparatively resistant. As the underlying mudstone weakens and gradually moves downslope, the overlying sandstone becomes undercut, leading to detachment and rockfall events.

Figure 1: Photograph showing Siddhababa rockfall area in the shaded zone

Pandey et al. (2021) developed a hydrological model using the Soil and Water Assessment Tool (SWAT) to simulate the hydrological behavior of the Tinau watershed and the Kuire Bhir area. The Tinau watershed receives an average annual rainfall of 1,801 mm, whereas the Kuire Bhir area records 2,390 mm, resulting in an average annual surface runoff of 0.107 m^3/s. The main objective of this research is to evaluate whether the construction of the Siddhababa Road Tunnel can provide a permanent solution to the rockfall hazards in the entire Siddhababa area and to assess whether the tunnel length should be extended beyond the currently excavated section.

2. METHODOLOGY

The study was based on both primary and secondary sources of information. Primary data were collected during fieldwork at the Siddhababa Tunnel site, where direct observations were made of geological structures, tunnel alignment, slope conditions, and ongoing construction activities. Photographs and detailed notes were taken to document rock types, slope stability concerns, and existing engineering structures in the area.

In addition to field observations, secondary sources were consulted to support the analysis. These included research articles, academic journals, government publications, newspapers, and online reports that provided technical as well as contextual information on the geological formations of the Siddhababa area, the history of rockfall incidents, and the progress of the tunnel project.

3. RESULT

Within the study area, the upper part of the Lower Siwalik (Arung Khola Formation) and the lower, middle, and upper parts of the Middle Siwalik (Binai Khola Formation) are exposed. On the right bank of the Chidiya Khola, gray mature to immature sandstone and pink mudstone are observed, with a sandstone-to-mudstone ratio of approximately 3:1. Groundwater occurs along the contact between sandstone and mudstone. An overhanging sandstone bed is visible, where the sandstone projects outward while the underlying mudstone retreats inward as it weakens and moves with water during the rainy season.

The fine-grained sandstone and mudstone suggest deposition in a meandering river environment, with lateral accretion being a common feature in this area as shown in figure 2. Four sets of joints are present, which contribute to wedge failure.

Attitude of bed: N58^{0}W/25^{0}NE

Figure 2: Photograph showing inter-bedding of thin mudstone and thick sandstone at right bank of Chidiya Khola, upper part of Lower Siwalik.

When the proportion of sandstone greatly exceeds that of mudstone, and salt-and-pepper sandstone appears, the sequence belongs to the Middle Siwalik (Binai Khola Formation). Such features were observed in the Ramapithecus Park area. Four sets of joints are commonly developed here, contributing to wedge failures.

Moving from Nagdhunga towards Dobhan, pebble sandstone is exposed at a sharp bend along the Siddhartha Highway, representing the upper part of the Middle Siwalik. The Middle Siwalik was deposited by a braided river system.

A rockfall protection structure using stone masonry columns (or retaining piers) built beneath an overhanging rock face as shown is figure 3. The overhanging sandstone bedrock is prone to weathering and rockfall, especially along joints and bedding planes. To mitigate this hazard, stone masonry columns have been constructed to provide vertical support to the rock mass above. These columns act as artificial buttresses, reducing the risk of large rock blocks detaching and falling onto the slope or road below.

ISSN: 3021-937X (Print)

The gaps between the columns allow water and small debris to pass through while maintaining stability for larger rock overhangs. This type of protective structure is commonly used in hilly and mountainous terrains where natural overhangs develop, particularly in weak sedimentary formations like sandstone–mudstone alternations.

Since the opening of the Siddhartha Highway, the Siddhababa section has been recognized as one of the most hazardous road corridors in Nepal due to frequent rockfalls and landslides. Over the past decade (2015–2025), numerous major and minor accidents have been documented, leading to significant loss of life and property damage. During this period, more than eight people have been killed and over fifty passengers have suffered serious injuries as a direct result of falling rocks and slope failures.

Figure 3: Photograph showing column to support hanging block, a way of mitigation rock fall.

One of the notable incidents occurred in September 2017, when a massive rockfall struck a truck and a car traveling along the Highway as shown in Figure 4.

Figure 4: Photograph showing a vehicle was destroyed due to rock fall.

The impact destroyed both vehicles, caused the death of one person, and left eight passengers injured. Similar smaller-scale events, though less publicized, have also contributed to traffic disruptions, vehicle damage, and recurring risks for commuters.

The southern portal of the under-construction Siddhababa road tunnel is situated in one of the most rockfall-prone zones along the highway. Recognizing the high degree of slope instability, extensive protective measures have been carried out around the peripheral portion of the portal.

Figure 5: Photograph showing south portal of Siddhababa road tunnel

These slope protection works include surface stabilization, structural reinforcements, and drainage provisions to minimize the risk of rock detachment and mass movement. To effectively manage groundwater seepage, several weep holes have been installed, allowing subsurface water to discharge safely and reducing pore-water pressure within the slope materials as given is figure 5. These interventions not only enhance the stability of the tunnel portal but also contribute to the long-term safety of the entire roadway section.

The northern portal of the under-construction tunnel is located on the uphill side of the Ramapithecus Park area along the Siddhartha Highway as in figure 6. Geologically, this portal lies within the Middle Siwalik Formation, where sandstone is more dominant than mudstone. Due to the natural slope instability associated with the lithological composition and steep terrain, slope protection has been recognized as an essential requirement around the peripheral portion of the portal.

The Siddhababa Tunnel Project is a major road infrastructure initiative along the Siddhartha Highway in Nepal, aimed at enhancing road safety and improving transportation efficiency in one of the country's most hazardous sections. The project involves the planning, design, engineering, procurement, construction, and commissioning of a double-lane standard highway tunnel, along with five years of service operation and maintenance. In addition to the tunnel, the project includes critical safety measures such as rockfall mitigation, construction of rock shed structures, and road improvement works to address the long-standing issues of slope instability and frequent accidents in the Siddhababa area. The project extends from chainage 28+200 to 30+600, comprising a tunnel of 1126 meters in length; a rock shed structure of 780 meters, and road improvements covering 2398 meters. With a total contract number of NRs. 7.34 billion (including VAT and PS), the project commenced on 23 March 2022 and is scheduled for completion by 22 March 2027, representing a significant government investment in safer and more reliable road connectivity for the region.

Figure 6: Photograph showing northern portal of Siddhababa road tunnel

The Siddhababa rockfall zone covers a total area of approximately 1.12 square kilometers with a perimeter of 6,402 meters. The highway section from the Welcome Gate to Palpa Gate, spanning the Chidiya Khola to Nagdhunga area along the Siddhartha Highway, measures 2.3 kilometers in length. The primary focus of this study is to examine why the Siddhababa Tunnel has been constructed with a relatively short length, despite the main rockfall-prone area extending over 1.8 kilometers.

Figure 7: Photograph showing under construction tunnel (in green) and proposed tunnel (blue)

Due to this limited tunnel length, the project cannot provide a permanent solution to the rockfall hazard along the highway. While slope protection measures have been proposed for the remaining sections of the under-construction tunnel, such measures are less effective compared to tunneling.

Although slope stabilization may require more than double the investment, the tunnel approach offers a long-term, permanent solution to the recurrent rockfall problem in this critical section of the Siddhartha Highway. Therefore, the tunnel, despite its short length, addresses only a portion of the hazard, leaving the majority of the rockfall zone inadequately protected.

4. DISCUSSION

In Nepal, numerous north-south highways pass through river corridors and valleys formed by river incision, resulting in an angular relationship between the rock strata and the roadway, north-south road connect Terai to mountainous region i.e. Karnali river corridor, Kaligandaki, Dudhkunda river (Bhandari & Pokhrel, 2022, Sherpa et al. 2024). Highway construction in these areas often involves uncontrolled toe cutting of hills, which significantly undermines the stability of slopes.

The rock mass is highly fractured, with multiple joint sets dipping downslope at 30°–45°, nearly parallel to the slope face, creating unfavorable conditions for stability. Bedding planes dipping in the same direction may cause planar failures, while intersecting joints allow wedge failures. Steeply dipping sandstone beds (≥60°) show toppling instability, especially where weathering and road cuts have weakened basal support (Singh & Goyal, 2020). Heavy monsoon rainfall occurs in the Siddhababa zone, with an average annual precipitation of over 3,000 mm, leading to infiltration along joints and bedding planes. These increases pore water pressure, reduces shear strength, and allows sliding (Shrestha & Aryal, 2011). This debris can easily be mobilized into small-scale rockfalls and slides under intense rain. Field observation at the cliff showed talus deposits and scarps, pointing to the extensive past history of rockfall activity (Upreti, 2001).

Rock anchors and bolts to stabilize loose blocks. Wire mesh netting to trap smaller rocks that are falling. Surface drainage systems to channel runoff and minimize infiltration (Department of Roads, 2021). The interbedded lithology of mudstone, shale, and sandstone with poor strength, together with bedding planes dipping downslope and multiple joint sets, are the main controls on slope instability (Pokhrel et al. 2022; Koirala & Adhikari, 2022). In addition to the weak rock mass created by weathering and lithological contrasts, the rock mass is extremely prone to rockfall.

5. CONCLUSIONS

This research has following conclusions:

- The Siddhababa area belongs to the upper part of the Lower Siwalik and the lower, middle, and upper parts of the Middle Siwalik. Moving from south to north, the proportion of sandstone increases relative to mudstone, influencing the slope stability and rockfall potential.
- The primary factors contributing to rockfall and landslides include alternating beds of sandstone and mudstone, unfavorable bed orientation, four sets of joints, highway alignment, unmanaged road cuts, and heavy monsoon precipitation.
- The under-construction tunnel measures 1,126 m in length, accompanied by a 760 m rock shed and 2,398 m of road improvement, with a total cost of Nrs. 7.34 billion. Despite these measures, the current tunnel does not fully cover the main rockfall-prone area.

- This research recommends constructing a longer tunnel of 1,800 m, which would provide a permanent solution to the recurrent rockfall hazards in the Siddhababa section.
- Road tunnels, although requiring higher initial investment, are the most effective and long-term solution for slope stability and road safety in mountainous countries like Nepal.

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HIGH-MOUNTAIN HAZARD CASCADES AND SEDIMENT FLUXES DURING THE 2012 SETI RIVER FLOOD TRIGGERED BY CIRQUE FAILURE, ANNAPURNA HIMALAYA

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ABSTRACT

On 5 May 2012, a catastrophic flood along the Seti River in central Nepal caused 72 fatalities and extensive damage across more than 40 km downstream to Pokhara, Nepal's second largest city. This event was triggered by cirque failure due to ice melting on the western slopes of Annapurna IV, which generated large rock avalanches that entered the Seti River valley. The mass movement temporarily dammed the river, producing a landslide-dam outburst flood (LDOF) that evolved into a complex hazard cascade. Field evidence and remote-sensing analysis indicate that the avalanche and subsequent damming mobilized extraordinary volumes of sediment and debris, leading to high-magnitude downstream flooding. The flood destroyed 20 houses, one public building, two temples, 500 m of roadway, two suspension bridges, and two water supply systems. To quantify flood dynamics, terrain data derived from a 12.5 m resolution DEM were incorporated into HEC-RAS for hydraulic modeling. Simulations estimated inundation extents within Pokhara of 2.76, 3.05, and 3.59 km^2 for 20-, 50-, and 100-year return periods, respectively, with Laltin Bazar, Gaighat, and Ramghat identified as critical risk zones. Hydraulic outputs further suggest debris velocities approaching 12 m/s near Kharapani and peak discharges of 8400 m^3/s. These findings underscore the role of cryosphere-driven cirque failures in initiating multi-stage geomorphic hazard cascades in the Himalaya and provide quantitative insight into sediment transport and floodplain risk, offering a foundation for enhanced hazard assessment and disaster preparedness in the Pokhara Valley.

Keywords: *Cirque failure, Rock avalanche, Landslide-Dam Outburst Flood (LDOF), Sediment transport, Seti River, Annapurna Himalaya*

1. INTRODUCTION

Mountainous regions worldwide are increasingly vulnerable to complex natural hazards, particularly in areas where human settlements and infrastructure intersect with active fluvial and slope processes (Fort, Hock et al., 2015, 2019). The central Nepal Himalaya exemplifies such a setting, where steep topography, high-relief river valleys, and cryospheric features combine to generate high-magnitude geohazards. The Annapurna III massif, the Sabuche Cirque, and the Machhapichhare range are underlain by Cambrian to Cretaceous sedimentary sequences, dominated by calcareous, largely unmetamorphosed rocks (Fort, Hormann, 1987, 1974). These formations form the structural and lithological framework that governs slope stability, mass wasting, and river incision patterns across the region. Over a longitudinal extent of approximately 70 km, the Seti Khola actively incises through its own sediments, producing broad, unpaired terraces up to 100 m in height (Fort, Stolle et al., 2010, 2017). These terraces alternate with steep gorges, which are typically short (< 1 km), narrow (< 10 m), and up to 90 m deep, incised into resistant calcareous conglomerates of the Ghachok Formation and the

Lesser Himalayan bedrock sequence (Stolle et al., 2019). Fort (2010) also reported that the interaction between fluvial processes and soluble carbonate lithologies has led to karst-related landforms, including potholes, subterranean tunnels, and caves, which further complicate local hydrology and sediment transport.

Pokhara, Nepal's second largest city, is constructed atop a large (> 120 km^2) intramontane alluvial fan of the Seti Khola. This fan comprises three major depositional units, with the youngest being the 60–100 m thick Pokhara Formation. According to Fort (2010) and Schwanghart et al. (2016), this unit formed from (post-)seismic sediment pulses during the 12th to 14th centuries CE, indicating the combined influence of tectonics and fluvial processes on sediment redistribution. The Pokhara Formation consists predominantly of unconsolidated gravels, which overlie the more indurated, yet undated, Ghachok Formation (Fort, Hormann, 1987, 1974). Such stratigraphic configurations strongly influence the susceptibility of the fan to rapid erosion, channel incision, and flood propagation.

The geomorphology of the Seti River basin, in combination with cryosphere-driven processes such as cirque failure and glacial melt, renders the region prone to multi-stage hazard cascades. These include rock avalanches, landslide-dam formation, and subsequent outburst floods, which pose significant risk to downstream communities, infrastructure, and sediment-laden river systems (Fischer, 2023). Quantifying sediment transport, debris flow dynamics, and floodplain inundation is therefore critical for understanding hazard potential and developing mitigation strategies in the Pokhara Valley.

2. METHODS

The methodology of this study integrates field observations, remote sensing data, historical records, and numerical modeling to analyze the geomorphic processes, sediment transport, and flood dynamics associated with the 2012 Seti River disaster.

2.1 STUDY AREA AND DATA COLLECTION

The Seti River basin, central Nepal, encompasses steep mountainous terrain, glacial cirques, and active fluvial systems. Field surveys were conducted to document evidence of rock avalanches, landslide dam formation, and channel morphology. Damage assessment downstream in Pokhara was based on post-flood reports, satellite imagery, and governmental records. Morphometric and stratigraphic information of the Pokhara Formation and Ghachok Formation was compiled from previous studies (Fort, Fort, Stolle et al., Schwanghart et al., ICIMOD, 1987, 2010, 2017, 2016, 2012).

2.2 TOPOGRAPHIC ANALYSIS AND DEM PROCESSING

Digital Elevation Models (DEM) with 12.5 m resolution were employed to derive terrain parameters including slope, aspect, elevation, and drainage patterns. Terrain preprocessing and hydrological analysis were performed using ArcGIS and QGIS software. DEMs were used to reconstruct pre-flood topography, identify potential avalanche release zones, and delineate the floodplain of Pokhara (Fischer, SANDRP, Basnet and Acharya, 2023, 2014, 2019).

2.3 REMOTE SENSING AND GEOMORPHIC MAPPING

High-resolution satellite imagery and aerial photographs were analyzed to delineate landslide deposits, debrisflow paths, and river terraces. Morphometric analyses of cirques, gorges, and

ISSN: 3021-937X (Print)

alluvial fan deposits were undertaken to estimate the spatial extent and approximate volume of material mobilized during the hazard cascade. Georeferenced datasets further facilitated the identification of flood-inundated zones, infrastructure damage, and key hazard hotspots in the Seti River basin (Fischer, 2023).

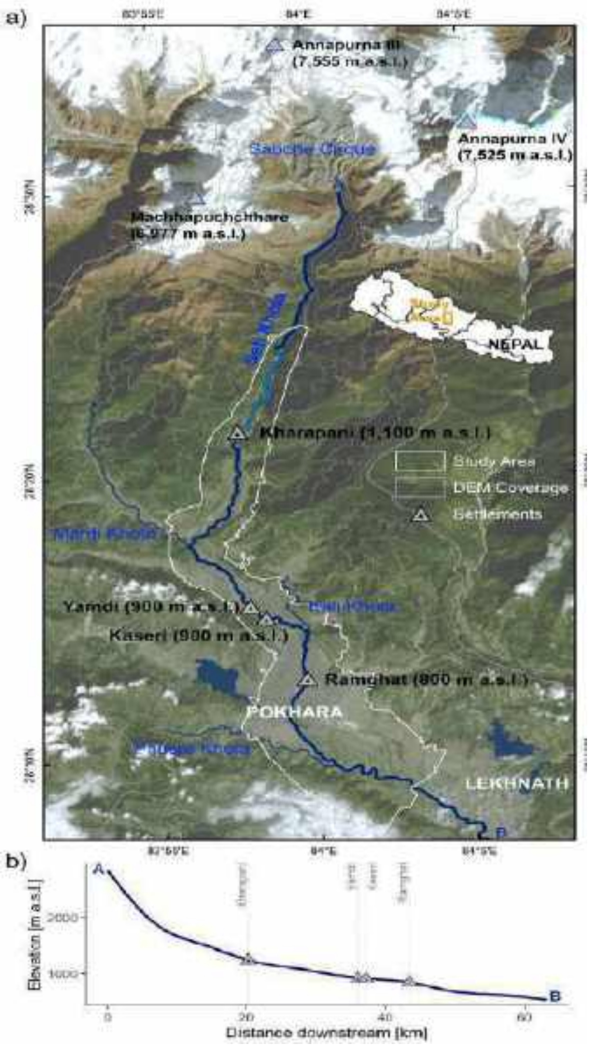


Figure 1: The Pokhara Valley and the Seti Khola as of November 2021. (a) Model domain of the HEC-RAS (Hydrologic Engineering Center's River Analysis System) and manually derived land cover mapping, delineated by the white polygon. The most severe damages during the May 2012 flood occurred along the uppermost inhabited reach of the Seti Khola (light blue). Grey triangles denote key settlements referenced in this study. Background image from PlanetScope Planet Team (2017); contour lines (500 m spacing) are derived from the AW3D DEM Japan Aerospace Exploration Agency (JAXA) et al. (2022); administrative boundaries are provided by the UN OCHA Field Information Services Section OCHA FISS (2020). (b) Smoothed longitudinal profile of the Seti Khola extending from the Sabche Cirque (A) to the south-eastern periphery of Lekhnath (B), adapted from Fischer (2023)

2.4 SEDIMENT AND MATERIAL TRANSPORT ESTIMATION

Available field and literature data were used to quantify sediment and debris volumes transported during the rock avalanche and subsequent landslide-dam outburst flood. Sediment transport estimates were derived using:

- Volume measurements of avalanche and landslide deposits in mapped zones (Japan Society of Civil Engineers (JSCE), 2012).
- Morphometric scaling relations between slope, catchment area, and expected debris volume (Stolle et al., 2019).
- Peak discharge and velocity values from field reports and HEC-RAS modeling (Basnet and Acharya, 2019).

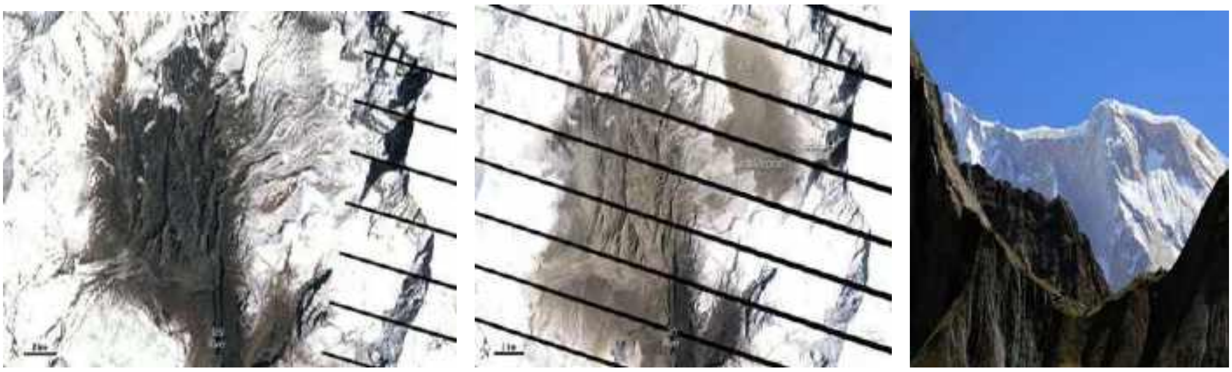
2.5 HYDRAULIC MODELING AND FLOODPLAIN ANALYSIS

HEC-RAS software was used to simulate water surface elevations, peak flow, and flood extents under different return periods (20-, 50-, 100-year). Terrain and river cross-section data derived from DEMs served as input for one-dimensional and two-dimensional hydraulic models.

Model outputs were validated using post-flood inundation extents, velocity estimates (~12 m/s at Kharapani), and peak discharge (~8400 m^3/s) reported in previous studies (Fischer, Basnet and Acharya, 2023, 2019).

2.6 HAZARD ASSESSMENT AND RISK MAPPING

Inundation extents, terrace and gorge morphology, and sediment transport were integrated into a GIS-based hazard assessment framework. Flood-prone zones within Pokhara (e.g., Laltin Bazar, Gaighat, and Ramghat) were delineated, and the interaction between cryosphere-driven cirque failure, rock avalanche, and downstream flooding was analyzed to identify multi-stage hazard cascades (Fischer, 2023).



(a) BEFORE (b) AFTER (c) NASA EO

Figure 2: Satellite imagery of the Seti River region documenting the 2012 flood impact. (a) The same area on April 12, 2012, before the event. (b) The area on May 6, 2012, roughly 25 hours after the landslide-triggered flood, showing extensive debris deposition. (c) A broader context view from the NASA Earth Observatory, acquired October 7, 2013, showing the lasting geomorphic change.

2.7 SYNTHESIS AND ANALYSIS

All datasets, including DEM, satellite imagery, field measurements, and HEC-RAS outputs, were synthesized to produce quantitative and qualitative insights into the processes that triggered the 2012 flood. Emphasis was placed on the links between cirque failure, landslide-dam formation, sediment transport, and flood propagation, providing a framework for hazard assessment and disaster preparedness planning.

3. RESULTS

The following key points derived from the review of previous studies have been integrated to support and complete the overall conclusion of this work.

3.1 SEDIMENT MASS AND EVENT DISCHARGE

The satellite imagery of the study area captures the rapid sediment fluxes associated with a cirque failure. This failure, induced by ice melting in the western sector of Annapurna IV, triggered rock avalanches that entered the Seti River, forming a natural dam. The damming subsequently led to a Landslide Dam Outburst Flood (LDOF), as shown in Fig. 4.

The volume of deposited sediments was estimated using the geometrical dimensions of the deposit. The volume of solids, V_s, was calculated as:

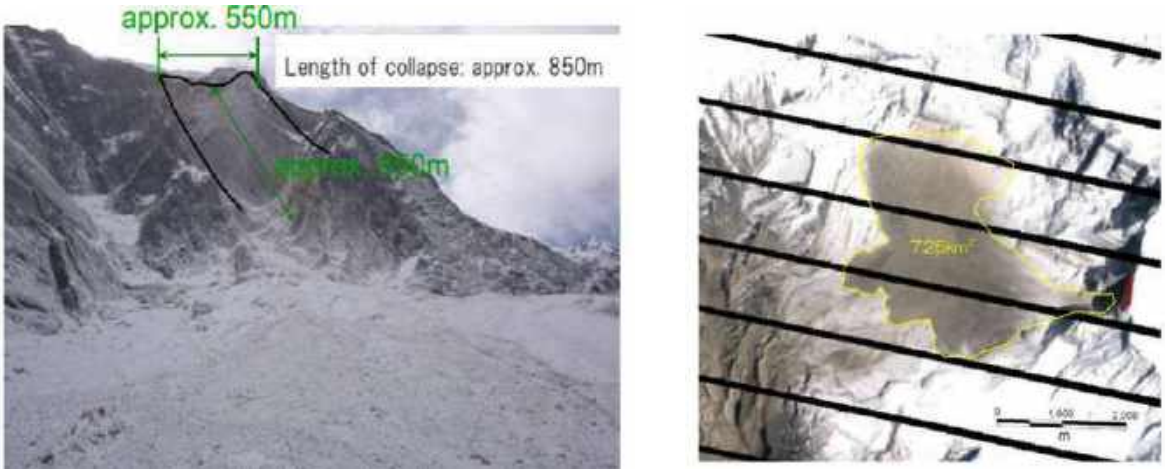
$$V_s = B \times D \times H = 550\text{m} \times 70\text{m} \times 850\text{m} = 32{,}725{,}000\text{m}^3$$

where B, D, and H represent the width, depth, and height of the deposit, respectively (Fig. 3a).

The sediment deposit volume, V_d, as illustrated in Fig. 3b, was determined from the area and mean thickness of the deposit:

$$V_d = A \times h = 7250000\text{m}^2 \times 2\text{m}$$
$$= 14{,}500{,}000\text{m}^3$$

where A is the planimetric area and h is the mean thickness of the sediment layer.



(a) Volume of collapse material from the cirque *(b) Deposition area (remote sensing)*

Figure 3: Source and sink analysis of the 2012 Seti Flood event. (a) illustrates the volume of material estimated to have collapsed from the cirque wall, representing the event's source. (b) shows the vast extent of the resulting deposition area downstream, as identified through remote sensing analysis, representing the primary sink Japan Society of Civil Engineers (JSCE) (2012).

The total sediment flux associated with the event is then estimated as the difference between the total solid volume and the deposited volume:

$$\text{Sediment flux} = V_s - V_d$$
$$= 32{,}725{,}000\text{m}^3 - 14{,}500{,}000\text{m}^3$$
$$= 18{,}225{,}000\text{m}^3$$

The estimated volume of the sediment deposit was 32,725,000m^3. Using representative bulk density values for coarse, unsorted debris, the total transported sediment mass M was calculated to be:

$$M = 58.9\text{Mt} \quad \text{for } \rho_b = 1.8\text{tm}^{-3}$$
$$M = 65.5\text{Mt} \quad \text{for } \rho_b = 2.0\text{tm}^{-3}$$

Assuming this mass was transported as a hyperconcentrated flow with a volumetric sediment concentration C_s = 0.40 over a duration of 5min and2h. The mean and peak discharges are calculated based on the transported sediment volume V_t = 18,225,000m^3. The governing equation for the mean discharge of the sediment-water mixture is:

$$Q_{\text{mean}} = \text{V}_\text{t} / \text{C}_\text{s} \,.\, \text{t}$$

The peak discharge is estimated as twice the mean value:

$$Q_{\text{peak}} = 2 \times Q_{\text{mean}}$$

3.1.1 CALCULATION FOR A 5MIN EVENT DURATION

$$t = 5\text{min} = 300\text{s}$$
$$Q_{\text{mean}} = 18{,}225{,}000\text{m}^3 / 0.40 \times 300\text{s}$$
$$= 151{,}875 \text{ m}^3\text{ s}^{-1}$$
$$Q_{\text{peak}} = 2 \times 151{,}875\text{m}^3\text{ s}^{-1}$$

$= 303{,}750 \text{ m}^3 \text{ s}^{-1}$

3.1.2 CALCULATION FOR A 2H EVENT DURATION

$$t = 2\text{h} = 7{,}200\text{s}$$

$$Q_{\text{mean}} = 18{,}225{,}000\text{m}^3 / 0.40 \times 7{,}200\text{s}$$

$$\approx 6{,}330\text{m}^3 \text{ s}^{-1}$$

$$Q_{\text{peak}} = 2 \times 6{,}330\text{m}_3 \text{ s}^{-1}$$

$$\approx 12{,}660\text{m}^3 \text{ s}^{-1}$$

3.2 HYDRAULIC MODELING WITH THE MANNING EQUATION

The Manning equation was solved numerically to find the flow depth y required to achieve the peak discharge for a range of channel widths b and bed slopes θ. The governing equation and parameters are:

$$Q = AR^{2/3}S^{1/2} / n$$

Roughness: Manning's $n = 0.04$ (rocky, irregular mountain channel).

Channel Geometry: Rectangular cross-section $A=b \cdot y$, $R=b \cdot y / b+2y$

Slope: $S = \tan(\theta)$, where θ is the bed slope angle in degrees.

3.3 RESULTS FOR MODERATE SLOPES

For slopes up to approximately 30° (see Table 1), the model yields hydraulically reasonable flow depths (e.g., 10m to 20m for a 50m wide channel). These conditions are consistent with those observed during large-scale outburst floods.

Table 1: Comparison of calculated peak flow depths for different event duration scenarios (n = 0.04).

Width, b (m)	Slope, θ (°)	Peak Flow Depth, y (m)	
		5 min event Qp = 303,750 m³ s⁻¹	2 h event Qp = 12,660 m³ s⁻¹
10	10	216.8	30.1
	15	139.4	19.4
	20	100.3	14
	30	59.2	8.3
20	10	153.3	21.3
	15	98.6	13.7
	20	70.9	9.9
	30	41.9	5.8
50	10	96.9	13.5
	15	62.3	8.7
	20	44.8	6.3
	30	26.5	3.7
100	10	68.6	9.5
	15	44.1	6.1
	20	31.7	4.4
	30	18.7	2.6

3.4 EXTENDED ANALYSIS TO EXTREME SLOPES

The analysis was extended to include near-vertical slopes to explore the theoretical behavior of the Manning equation under extreme conditions. It is critical to note that for slopes steeper than approximately 25°, the Manning equation is applied far beyond its intended use case for open-channel flow. Flows on such slopes are better described by models for sheet flow, waterfalls, or granular avalanches. The results for high slopes (Table 2) are presented for mathematical completeness.

Table 2: Calculated flow parameters for selected slopes and widths (n=0.15, ρ = 1,000kgm^{-3}, g = 9.81ms^{-2}).

Slope (°)	**Width b (m)**	**5-min Peak (Qp = 303,750 m³ s⁻¹)**			**2-hr Peak (Qp = 12,660 m³ s⁻¹)**		
		y (m)	**R (m)**	**(kPa)**	**y (m)**	**R (m)**	**(kPa)**
25	20	151.5	9.4	42.9	42.4	8	36.7
	40	77.6	15.9	72.8	19.6	8.4	38.6
	60	53.4	18	82.5	13.6	8.5	39.3
	80	41.1	18.9	86.6	10.5	8.6	39.6
	100	33.5	19.3	88.6	8.6	8.6	39.8
50	20	110.6	9.2	107.5	30.8	7.8	90.9
	40	56.6	15.5	182.2	14.3	8.1	94.9
	60	38.9	17.5	205.7	9.8	8.2	96.6
	80	29.9	18.4	216.4	7.6	8.2	97
	100	24.4	18.8	221	6.2	8.3	97.4
75	20	75.6	8.8	323	20.5	7.4	270.8
	40	38.9	14.8	541.6	9.5	7.8	284.1
	60	26.8	16.8	615.1	6.5	7.9	288.7
	80	20.6	17.7	647.7	5	7.9	290.5
	100	16.8	18.1	662.3	4.1	8	291.5

3.5 INTERPRETATION OF MODEL BEHAVIOR AND LIMITATIONS

The results in Table 2 reveal clear mathematical trends which signify a profound breakdown in the physical realism of the Manning model at extreme slopes.

3.6 BED LOAD TRANSPORT POTENTIAL

This document presents a corrected calculation for the critical particle diameter that can be mobilized by a high-velocity flow, using the Shields criterion. The bed shear stress (τ) has been updated based on simulated flow parameters for a catastrophic flood event.

The potential sediment size that can be mobilized is estimated using the Shields criterion, which relates the applied bed shear stress to the size of the largest particles a flow can transport. The relation for the critical particle diameter is expressed as:

$$d = \tau / \theta_c (p_s - p) g$$

where τ is the applied bed shear stress, θ_c is the critical Shields parameter, ρ_s is the sediment density, ρ is the fluid density, and g is the gravitational acceleration.

Assuming a bed shear stress of τ = 270.8kPa, corresponding to a steep gradient of 75° and a narrow channel width of 20m, and τ = 36.7kPa, corresponding to a steep gradient of 25° and the same channel width of 20m, a comparative analysis was performed. The parameters considered are presented in Table 3.

3.6.1 CASE 1: STEEP-GRADIENT (75°) AND NARROW CHANNEL (20M)

This case represents an extremely high-energy event, such as a glacial lake outburst flood. The bed shear stress is calculated to be τ = 270.8kPa. The corresponding critical particle diameter is:

$$d = 270.8\text{kPa} / 0.05(2{,}650\text{kgm}^{-3} - 1{,}000\text{kgm}^{-3})\ 9.81\text{ms}^{-2}$$
$$\approx 334.6\text{m}$$

This result indicates that the flow is theoretically capable of mobilizing exceptionally large geological features on the scale of a small hill, highlighting the immense power of such catastrophic events.

3.6.2 CASE 2: LOWER-GRADIENT (25°) AND NARROW CHANNEL (20M)

This case represents a less extreme, though still highly energetic, flood event. The bed shear stress is significantly lower at $\tau = 36.7$kPa. The critical particle diameter is calculated as:

$$d = 36.7\text{kPa} / 0.05\,(2{,}650\text{kgm}^{-3} - 1{,}000\text{kgm}^{-3})\; 9.81\text{ms}^{-2}$$
$$\approx 45.35\text{m}$$

While substantially smaller than the first case, this result still suggests the potential to transport very large boulders, far exceeding the size typically found in fluvial systems.

Table 3: Comparison of Critical Particle Diameter for Two Conditions

Parameter	Case 1 (75°)	Case 2 (25°)
Bed Shear Stress (τ)	270.8kPa	36.7kPa
Calculated Diameter (d)	334.6m	45.35m

3.7 VELOCITY-BASED DAMAGE POTENTIAL

The destructive power of a boulder during a high-energy flood event, such as a Glacial Lake Outburst Flood (GLOF), is fundamentally governed by its kinetic energy (*KE*). The relationship is given by the fundamental equation:

$$\text{KE} = \text{mv}^2/2 \qquad (1)$$

where *m* is the mass of the boulder and *v* is its velocity. This relationship is critical, as it reveals that the boulder's destructive force increases quadratically with its velocity; a mere doubling of its speed results in a quadrupling of its kinetic energy as illustrated in Fig. 4.

The boulder's massive size contributes an enormous mass (*m*), which is a function of its density (ρ) and volume. For a spherical boulder, this is calculated as:

$$m = (\rho \times 4\,\pi r^3) / 3 \qquad (2)$$

where *r* is the boulder's radius. This substantial mass further amplifies the kinetic energy, making large boulders exceptionally potent agents of geomorphic change.

To quantify the complex interaction between this kinetic energy and the channel's geology, a relative damage potential unit (DPU) is proposed. This metric is defined by the formula:

$$\text{DPU} = (\text{mv}^2/2) / \text{Resistance Factor} \qquad (3)$$

This metric takes the boulder's kinetic energy and normalizes it by the bedrock's inherent strength, represented here as a generalized *Resistance Factor* (a property encompassing compressive strength, fracture density, and other lithological characteristics). This approach allows for a direct comparison of the erosion potential across different scenarios and geological settings. The application of this concept demonstrates that even highly resistant rock types (e.g., granite with a high Resistance Factor) will sustain catastrophic scouring and fracturing when subjected to the extreme velocities and forces characteristic of GLOF events.

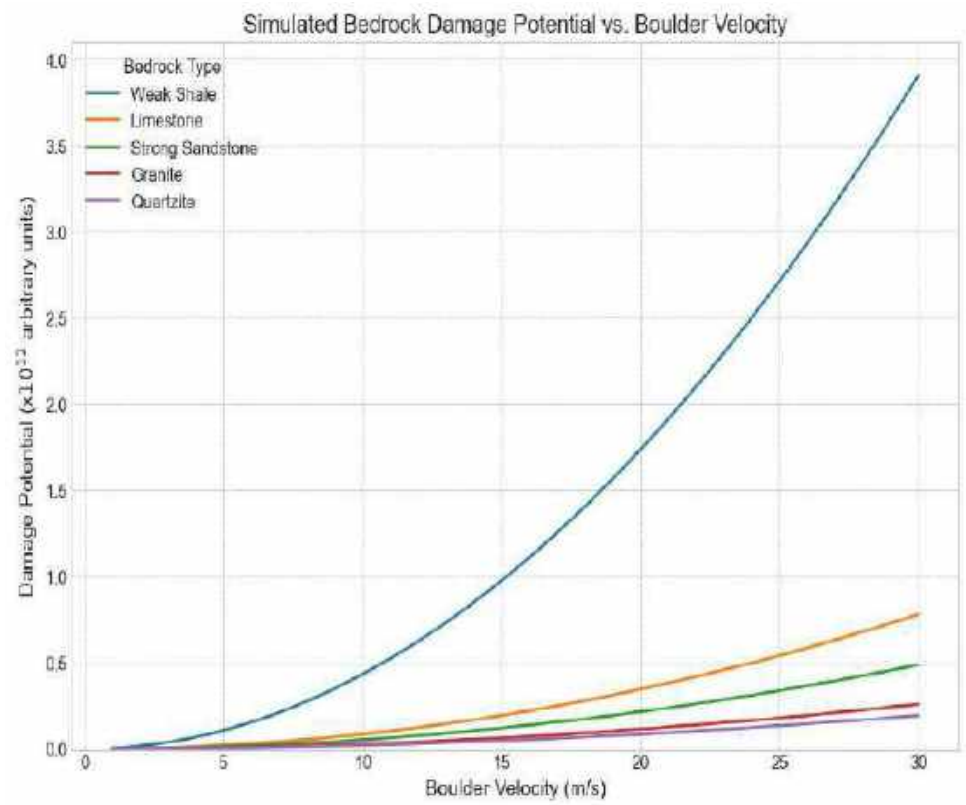
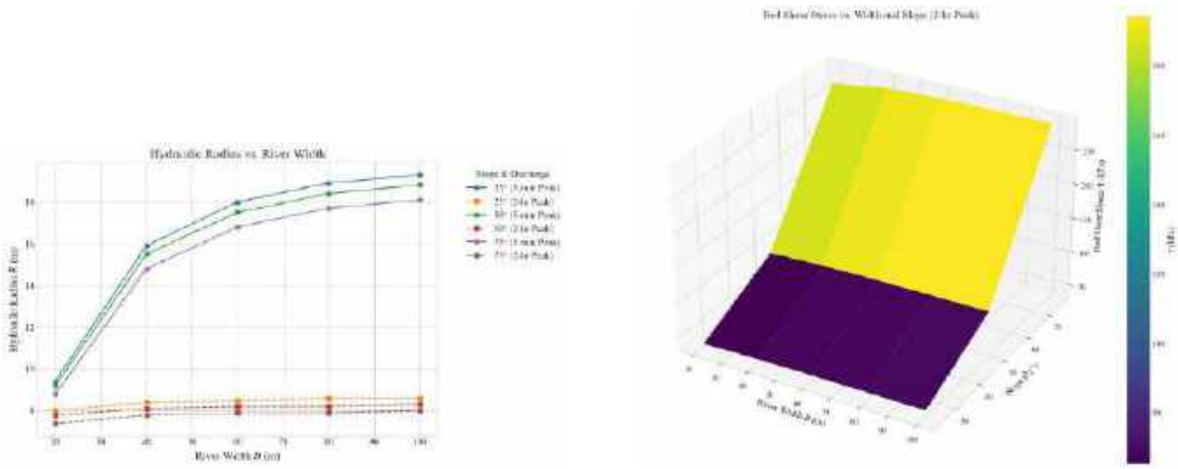


Figure 4: Theoretical relationship between boulder velocity and calculated damage potential for an 85m diameter boulder. The quadratic increase in kinetic energy leads to a catastrophic rise in erosive power at velocities typical of megafloods (> 15ms^{-1}).



(a) Hydraulic radius vs. width for different slope angles *(b) Bed shear stress vs. width and slope (2-hr peak)*

Figure 5: Graphical representation of the modeled hydraulic parameters for the 2-hour peak discharge scenario (Q_p = 12,660m^3 s^{-1}). (a) shows the relationship between channel width and hydraulic radius for various slope angles. (b) illustrates the resulting bed shear stress, demonstrating its dependence on both channel width and slope gradient.

3.8 MATHEMATICAL TRENDS

- **Depth Convergence:** As the slope $S = \tan(\theta)$ increases hyperbolically, the required flow depth y asymptotically approaches zero. This occurs because the gravitational forcing term $S^{1/2}$ becomes immense.

- **Hydraulic Radius Decay:** For a fixed width *b*, as depth *y* becomes very small, the hydraulic radius *R* approaches zero.
- **Shear Stress Divergence:** The bed shear stress $\tau = \rho gRS$ increases hyperbolically with slope because *S* increases much faster than *R* decreases. The calculated values (e.g., 1,000kPa) exceed the shear strength of rock and soil.

3.9 PHYSICAL IMPLAUSIBILITY AND MODEL BREAKDOWN

The trends described above highlight the complete breakdown of the Manning model's physical realism:

- **Invalid Flow Regime:** A flow on an 80° slope is a free-falling avalanche or waterfall, not a gradually varied open-channel flow governed by frictional resistance.
- **Unrealistic Shear Stresses:** Shear stresses predicted for steep slopes (e.g., > 244kPa for a 100m wide channel at 75°) of 303,750cubic/meter are physically meaningless, as they suggest flow conditions that would pulverize the bedrock channel itself.
- **Transition to Other Formulations:** This analysis demonstrates that the Manning equation must be constrained to slopes where open-channel flow assumptions hold (typically $\theta \lesssim 30^\circ$). For steeper slopes, the phenomenon transitions to a regime requiring models from granular flow or avalanche theory.

Therefore, while the Manning model provides valid first-order estimates for plausible channel slopes, its predictions for extreme slopes are mathematical artifacts that vividly illustrate the boundary of its applicability. The results for $\theta > 30^\circ$ should be disregarded for physical analysis and serve only to demonstrate model limitations.

(a) 15 m height of suspension bridge destruction

(b) Main bridge damage in Machhapuchhre VDC

Figure 6: Evidence of the destructive force of the 2012 Seti Flood. (a) The complete destruction of the Kadoor suspension bridge, with an estimated scour depth of 15 meters. (b) Severe damage to the main bridge in Machhapuchhre VDC, illustrating the extensive impact on infrastructure ICIMOD (2012).

4. CONCLUSION

The catastrophic 2012 Seti River flood was initiated by a massive rock avalanche in the Annapurna Hills, where approximately 32,725,000m^3 of material collapsed due to cirque failure on the western flank of Annapurna IV, likely triggered by ice melt processes. This event formed a temporary landslide dam whose subsequent breach generated a powerful landslide dam outburst flood (LDOF) that transported approximately 18,225,000m^3 of sediment downstream while depositing 14,500,000m^3 within the proximal valley. Hydrodynamic modeling reveals the extreme nature of this event, showing that a 5min duration would require an implausible peak discharge of 303,750m^3 s^{-1}, while a more realistic 2h event still corresponds to an exceptional peak discharge of 12,660m^3 s^{-1}. The analysis demonstrates that bed shear stress ($\tau = \rho gRS$) increased drastically with both increasing river gradient and narrowing channel geometry, significantly amplifying the flood's destructive power. The event's path originating above 7,500m elevation, propagating through the constricting topography near Kharapani (1,100m), and ultimately impacting Pokhara at approximately 820m created ideal conditions for catastrophic damage, underscoring the profound hazards associated with climate-driven slope instabilities and subsequent LDOFs in high-mountain environments.

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CAUSES OF SIMALGAIRA LANDSLIDE, ITS EFFECT, AND FUTURE CONSEQUENCES

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ABSTRACT

Landslides are one of the most common and destructive forms of mass wasting in Nepal, particularly in the Higher, Lesser, and Siwalik zones. These hazards are most frequent during the rainy season due to heavy precipitation. The Simalgaira Landslide, located in the Lesser Himalaya, occurred six years ago and caused the death of two people. The landslide area is part of Simalgaira Village, ward-09, Bhanu Municipality, Tanahu District. Geographically, it lies in the mid-hill region of Nepal, with an elevation ranging from 600 to 700 meters above mean sea level. The site is situated about 1.2 km uphill from Badahare along the Dumre–Besishahar–Chame Highway (GPS: 28°04'35"N, 84°27'15"E). The main lithology of the area comprises highly weathered phyllite and quartzite, which are prone to weakening under water infiltration. The region is covered by peripheral vegetation, including Saal, Chilaune, Katus, and Bamboo trees. Human activities, steep slopes, and high rainfall have contributed to slope instability. The study aims to investigate the causes of the Simalgaira landslide and evaluate the possibility of future occurrences. Understanding these factors is essential for safeguarding lives, property, and infrastructure. This research emphasizes the need for detailed subsurface geological studies. The findings can guide mitigation strategies and risk management. Awareness and planning can help reduce landslide hazards in similar Himalayan regions.

Keywords: *Landslides, Precipitation, Steep slopes, Slope instability, Risk management*

1. INTRODUCTION

Landslide refers to the geological hazard known to be most frequent and devastating natural disaster especially in hilly and mountainous region. In other terms, it is the movement of rock mass, soil, debris, down the slope due to the force of gravity (Varnes, 1978; Dahal, 2012; Dahal et al., 2008). It usually happens when the driving force of the soil is higher than the resisting force. It can be affected from heavy rainfall, earthquakes, human activities, etc.

The landslide zone is about 1.2 km upill from Badahare along Dumre – Besishahar- Chame Highway as shown in Fig 1. The GPS coordinate of the location is 28°04'35"N and 84°27'15"E. It is the part of Lesser Himalaya. Politically, this area is situated at Simalgaira village, ward-09 of Bhanu Municipility, Tinau District. Geographically, it lies in mid land group of Nepal Himalaya. Bais Jangar, Badahare, Simalgaira,etc are the main settlement of the study area. The Trees likes Saal, Chilaune, Katus and Bamboo tree are found within peripheral parts of landslide. Elevation is 600 to 700 m from mean sea level.

Annually, landslide, debris flow and rock fall cause loss of hundreds of people, thousands of animals, million dollor of properties,etc due to high precipitation in Higher, Lesser and Siwalik zones of Nepal (Pokhrel et al., 2022; Bhandari & Pokhrel, 2022). Rainfall induced landslide of Marshyangdi River around Pallotari village cause loss of people, properties, and manmade structures (Bhandari et al. 2024). This area geology may be similar to that of Pallotari landslide. Therefore, government should invest to study landslide in Marshyangdi basin.

2. RESULT

In regional scale, this area belongs to Lesser Himalayan zone, Kuncha Formation (Dhital, 2015). In local scale, the main rock units are greenish grey, 15 cm 50 cm thick pysmmatic and politic phyllite and gray to milky quartzite are found. Three dominants set of joints are found in phyllite and planar types of sliding were observed in the field.

Figure 1: Photograph Showing Simalgaira landslide in 2076

2.1 ABOUT SIMALGAIRA LANDSLIDE

Even the major crown of the landslide was nearly 250 m above than the road level (foot) and about 5oo m from the past toe but toe is disturbed by human being for making another road and for cultivation land. The width of the main body was nearly 50 meters cracks (horizontal and vertical) on the top of the crown were visible by that time. The landslide is a shallow type of landslides. Unmanaged road cut, high precipitation, etc might be the main causes of landslide. The type of landslide seen was transitional slide where the mass of debris including mud clay with small chips of rocks was slided down the slope. Due to this landslide 2 people, 2 buffalo, 12 goats died in 2076.

2.2 REPEATED EPISODE OF LANDSLIDE WITHIN AREA

The area was not only affected by the landslide of 2076 B.S because the hazard flash second time as the major incident according to local residents. The first incident occurred around 2068 B.S. and was relatively smaller than the recent one. The consultations with villagers also revealed an important detail i.e., there used to flow a gully-type stream that originated near the 2076 landslide crest and flowed across the present village site. These evidences still exists today, as the same gully beneath the village continues to carry large volumes of water during the rainy season. In the past, the villagers reported that they diverted the natural gully channel to make space for settlement. After the recent disaster, the abandoned village now stands as a reminder that natural drainage patterns should never be disturbed.

2.3 CAUSES AND IMPACT

The main causes are mostly rough settlement, improper drainage system, short term vision on road construction. The landslide occurred twice and the recent one causing huge loss of two lives and loss of settlement.

2.4 MITIGATION MEASURES

For upcoming days certain things can be done like long term vision on development projects, disturbance on nature, making good drainage system, siren system to alert people and lastly awareness on people. Furthermore, remote casting and GIS techniques can be applied. The hydrological model using the Soil and Water Assessment Tool (SWAT) of the landslide affected area is the another options to mitigate landslide, the amount of precipitation within catchment area, surface runoff, percolation of precipitated water are needed to calculate, Pandey et al. (2021).

3. CONCLUSIONS

This study has following conclusions:

- The main lithology of the area comprises highly weathered phyllite and milky quartzite, which belong to the Kuncha Formation and are particularly prone to weakening under weathering and water infiltration.
- Landslides in the region are primarily triggered by a combination of factors, including improper road construction practices, steep slopes, heavy rainfall, and the establishment of settlements on unstable terrain.
- The Simalgaira Landslide caused significant loss, including two human lives, two large animals, twelve goats, and the destruction of six houses, roads, and other infrastructure, highlighting the vulnerability of the community.
- The repeated occurrence of landslides in this area indicates a high likelihood of future events. Consequently, the government should invest in detailed subsurface geological investigations to better understand the risks and implement effective mitigation measures.

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ISSN: 3021-937X (Print)

GROUNDWATER QUALITY ASSESSMENT OF DEEP TUBEWELLS OF CENTRAL REGION OF RUPANDEHI DISTRICT

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ABSTRACT

This study mainly emphasizes assessing the suitability of groundwater quality of deep tubewells for irrigation purposes in central region of Rupandehi district based on water quality parameters. A total of 11 water samples were analyzed from deep tubewells located in different locations of the study area. The water quality parameters, viz. sodium adsorption ratio (SAR), percent sodium (%Na), residual sodium carbonate (RSC), residual sodium bicarbonate (RSBC), Kelly's ratio (KR), magnesium adsorption ratio (MAR) and permeability index (PI) have been calculated for understanding water suitability for irrigation purposes. These irrigation parameters were correlated with standard permissible/desirable limits for the prevailing crops to irrigation use. Overall, SAR, % Na, RSC, RSBC, KR, MAR, and PI values of water samples indicate that they are suitable for irrigation. The result of this study may be helpful to the farmers and policy makers for groundwater resources planning and management.

Keywords: *Groundwater quality, Irrigation, Kelly's Ratio (KR), Permeability Index (PI), Sodium Adsorption Ratio (SAR), Deep tubewells*

1.INTRODUCTION

The suitability of water for irrigation is an important aspect of agricultural practices (Hasan et al., 2020). Contaminants in groundwater, such as heavy metals, high salinity, and excessive nutrients, have significantly deteriorated the quality of water used for agricultural purposes. This degradation has resulted into serious threats to crop health, leading to low productivity and poor crop yields posing a threat to food security (Mukherjee, 2021). Rapid population growth change in life style, industrialization, urbanizations can be the key factors in reducing water quality in the study area. The chemical alteration of infiltrated water depends on soil-water interaction, anthropogenic activities and dissolution of mineral (Plummer et al., 2003). As groundwater serves as a primary source for irrigation in many regions, its contamination disrupts the delicate balance of nutrients required for optimal plant growth (Hopkins et al. 2007). Consequently, farmers face challenges in maintaining soil health and achieving sustainable crop production.

Terai, the southern lowland plain, is highly productive land for cultivation because of the flat topography and fertile soil where most part of the study area situates. The main source and easily available source of water for all purposes is groundwater. Three governmental authorities are performing groundwater exploration and exploitation in the area. The Groundwater Irrigation Development Division and Bhairahawa Lumbini Groundwater Irrigation Project are distributing groundwater as an irrigation water.

This study attempted to assess the groundwater suitability of deep tubewells (depth more than 80m) for irrigation purposes considering various parameters in central region of Rupandehi district. This may be helpful in sustainable mitigation and management of groundwater resource of the study area.

2. OBJECTIVES

The major objectives of the study are:

a. To assess the groundwater quality of deep tubewells of Central Region of Rupandehi district.
b. To categorize the groundwater quality on the basis of different irrigation parameters.

3. STUDY AREA

The study lies in the Rupendehi District, south-western part of the Nepal. It is bounded by latitude 27^0 35' to 27^0 42' N and longitude 83^0 20' to 83^0 30'E. Most part of the area is relatively flat, and the elevation gradually increases towards the north. Location map is shown in Figure 1. It has sub-tropical climate characterized by hot summers and relatively cool and dry winters. Surface drainage is from north to south by means of rivers and streams.

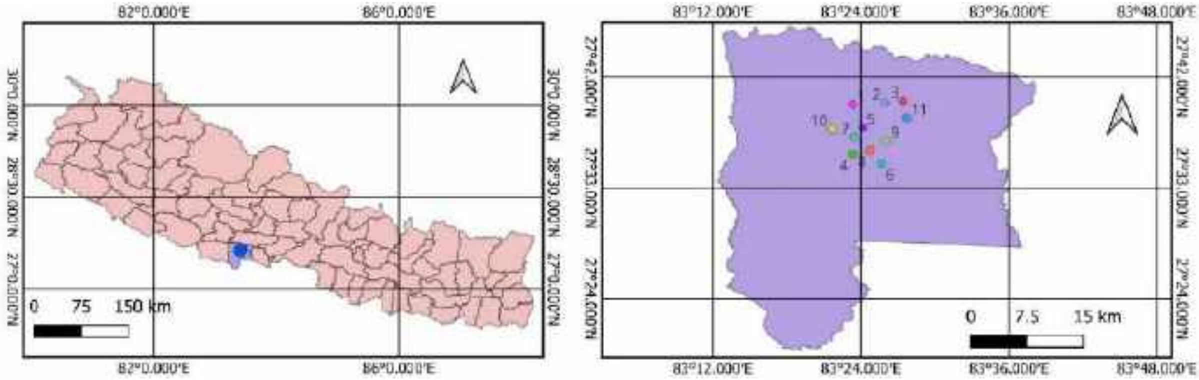

Figure 1: Study area with observation points

4. GEOLOGICAL AND HYDROGEOLOGICAL SETTING

Study area belongs to the Terai zone of Nepal. The Terai is the southernmost part of Nepal with flat topography which extends from Nepal-India border (south) to the Siwalik (north). The Terai Zone consists of alluvial deposits of Pleistocene age which is weathering product of rocks of the Siwalik and the Lesser Himalaya zones. Intercalation of coarse sediments is found throughout the study area. Thickness of sediments varies both in vertical and lateral directions. The proportion of the coarser sediments decreases from the north to the south (Pandey and Walraevens, 2019). Considering coarser sediments (sand, gravel and pebble) as an aquifer material, northern part of the study area has thick unconfined aquifer whereas, southern part has only semi-confined aquifer bounded by thick aquitard. Similarly, thickness of the aquifer decreases moving from the east to the west (Pandey and Walraevens, 2019).

5. METHODOLOGY

5.1 GROUNDWATER SAMPLING AND LAB WORK

The water quality data are obtained from Applied Geology and Hydrogeology laboratory, Ghent University, Belgium (Pandey and Walraevens, 2019). Major cations (Na^+, Ca^{2+}, Mg^{2+}, K^+, Fe^{2+}, Mn^{2+}, Al^{3+}, and NH_4^+), anions (Cl^-, SO_4^{2-}, NO_3^-, NO_2^-, HCO_3^-, CO_3^{2-}, PO_4^{3-}, and OH^-), and trace elements (F^- and Br^-) were measured. Na^+, Ca^{2+}, Mg^{2+}, K^+, Fe^{2+}, and Mn^{2+} were measured using Atomic Absorption Spectrometry (AAS). Cl^-, NO_3^-, NO_2-, PO_4^{2-}, and NH_4^+ were measured by spectrophotometry. HCO_3^- and SO_4^{2-} were measured after titration with HCl.

F^- and Br^- were measured with specific ion electrodes. In addition to the chemical properties of water, pH and EC were also measured using a pH electrode and an EC electrode, respectively.

5.2 HYDROGEOCHEMICAL INTERPRETATION METHOD

Piper diagram was plotted using the extension file of piper diagram using Microsoft Excel. The percentage of major cations and anions from each sample in (meq/l) was plotted in a separate triangular diagram. Then each point was transferred to the diamond shape diagram. The position of the point in this diagram gave the type of water. The water quality parameters, viz. sodium adsorption ratio (SAR), percent sodium (%Na), residual sodium carbonate (RSC), residual sodium bicarbonate (RSBC), Kelly's ratio (KR), magnesium adsorption ratio (MAR) and permeability index (PI) have been calculated for understanding water suitability for irrigation purposes. These irrigation parameters were correlated with standard permissible/desirable limits for the prevailing crops to irrigation use. Overall, SAR, %Na, RSC, RSBC, KR, MAR, and PI values of water samples indicate that they are suitable for irrigation.

Table 1: Irrigation water quality parameter indices

Parameters	Formulae	References
Sodium adsorption ratio (SAR)	$Na^+/ (\sqrt{(Ca^{2+}+Mg^{2+}/2)}$	Richard (1954)
Percent sodium (%Na)	$(Na^+ + K^+)/ (Ca^{2+}+Mg^{2+} + Na^+ + K^+) \times 100$	Wilcox (1948)
Residual sodium carbonate (RSC)	$(CO_3 + HCO_3) - (Ca^{2+} + Mg^{2+})$	Eaton (1950) and Richards (1954)
Residual Sodium Bicarbonate (RSBC)	HCO_3-Ca^{2+}	Gupta and Gupta (1987)
Kelly's ratio (KR)	$Na^+/ Ca^{2+}+ Mg^{2+}$	Kelly (1940)
Magnesium adsorption ratio (MAR)	$(Mg^{2+}/ Ca^{2+}+ Mg^{2+}) \times 100$	Paliwal (1972)
Permeability Index (PI)	$(Na + \sqrt{HCO3} / Ca + Mg + Na) \times 100$	Doneen (1964)

6. RESULTS AND DISCUSSIONS

From the piper diagram as in Figure 2, most of the samples are clustered towards the Ca corner, with a significant spread towards the Mg corner. This indicates that the dominant cations in these water samples are generally Calcium and Magnesium, suggesting a prevalence of alkaline earth metals over alkali metals.

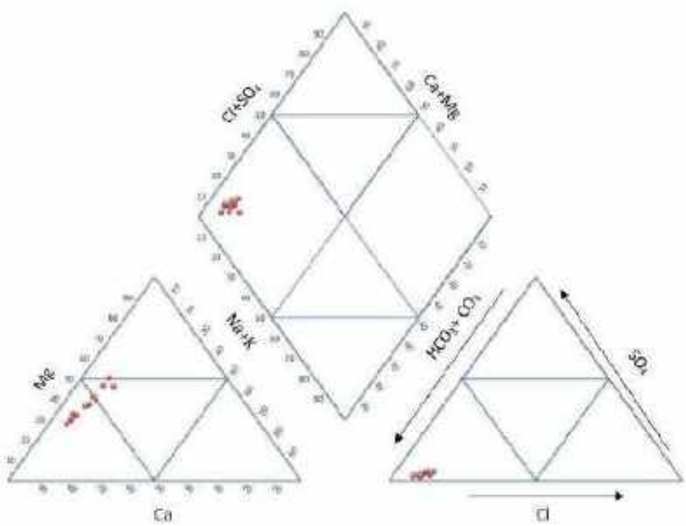

Figure 2: Piper diagram plot to know the water type, unit of ions plotted in this diagram is meq/l

In the lower right triangle (anions), plotting the relative percentages of Chloride (Cl), Sulfate samples are predominantly clustered towards the HCO_3+CO_3 corner. This indicates that bicarbonate and carbonate ions are the most dominant anions in these water samples, characteristic of fresh groundwater or water influenced by carbonate rock dissolution. There's a minor spread towards the Chloride corner.

This overall clustering suggests that the water samples are primarily Calcium-Magnesium Bicarbonate type water. This type of water is commonly found in areas with carbonate geological formations (like limestone or dolomite) where groundwater interacts with these rocks. Such water is typically fresh and often considered of good quality for various uses, including drinking and irrigation, though specific concentrations would need to be checked against standards. The tight clustering indicates a relatively uniform hydrochemical facies among the sampled locations.

Table 2: Calculated values of different parameters for irrigation water quality

Well No.	Location	SAR	%Na	RSC	RSBC	KR	MAR	PI
1	Semlar	0.207	9.92	-0.318	1.002	0.095	40.85	44.33
2	Motipur	0.187	8.43	-0.336	1.04	0.074	34.46	40.09
3	Shankhanagar	0.19	7.48	-0.673	0.791	0.069	31.33	39.04
4	S.Madanganj	0.238	10.33	-0.091	1.734	0.098	55.53	49.49
5	Pharsatikar	0.2	8.79	-0.352	1.047	0.083	39.42	42.1
6	Durganagar	0.19	9.31	-0.204	1.244	0.087	44.96	43.51
7	East Sitalpat	0.28	14.5	-0.516	1.319	0.117	52.91	52.54
8	W.Sakhuwani	0.178	10.27	-0.382	0.927	0.087	44.29	44.33
9	W.Pauni	0.214	10.45	-0.402	1.243	0.091	51.19	46.52
10	Puraini	0.158	6.44	-0.49	0.789	0.062	29.42	37.4
11	Driver toll	0.172	6.69	-0.734	0.853	0.061	34.61	38.36

The table 2 presents a comprehensive analysis of eleven different well locations, identified by "Well No." and "Location," across several water quality parameters. The parameters include Sodium Adsorption Ratio (SAR), Percentage Sodium (%Na), Residual Sodium Carbonate (RSC), Residual Sodium Bicarbonate (RSBC), Kelly's Ratio (KR), Magnesium Adsorption Ratio (MAR), and Permeability Index (PI).

In contrast, Well No. 10, Puraini, shows the lowest values for SAR (0.158), %Na (6.44), KR (0.062), MAR (29.42), and PI (37.4), indicating relatively better water quality with lower sodium and magnesium risks among these wells. The RSC and RSBC values, which are negative for all wells, suggest that carbonate and bicarbonate ions are not in excess compared to calcium and magnesium.

The table 3 classifies water samples based on various parameters into different quality classes, indicating the number of samples falling into each category. Across several parameters, all 11 samples consistently fall into the highest quality classifications.

Table 3: Classification of irrigation water quality based on different parameters (Modified after USDA, 1970)

Parameters	Water Class	Range	Number of samples
SAR	Excellent	< 10	11
	Good	10 to 18	Nil
	Fair	18 to 26	Nil
	Poor	> 26	Nil
%Na	Excellent	< 20 %	11
	Good	20 to 40%	Nil
	Permissible	40 to 60%	Nil
	Doubtful	60 to 80%	Nil
	Unsuitable	>80%	Nil
RSC	Good	< 1.25	11
	Doubtful	1.25 to 2.5	Nil
	Unsuitable	> 2.5	Nil
RSBC	Satisfactory	< 5	11
	Marginal	5 to 10	Nil
	Unsatisfactory	> 10	Nil
KR	Suitable	< 1	11
	Marginal	1 to 2	Nil
	Unsuitable	> 2	Nil
MAR	Suitable	< 50	8
	Unsuitable	> 50	3
PI	Suitable	> 75	Nil
	Good	25 to 75	11
	Unsuitable	< 25	Nil

For SAR (Sodium Adsorption Ratio) and %Na (Percentage Sodium), all 11 samples are categorized as "Excellent," with SAR values less than 10 and %Na less than 20%. This suggests a very low sodium hazard across all the analyzed water sources, making them highly suitable for irrigation without concerns about soil permeability or salinization caused by sodium. Similarly, for RSC (Residual Sodium Carbonate) and RSBC (Residual Sodium Bicarbonate), all 11 samples are classified as "Good" and "Satisfactory" respectively, indicating that the water does not pose an alkalinity hazard. KR (Kelly's Ratio) also shows all 11 samples in the "Suitable" class, with values less than 1. This implies a low risk of sodium-induced damage to soil structure. However, a divergence is observed for MAR (Magnesium Adsorption Ratio). For MAR, 8 samples are "Suitable" (MAR < 50), while 3 samples are "Unsuitable" (MAR > 50). This suggests that a subset of the water sources might have a magnesium-related issue, potentially affecting soil quality and crop yield. For PI, all the samples are classified as "Good" (PI between 25 and 75), This indicates that all the samples have good permeability characteristics.

In summary, while the water quality appears excellent to good for most parameters across all samples, MAR identifies a few samples that might be problematic, indicating that some well locations from the previous table might need careful consideration for long-term irrigation use.

ISSN: 3021-937X (Print)

Groundwater of the area is slightly acidic to basic. Calcium bicarbonate is dominant water type of the area. Most of samples are fresh, moderately hard calcium bicarbonate water type and are surplus in (Na^{+}+ K^{+}+ Mg^{2+}). The sources of these ions in the water are from dissolution of calcite, dolomite, feldspar, and pyrite. Quality of water in terms of inorganic constituents is good both for irrigation and drinking purposes.

7. ADDITIONAL

Table 4: Analytical lab result (modified after Pandey and Walraevens, 2019)

Units	1	2	3	4	5	6	7	8	9	10	11
pH	7.19	7.28	7.37	7.33	7.29	7.26	6.81	7.19	7.28	7.05	7.17
EC (µS/cm)	280	298	342	301	281	285	341	265	282	381	327
Na^{+} (meq/l)	0.306	0.296	0.324	0.324	0.294	0.28	0.408	0.262	0.294	0.262	0.281
K^{+} (meq/l)	0.029	0.034	0.028	0.025	0.026	0.024	0.114	0.071	0.032	0.027	0.026
Ca^{2+} (meq/l)	1.916	2.615	3.209	1.462	2.149	1.772	1.631	1.646	1.571	3.063	2.999
Mg^{2+} (meq/l)	1.32	1.376	1.464	1.825	1.399	1.448	1.835	1.309	1.645	1.279	1.587
Mn^{2+} (meq/l)	.0001	.0001	0	.0002	.0002	0	.0002	0	.0001	.0001	.0001
Cl^{-} (meq/l)	0.472	0.495	0.314	0.337	0.483	0.337	0.371	0.322	0.426	0.374	0.434
SO_4^{2-} (meq/l)	0.145	0.15	0.079	0.084	0.088	0.109	0.146	0.121	0.092	0.105	0.083
NO_3^{-} (meq/l)	0.098	0.047	0.226	0.077	0.046	0.099	0.22	0.13	0.116	0.084	0.209
NO_2^{-} (meq/l)	.0004	.0002	.0004	.0002	.0004	.0004	.0002	.0002	.0004	.0002	.0007
HCO_3^{-} (meq/l)	2.918	3.655	4	3.196	3.196	3.016	2.95	2.573	2.814	3.852	3.852
PO_4^{3-} (meq/l)	.0018	.0021	.0021	.0021	.0021	.0021	.0025	.0025	.0028	.0028	.0028
TDS (mg/l)	270.1	328.3	363.7	275.4	287.3	268.2	282.7	240.5	258.3	342.4	354.2
F^{-} (meq/l)	.0089	.0058	.0047	.0053	.0053	.0058	.0068	.0063	.0063	.0058	.0047
Br^{-} (meq/l)	.0013	.0011	.0019	.0011	.001	.001	.0028	.001	.0014	.001	.0021

8. CONCLUSIONS

The water quality parameters, viz. sodium adsorption ratio (SAR), percent sodium (%Na), residual sodium carbonate (RSC), residual sodium bicarbonate (RSBC), Kelly's ratio (KR), magnesium adsorption ratio (MAR) and permeability index (PI) have been calculated for understanding water suitability for irrigation purposes. These irrigation parameters were correlated with standard permissible/desirable limits for the prevailing crops to irrigation use. Overall, SAR, %Na, RSC, RSBC, KR, MAR, and PI values of water samples indicate that they are suitable for irrigation. The result of this study may be helpful to the farmers and policy makers for groundwater resources planning and management. Artificial recharge methods might be adopted to suitable crops or lower chemical concentrations in groundwater could be grown to maintain the existing water quality. Still, it is suggested that a regular monitoring of groundwater quality should be done. Moreover, the farmers should also be apprised about sustainable agricultural practices and the importance of maintaining clean groundwater resources that can help to enhance the agricultural productivity.

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ISSN: 3021-937X (Print)

GLACIAL LAKE OUTBURST FLOODS (GLOFS) IN THE MANASLU REGION

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ABSTRACT

The Manaslu region of Nepal, situated in the central Himalaya exposed the threat of glacial lake outburst floods (GLOFs) due to the rapid increase in temperature that melts the glaciers which results in forming large glacier lakes. Glacier lake outbursts flood (GLOFs) is among the most significant climate-induced hazards in the Himalayas. In the Manaslu region, rapid glacier retreats due to rising temperatures has resulted in the expansion of lake such as Prok Pokhari, Thulagi Lake, and Birendra Lake and so on, which have shown accelerated growth over the last three decades (Bajracharya, Mool, & Shrestha, 2007). When these glacier lakes break, sudden flood known as Glacier Lake outburst flood (GLOFs) occur that causes severe downstream damage to settlements, agricultural land, threating livelihoods, and infrastructure along the Budhi Gandaki and Marsyandi river basin. (ICIMOD, 2011). Recent studies have highlighted that Birendra Lake situated at Samagaun in Gorkha district, is among the most hazardous lakes due to rapid expansion and exposure to avalanches (Poudel, et al., 2025). Between 1990 and 2020, Birendra lake was expanded approximately from 0.23km^2 to 0.62km^2, that nearly tripling in area with its water volume exceeding 30 million m^3 (Khadka, 2025). Similarly, from the past studies and recent events on 21 April 2024, an ice debris avalanche into Birendra Lake which generate a displacement wave and downstream flooding in the Budhi Gandaki basin that rapidly convert a mountain lake into a destructive flood source (Majharjan, et al., 2024). This study also emphasize on how GLOFs form, what risks they bring to local communities and why monitoring and preparedness are important by using the preventive measures such as early warning systems and community awareness that helps in reduce the risk of GLOFs in the Manaslu region (Shrestha, 2024).

Keywords: *Glacial Lake Outburst Flood, Birendra Lake, Moraine-dammed Lake, Glacier retreat*

1. BACKGROUND

In the Manaslu region of Nepal, the occurrence of Glacial Lake Outburst Floods (GLOFs) has become a significant concern due to the retreat of glaciers and the formation of unstable moraine-dammed lakes (Poudel, et al., 2025). Birendra Lake, situated at an elevation of approximately 3,700 meters above the sea level in Gorkha District, which is one such lake that has been identified as a potential GLOF hazard (Chaulagain, 2025). The lake has been forming since before 1967, and overtime it has indicating an increase in volume. The primary dam of the lake comprises a terminal moraine, which is susceptible to failure due to factor such as increase glacier melt, seismic activity and avalanches. On April 2024, a massive ice avalanche from the Manaslu glaciers snout entered Birendra Lake, generating a surge wave displacing a substantial volume of water into the Budhi Gandaki River. This sudden release led to a rapid rise in the river's water level causing downstream flooding and the infrastructure damage and threating livelihoods and hydropower projects. (Majharjan, et al., 2024).

2. RESEARCH AIM

The aim of this article is to assess the potential risks of GLOFs in the Manaslu region and raise awareness about hazards posed by unstable glacial lakes.

3. OBJECTIVES

The objectives of this study are:

1. To identify and document the past GLOFs events and their socio-economic impacts.
2. To evaluate the current risk levels of potentially dangerous glacial lakes.
3. To suggest the community-based adaption and early-warning measures to mitigate hazards.
4. To assess the April 2024 Birendra lake outburst event and its downstream impacts.

4. RESEARCH QUESTIONS

The following research questions signify the study:

1. What were the primary causes and impacts of the April 2024 Birendra lake outburst event?
2. What strategies and policies can be recommended to mitigate the impact of future GLOFs on local populations and ecosystems?

5. MATERIALS AND METHODOLOGY

This article is based on secondary sources including published research paper, past flood events, journals with open-access database of ICIMOD.

6. RESULT

The Manaslu region in Nepal, notably home to Birendra Lake (Birendra Tal) situated at approximately 4,500 meters above the sea level has significant glacial lake outburst floods (GLOFs) in the recent years (Poudel, et al., 2025). On April 21, 2024, a massive ice avalanche from the Manaslu Glacier triggered a surge wave in Birendra Lake, leading to a sudden release of water into the Budhi Gandaki River, in Gorkha District. This event damaged over 35 households, multiple bridges, and trekking routes and forced temporary evacuation in Samagaun village (Majharjan, et al., 2024). The historical records document a GLOF in the Budhi Gandaki basin during the 1970s, which damaged agricultural land and disrupted local settlements (Reynolds, 2000). Similarly, Satellite analyses show that Birendra Lake expanded from approximately 0.23km^2 in 1990 to 0.62km^2 in 2020, with an estimated volume exceeding in 30 million m^3. This incident also reveal that the lake had previously experienced outbursts, indicating a recurring risk in the area. The research highlighted the region and the increasing frequency of such events due to climate change induced glacier retreat and instability. This study also finds the urgent need for comprehensive monitoring and mitigation strategies to safeguard downstream communities and infrastructure from future GLOFs (Khadka, 2025) .

Also, these studies using satellite imaginary, hydrodynamic modelling, and field observations revealed that the lake had been gradually expanding over decades, increasing the risk of sudden outbursts (Shrestha, 2024). The event highlighted the urgent need for continuous monitoring of glacial lakes, development of early warning systems, and implementation of community-based disaster preparedness strategies (ICIMOD, 2011). Furthermore, analyses of recurring avalanche hazards emphasize the climate change and glacier dynamics are likely to exacerbate such risks in the future, underscoring the importance of proactive mitigation measures (Chaulagain, 2025).

Figure 1: Birendra Lake (Birendra Tal)

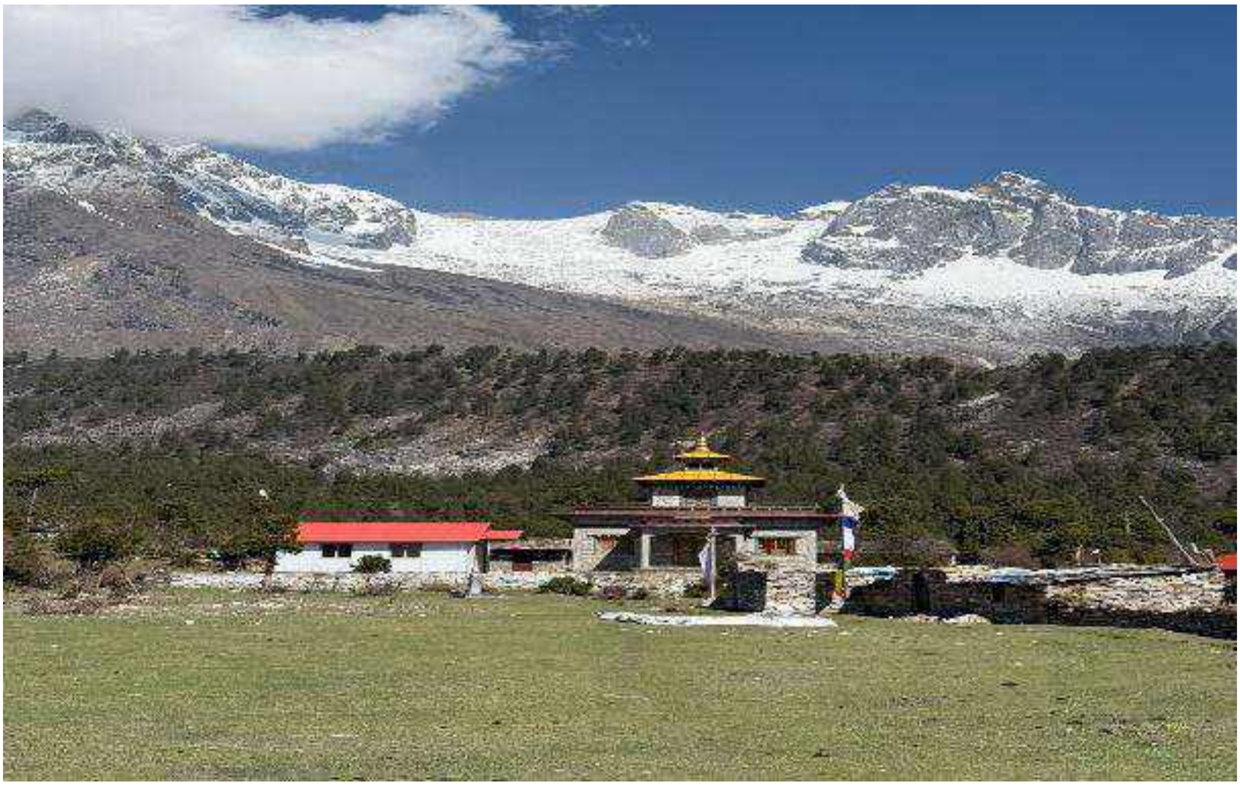

Figure 2 : Manaslu Peak seen from Samagaun village (Gorkha District)

7. DISCUSSION

The risk of a glacial lake outburst flood (GLOFs) in the Manaslu region has become a serious concern due to the rapid expansion of Birendra Lake, which is dammed by fragile moraine walls formed by retreating glaciers (Shrestha, 2024). Similarly, these studies indicates that if the moraine were to fail even partially, massive floods could rush down the Budhi Gandaki valley with peak discharges reaching several thousand cubic meters per second threating villages, agricultural land and local infrastructure (ICIMOD, 2011). Also, different bridges, farmland, trekking routes, house lands were affected due to the devastating outburst flood (Majharjan, et al., 2024). Different historical records and field surveys also confirm that past outburst event in the Central Himalayas have left widespread geomorphic scars with illustrating the destructive power of even medium scale GLOFs (Reynolds, 2000). Similarly, beyond the physical hazards, the socio-economic effects are equally concerning. Agriculture and trekking-two pillars of the local economy are highly vulnerable to trail destruction, crop loss, and reduced tourism following GLOFs (Chaulagain, 2025).

8. CONCLUSION

The Manaslu region faces a significant threat from glacier lake outburst floods (GLOFs), particularly from Birendra Lake where, rapid glacier retreat is enlarging lakes and weakening moraine dams (Bajracharya, Mool, & Shrestha, 2007). The study highlights the urgent need for continuous monitoring of potentially dangerous lakes such as Birendra and Thulagi lakes. Modelling shows that potential breaches could release floods of several thousand cubic meters per second destroying settlements, farmland and trekking infrastructure for the local economy. While, the past Himalayan GLOFs illustrate the lasting environmental and social consequences of such disaster like destruction of bridges, trekking trails, and agricultural land leaving long term scars on both landscapes and livelihood (Reynolds, 2000). By documenting lake expansion, assessing past outbursts, and evaluating vulnerabilities, this study shows that proactive measures are urgently required. Sustainable development and community safety in the Manasalu region cannot be achieved without systematic monitoring, investment in early-warning systems, and strong local disaster preparedness (ICIMOD, 2011).

9. ACKNOWLEDGEMENT

I would like to express my heartfelt thanks to the Department of Geology, Ghantaghar Kathmandu, for providing me the opportunity to be the part of the 'Geo-World Journal' and I would also thank my friends and editorial team for their valuable suggestion and unwavering support throughout the publication process.

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ISSN: 3021-937X (Print)

THE FLOOD AND CHALLENGES OF RASUWAGADHI, KERUNG BORDER

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ABSTRACT

This article concerns a glacial lake outburst flood (GLOF) that took place on 8 July 2025 from Puruogangri Glacier in Tibet, which particularly impacted Rasuwagadhi, one of the most significant customs checkpoints on the border of Nepal and China. The outburst flooding led to the destruction of crucial infrastructure such as the Nepal-China Friendship Bridge, highways, and four hydropower plants, resulting in a loss of almost 9% of the total electricity generation capacity of Nepal. Moreover, the disaster claimed the lives of at least nine individuals and left nineteen others missing. The paper investigates the available meteorological information, satellite imagery, and analysis of secondary disaster reports to understand the impacts and the primary reasons behind the phenomenon. The analysis indicated that the catastrophic event was not a result of high abnormal precipitation, but rather, was triggered by rapid glacial melting and the sudden growth of a supraglacial lake during the 2024-2025 period. Cross-sectional data from GLOF events in the Himalayas in Nepal, in India, and Peru demonstrates the recurring and cross-border characteristics of GLOF events in high mountain regions. The paper outlines the need for proper management of the effects of climate change as it concerns bolstering glacier hazards in addition to which, 'systematic monitoring', 'international collaboration', and 'framework risk mitigation' must not be overlooked.

Keywords: *Glacial Lake Outburst Flood (GLOF), Himalayan cryosphere, Climate change impacts, Hydropower vulnerability, Transboundary water governance, Disaster risk reduction, Remote sensing, High Mountain hazards*

1. BACKGROUND

Rasuwagadhi is known as a major Himalayan customs checkpoint located in Rasuwa district of Nepal. It lies along the Rasuwagadhi - Kerung road, which connects Kathmandu with Tibet directly. This road serves as an important trade route between Nepal and China. Local communities live in the hilly terrain at an elevation of about 2,800 to 3,000 meters, sustained by the Bhotekoshi River that gives life to the region.

As Nepal's second official border checkpoint with China, this location carries both economic and geopolitical importance (Figure I shows this border before the devasting flood). The Lhende and Kerung rivers of Tibet are the main sources shaping the Bhotekoshi Valley. Since these Himalayan rivers flow with great force, the risk is ever-present.

2. LITERATURE REVIEW

Glacial lake outburst floods (GLOFs) are a well-documented consequence of glacier retreat and shifting cryospheric dynamics, driven by increased meltwater and changes in permafrost and debris cover (Ives, Shrestha, & Mool, 2010). Foundational research established hazard contexts and risk assessment methods for the Himalayas (Khanal, Mool, Shrestha, & Bajracharya, 2015), while broader socioenvironmental studies show how glacier change intersects with local livelihoods and governance (Carey, 2010). Studies of permafrost thaw and landslides highlight cascading dynamics in which slope failures and rock–ice avalanches can either form new lakes or directly trigger catastrophic floods, as seen in the Chamoli disaster (Shugar, et al., 2021) (Huggel, Clague, & Korup, 2012). Remote sensing and satellite imagery are now central for monitoring lake development and mapping post-event impacts (GoogleEarth, 2025) (ICIMOD, International Centre for Integrated Mountain Development, 2020), yet inventories emphasize that many potentially dangerous features remain under-observed without systematic and frequent monitoring.

Figure 1: Kerung Border before flood, Source: *(RSS, Rastriya Samachar Samiti, 2023)*

The 2025 Rasuwagadhi flood underscores these gaps. Preliminary analyses attribute the event to supraglacial lake drainage and note rapid, transboundary impacts on infrastructure and communities (TheKathmanduPost, 2025). Despite the involvement of national agencies and forecasting institutions, the disaster highlighted challenges of short warning times, limited cross-border data sharing, and roadside cargo staging that exacerbated exposure. Taken together, the literature points to four urgent priorities: expand monitoring of debris-covered glaciers and supraglacial ponds, integrate remote sensing with real-time forecasting and community alert systems, apply established GLOF risk assessment frameworks to supraglacial and cascading triggers, and strengthen investment in prevention and resilient infrastructure design (Ives, Shrestha, & Mool, 2010) (Khanal, Mool, Shrestha, & Bajracharya, 2015) (ICIMOD, Preliminary analysis of the Rasuwagadhi flood: Evidence of supraglacial lake drainage, 2025).

3. OBJECTIVES

This report is prepared with the intention of meeting a number of major goals, outlined below:

1. To discuss the causes and effects of the July 8, 2025 Rasuwagadhi flood.
2. To discuss the impact of climate change and review the event in relation to other GLOFs in Nepal and elsewhere.

3. To advise essential steps to reduce disaster risk through tracking, preparation, and collaboration.

4. RESEARCH GAP AND PROBLEM STATEMENT

The lack of preparedness towards GLOFS while considering it one of the most dangerous climatic threats in the Himalayas is shocking. The Rasuwagadhi flood is an excellent example that shows the extent to which rapidly draining supraglacial ponds can destroy bridges, hydropower plants and trade routes in a matter of hours. Very few infrastructures in Nepal have GLOF risks incorporated in their planning.

Many lakes that are located in Tibet and floods that occur in Nepal downwards are a result of the lack of coordinated relations between Nepal and China. This impacts the flood preparedness as the warning and response mechanisms are not coordinated. The other issue is that while supraglacial ponds are dangerous, monitoring still only focuses on larger moraine-dammed lakes.

The lack of understanding of the economic and environmental costs associated with GLOF is alarming. The potential losses are higher than the cost that needs to be incurred for the preventive measures. However, the comparison is absent which leads the government to not spend money for the long-term plan. There is a strong need of research in cross-border electronic real time monitoring, resilient infrastructure, shared border data, and low-cost strategies on risk reduction.

5. MATERIALS AND METHODS

All the information and data applied in the current paper were collected through secondary sources, and these are peer-reviewed journal publications, reports, and news articles regarding Glacial Lake Outburst Floods (GLOFs) in the Himalayas and concentrating chiefly on the Rasuwagadhi - Bhotekoshi section. Information on flood events, lake and river behavior and observation networks and mitigation actions were abstracted, collated and enriched by information gathered through consultations with colleagues and experts.

6. CASE STUDY

6.1 THE FLOOD OF JULY 8, 2025

Around 3:15 a.m. on July 8, 2025, a sudden and massive flood struck on the Bhotekoshi River. The flood destroyed the Nepal - China Friendship Bridge, swept away customs infrastructure, damaged roads, and caused severe losses to hydropower projects. Hundreds of trucks, electric vehicles, and heavy machinery were reported to have been carried away by the river. Storage warehouses were destroyed, and commercial activities came to a halt (Figure 2 illustrates the Kerung border after the flood).

This year's monsoon caused major damage along the Galchi - Trishuli - Rasuwagadhi highway. Continuous rainfall triggered landslides, damaging over one kilometer of the highway. Local bridges and slopes along this trade route, which connects Nepal with Tibet, also collapsed. As a result, trade activities between the two countries, as well as local movement, were disrupted. The damage not only halted commerce but also severed contact with the border area.

In terms of human loss, at least nine Nepalis were killed and nineteen went missing, including some Chinese nationals (Nepal Disaster Risk Reduction Authority, 2025).

Figure 2: Kerung Border after flood, Source: (RSS, Rastriya Samachar Samiti, 2025)

The initial rescue managed to bring more than fifty people to safety. Four major hydropower projects were affected: Rasuwagadhi (111 MW), Trishuli - 3A (60 MW), Trishuli (21 MW), and Mailung (15 MW). This resulted in a loss of about 8 - 9% of the national power generation capacity (Nepal Electricity Authority, 2025). The Prime Minister was compelled to declare a state of emergency.

6.2 CAUSE OF THE FLOOD

The flood was not related to rainfall. Satellite images and meteorological data confirmed that there had been no unusual precipitation (NOAA, 2025); (ECMWF, 2025). However, the water level in the upper Bhotekoshi region suddenly rose by 3 - 4 meters, which is typically a sign of a glacial lake outburst. Research indicates that the flood (GLOF - Glacial Lake Outburst Flood) was triggered by the bursting of a supraglacial lake formed in the Puruogangri Glacier in Tibet. Due to abnormal temperatures, the lake had expanded rapidly in 2024 - 25 and eventually burst on July 8 (ICIMOD, Preliminary analysis of the Rasuwagadhi flood: Evidence of supraglacial lake drainage, 2025).

7. DISCUSSIONS

The following discussion explores historical incidents, the danger today, and key mitigation strategies for Glacial Lake Outburst Floods (GLOFs) in the Himalayas and sheds light on key lessons in monitoring, infrastructure, community preparation, and trans-frontier cooperation.

7.1 HISTORY AND COMPARISON

In Nepal, the Dig Tsho glacial lake outburst in 1985 swept away hydropower projects and hundreds of homes (Ives, Shrestha, & Mool, 2010). In 2021, a flash flood in Chamoli, India, claimed more than 200 lives (Shugar, et al., 2021). Similarly, in Peru, a glacial lake outburst in 1941 caused thousands of deaths (Carey, 2010). These examples show that such risks are not limited to the Himalayas but are shared across other mountain regions as well.

7.2 CLIMATE CHANGE AND RISK

Research has shown that the average temperature in the Himalayas is rising at twice the global rate. This has caused glaciers to melt rapidly, forming new lakes. According to ICIMOD, there are currently about 5,000 glacial lakes in Nepal, which is 14% more than in 1990 (ICIMOD, International Centre for Integrated Mountain Development, 2020). This trend is increasing the risk of floods in the coming years.

7.3 LESSONS AND PREPAREDNESS: MANAGING GLACIAL LAKE RISKS

The flood in the Rasuwagadhi region has highlighted the emerging climate risks in the Himalayas and the challenges of managing them. The key lessons observed from this event are as follows:

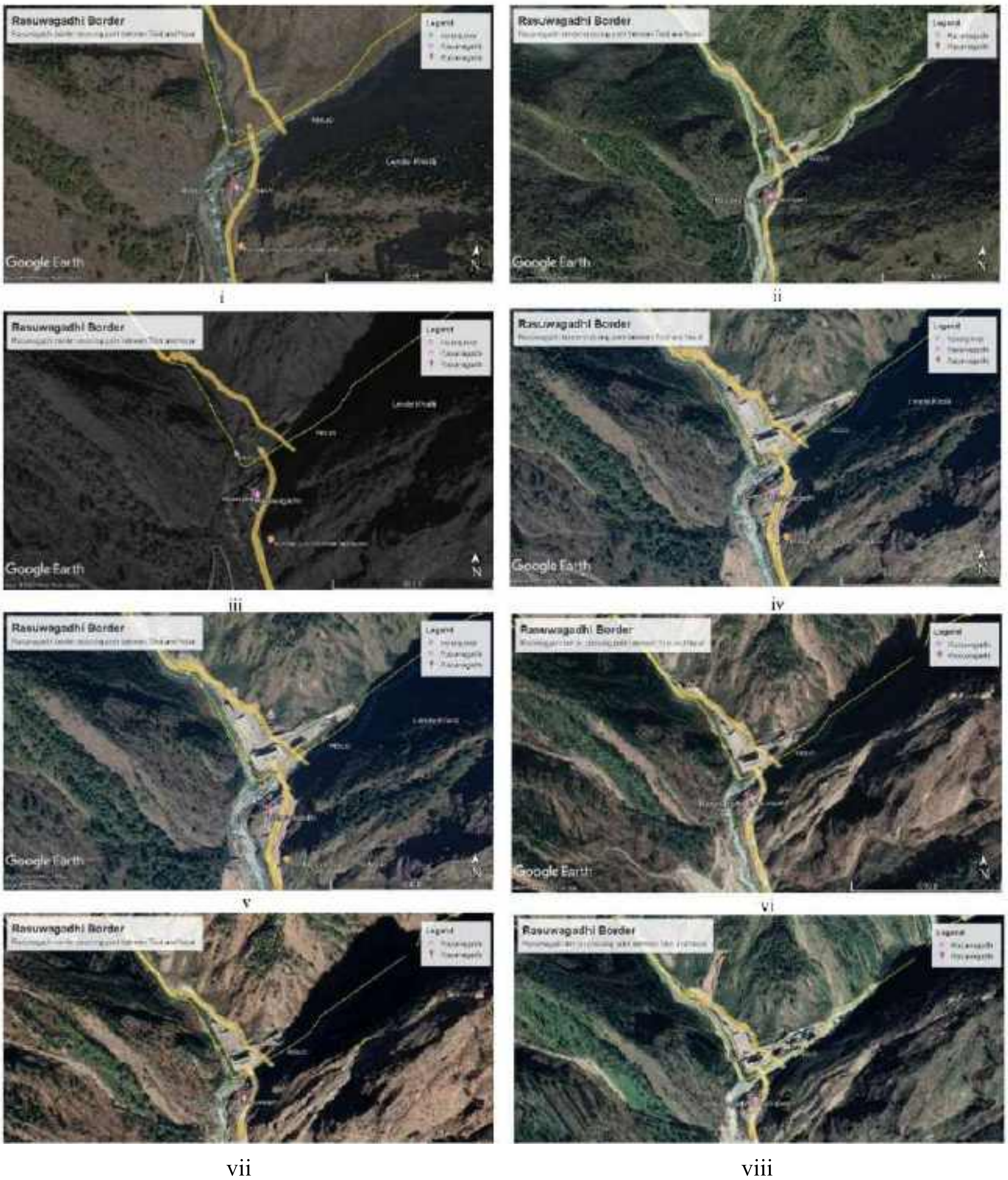

Figure 3: Satellite images of Kerung border area from 2005 to 2021. i.e. (i) 2005, (ii) 2011, (iii) 2012, (iv) 2014, (v) 2015, (vi) 2017, (vii) 2020, (viii) 2021 Source: *(GoogleEarth, 2025)*

7.4 MONITORING AND EARLY WARNING SYSTEMS

Glacier lakes are constantly dynamic. Melting snows, warmer temperatures, and unstable geology equate to fast shifts in pressure and in levels. Continuous monitoring through satellite imagery, aerial photography, and ground-based sensors is therefore essential. If this data is collected in real time and linked to local warning systems, communities at risk can be alerted on time, helping reduce both human and material losses.

7.5 LAKE MANAGEMENT

The prevention of sudden glacier lake outburst floods (GLOFs) is by carrying out controlled release of the water. This is achieved by the use of artificial channels, intake piping systems, or siphoning systems. Such management helps balance water pressure within the lake and reduces the risk of sudden outflows.

7.6 INFRASTRUCTURE STRENGTHENING

Mountain sites are vulnerable to risk in road and bridge ventures and hydropower. To make these structures sustainable in the long term, additional safety standards must be incorporated into their design. For example, bridges should be built to withstand maximum possible flood levels, road drainage systems should be improved, and hydropower plants should include emergency spillways.

7.7 COMMUNITY PREPAREDNESS

Technical systems alone are not enough; active community participation is crucial in risk management. Local residents must be equipped with emergency response plans, safe site identification, and regular rescue drills. Training schools, women's groups, and local organizations can make disaster response systems faster and more effective.

7.8 CROSS-BORDER COOPERATION

Glacial lakes and their risks are not confined to a single country's boundaries. For Himalayan nations like Nepal and China, data sharing, joint monitoring systems, and rapid exchange of emergency information can take risk management to a new level. Such cooperation strengthens scientific research while also creating an environment for immediate assistance during emergencies.

8. CONCLUSION

The Rasuwagadhi flood from July, 8, 2025 was a result of the sudden bursting of a supraglacial lake which was formed over the Puruogangri Ice Field of Tibet. It diminished the output of the hydropower plants by flattening the Nepal-China Friendship Bridge which connects the two nations along with the highways. Furthermore, the flood also caused the death of numerous people along with disrupting trade and daily routines which showcase the severity of glitches which result from glacial hazards. The report validated the hypothesis which said the flood was a consequence of abnormal rainfall while in truth, it was a result of climate change accelerated climbing glacier melting. Within Nepal, India, and Peru the series of events demonstrates that mountainous regions around the world have become repeating the phenomenon of glacial lake bursting floods. The Rasuwagadhi GLOF exemplifies how climate change contributes to the expanding glacial lakes in the Himalayans and the increasing threats to the surrounding people and the structures.

There should be community drills to strengthen the proactive withstanding climate change assistance as a country. More so, a trilateral agreement should be reached to allow Hotak, China, and Nepal, to provide instantaneous data for monitoring and response over shared glacial hazards. Systematic monitoring and obstruction should be upheld so that relationships can be fostered while reducing risk. Moving forward, this study suggests that without preparedness measures for GLOF occurrences and cross-border partnerships, GLOF activity will continue to pose risks to life, infrastructure and the economy of the area.

9. ACKNOWLEDGEMENT

I thank the Geology Department of Tri-Chandra Multiple Campus for providing an space to write an article on a topic of own choice to be published on the Geoworld Student's Journal. I appreciate for providing online database, articles and reports to the International Centre for Integrated Mountain Development (ICIMOD), the National Oceanic and Atmospheric Administration (NOAA), the European Centre for Medium-Range Weather Forecasts (ECMWF), the National Disaster Risk Reduction Authority of Nepal (NDRRA), and the Nepal Electricity Authority (NEA).

I thank the researchers and scholars whose initial contributions to climate science and glaciology have richly enriched this analysis. Finally, I honor the courage of the Rasuwagadhi and responder communities whose experiences in the disaster render this study so relevant. This study is a testament to the essential contribution of academic investigation to the resolution of real-world environmental challenges.

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ISSN: 3021-937X (Print)

IMPACT OF MULTI-GEOHAZARDS IN SINDHUPALCHOK DISTRICT

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ABSTRACT

This article focuses on the impacts of multiple geohazards such as landslide, floods and earthquake that have occurred in the Sindhupachok district. Geohazards are referred as geological hazards. They are naturally occurring geological processes or states that threaten people, assets, or the environment. Sindhupalchok district of Nepal is greatly susceptible to geohazards that significantly impact its people, environmental status, economy, psychological trauma, property, infrastructure and its services. The hazard is often ignited by steep topography, fragile geology, and increasing weather variability in the district. The district has faced major catastrophic events such as 2014 Jure Landslide, 2015 Gorkha Earthquake and 2021 Melamchi flood which resulted in significant loss of lives, environmental impact and economic loss.

Keywords: *Geohazards, Sindhupalchok, Gorkha earthquake*

1. INTRODUCTION

Nepal, which is located in the central part of one of the youngest and most active mountain ranges – the Himalaya – is formed by the ongoing convergence of two active tectonic plates. It is a country prone to various natural hazards such as landslides, avalanches, debris flow, flash floods, glacial lake outburst floods, earthquakes and thunderstorms because of its fragile and complex geological setting, physical diversity and climatic variation (ICIMOD, 2021).The susceptibility of Nepal to disasters from the active tectonics of the region, fragile geology, rugged terrain, and unreliable weather induces severe loss in terms of human and property damage every year and affects the overall economic of the nation. Nepal experiences a higher incidence of natural disasters, such as landslides, relative to its territorial area and population density (Petley et al., 2007). These hazards, particularly landslides, are particularly prominent during the monsoon season and major earthquake events.

The area of study, Sindhupalchok district is located in the Bagmati province of Central Nepal, north-east of Kathmandu city. The study area geographically lies between 27º42' to 28°11' N latitude and 85°27' to 86°06' E longitude. Sindhupalchok district is bordered to the north by Tibet, east by Dolakha and Ramechhap districts, south by Kavrepalanchok and Kathmandu district, and west by Nuwakot and Rasuwa districts. The study area covers an area about 2542 km^2 of the total area of Nepal.

Topographically, the Sindhupalchok district contains a very diverse landscape, from low river valleys to lofty Himalayan summits. Its altitude changes radically from approximately 700 meters in the south to more than 6,500 meters in the north. Steep slopes, deep V-shaped valleys, and high ridges make up the terrain in the area.

Due to its geology of metamorphic rocks, the region is prone to landslides during the monsoon season. It contains some big rivers like the Bhote Koshi, Sunkoshi, and Melamchi that flow through the district, forming deep gorges. The Jugal Himal mountain range with snow-covered peaks is located in the north, and parts of Langtang National Park are included within. The district also contains natural attractions like the Panchpokhari lakes and Tatopani hot springs.

The climate of Sindhupalchok is as varied as its topography, with six zones based on altitude, from tropical to nival. The district experiences four main seasons. Spring is a suitable time for trekking because the weather is warm. Summer brings the monsoon with intense rain and potential landslides. Autumn is the ideal time to travel with clear weather and favorable conditions. Winters are cold, with snow at higher elevations and excellent mountain views.

2. OBJECTIVE

The objective of the article is to understand the socio-economic and environmental consequences of recurrent geohazards such as landslides, floods and earthquakes, in the district of Sindhupalchok, Nepal.

3. RESEARCH QUESTIONS

The following research questions signify the study:

1. What influences the most to drive geological hazards like landslides, floods and earthquake in Sindhupalchok district?
2. What are the impacts of Geohazards in Sindhupalchok district?

4. METHODOLODY AND MATERIALS

The research solely depends on the secondary sources like reports, journals, articles, and website to obtain the data and detailed research on the books pertaining to research areas. Remote sensing and satellite images are used in this article to understand the impact of geohazards from the past to present days.

5. GENERAL GEOLOGY OF SINDHUPALCHOK DISTRICT

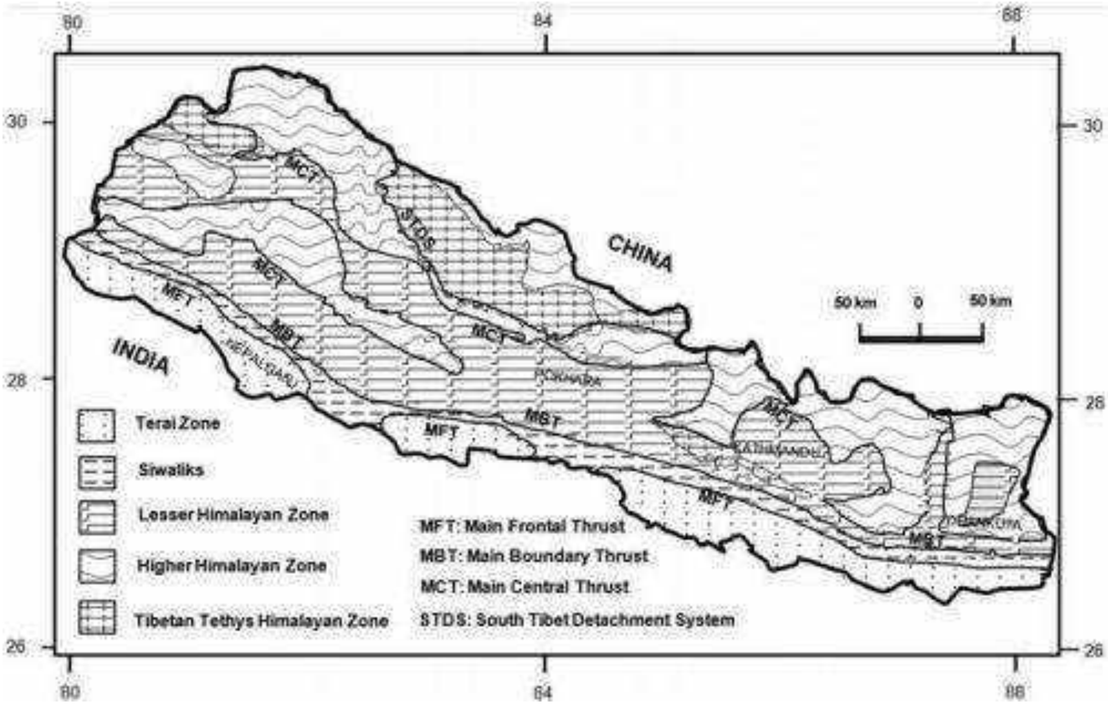

Figure 3: Generalized geological map of Nepal (adapted from Dhakal 2014)

The Sindhupalchok District lies in the central Himalayan arc, a region defined by intense, ongoing tectonic collision between the Indian and Eurasian plates. Its geological structure is highly complex, characterized by steep topography, deep river valleys, and deeply fractured rock formations, making it exceptionally vulnerable to seismic and hydro-meteorological hazards.

Many geological studies have been carried out in the Sindhupalchok district. Sindhupalchok district is divided into two parts by Main central thrust, they are southern and northern part. The southern part of Sindhupalchok district is composed of Phyllite, schist (mica-rich), quartzite, limestone, and granite gneiss which are highly weathered, fractured and weak. The complex geology and geomorphology make them highly susceptible to failure during earthquakes and heavy rainfall, resulting in the massive debris flows observed during the monsoon seasons (Yin et al., 2020). The northern part is near to the China border and mainly composed of high-grade metamorphic rocks, primarily garnet-mica gneiss, kyanite-sillimanite gneiss, and migmatite with steep slope. The ongoing natural process of glacial lake outburst in the northern part leads to the large rockfalls and catastrophic flash flood in the southern part of the district.

5.1 MAJOR GEOLOGICAL ZONES

The district's terrain can be broadly categorized into two major lithotectonic units: (Godard et al., 2017; Yin et al., 2020):

Geological Zone	Location (Elevation)	Dominant Rock Types	Stability and Characteristics
Lesser Himalayan Sequence (LHS)	Southern and Central areas	Phyllite, schist (mica-rich), quartzite, limestone, and granite gneiss.	Highly weathered, fractured, and intensely folded. Extremely prone to shallow and deep-seated landslides due to the abundance of weak schists and phyllites.
Higher Himalayan Crystalline (HHC)	Northern areas (near the Tibetan border)	High-grade metamorphic rocks, primarily garnet-mica gneiss, kyanite-sillimanite gneiss, and migmatite.	Generally, more resistant crystalline rocks, but the steep slopes and glacial erosion still lead to large rockfalls and deep-seated mass movements.

6. GEOMORPHOLOGICAL FEATURES

The high geological instability is amplified by the rugged topography and drainage patterns: (Martha et al., 2021):

- **Steep Slopes**: The average slope angle is very high, accelerating gravitational processes like erosion, rockfall, and landslide propagation.
- **Deep River Incision**: Major rivers like the Bhote Koshi, Melamchi, and Indrawati have rapidly incised into the unstable terrain, leading to lateral erosion and the formation of steep valley walls which become unstable when saturated.
- **Alluvial and Colluvial Deposits**: Valley bottoms and lower slopes are often covered by thick, loose deposits (colluvium from previous landslides, and alluvium from river deposition). These unconsolidated materials are easily mobilized by flash floods and debris flows, representing a major risk to settlements located in the valleys (Martha et al., 2021)

ISSN: 3021-937X (Print)

7. RESULTS

7.1 LANDSLIDE

A landslide is defined as the movement of a mass of rock, debris, or earth down a slope. Landslides are a type of "mass wasting," which denotes any down-slope movement of soil and rock under the direct influence of gravity (USGS). There are various controlling factors of Landslide which includes slope, aspect, elevation, curvature, distance from road, distance from fault, NDVI, Precipitation, lithology and geological structures. Similarly, Saturation significantly affects slope stability, particularly in landslide-prone areas like Jure Slope in Nepal (Dahal, 2012).

Figure 2: Ramche village before jure landslide (2013)

Figure 3: 2014 jure landslide

Figure 4: Jure landslide showing Phyllite exposed rock

Figure 5: Jure (2021) from google earth image

On the night of 2nd August 2014 (02:30 AM), a huge landslide, famously known as "Jure Slide", took place along Sunkoshi River valley on Araniko Highway that connects Kathmandu with Tibet. The landslide killed 156 people who were on sleep in their houses, savaged 120 houses, partially damaged 37 more, dammed Sunkoshi River creating an artificial dam of approximately 50 m high and an approximately 3 km long reservoir was formed. (panthi, 2021). During the whole month of August, the authorities and the army managed to drain the lake in order to avoid a potential dam collapse and a disaster by flooding downstream. In addition, a road was built very quickly in the opposite slope of the rockslide. The main road was reopened in November 2014 crossing the rock avalanche deposit to reach China border. Rocky steep slope on right bank of lake is used for earthen road construction. After the quick draining of the lake water on October 5, 2014, many landslides were induced or reactivated on the slopes along the lake shore (Jaboyedoff, et al., 2015). The dam drained slowly and slowly in mean time but after two months, the dam burst and flood was occurred in the downstream area impacting the Khadichaur bazar. The jure landslide is the deadliest event in the history of Sindhupalchok district which causes damaging of various infrastructure, enterprises, Araniko highway, habitat loss and human life loss.

7.2 EARTHQUAKE

An earthquake is a ground shaking that takes place swiftly when the Earth's crust releases a burst quantity of energy. The energy propels in the form of seismic waves and makes the ground oscillate. Most earthquakes are a result of tectonic plate movement. The Earth's crust is composed of huge pieces that are moving gradually, called tectonic plates. Earthquakes happen when plates are in contact at their boundaries in a different way such as convergent plates and divergent plates.

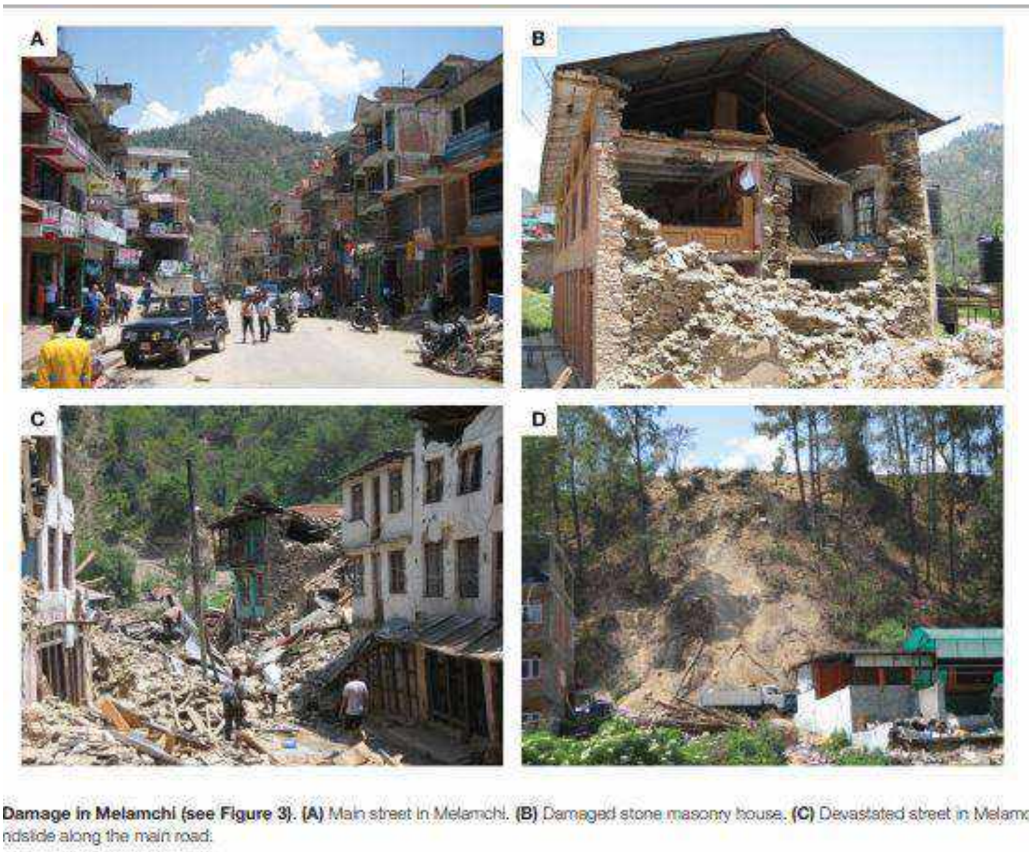

Figure 6: After 2015 Gorkha Earthquake (source from online media)

Although these plates are constantly in motion, they sometimes get caught at their borders due to friction. As the plates keep on moving, a pressure build-up takes place. When the pressure is great, the plates jerk suddenly and a huge quantity of energy gets released that we feel as an earthquake.

2015 Gorkha Nepal earthquake inflicted extensive damage and loss in entire Nepal but specifically the Sindhupalchok district was the worst affected district due to earthquake in 2015. 3075 individuals in total died and 1230 of them were children and 1450 were injured (Goda, et al., 2015). Apart from loss of life and damage in property, the disaster affected the ecological wellbeing, geology and the biodiversity for the region besides affecting the wildlife and the fresh water resource in the region (Goda, et al., 2015).The ground shaking from the earthquake undermined soil and rock on slopes around the district. This made landslides happen more and more, and that in turn made the region more at risk for subsequent floods.

7.3 FLOOD

A flood refers to a condition where the water overflows and inundates normally dry ground. It is the most widespread and common type of natural disaster globally. Floods can occur at various scales and via various routes such as river flood, flash floods, coastal floods, ponding and urban floods. There are various causes such as Climate change, Damming of River, heavy rainfall. deforestation and urbanization.

Figure 7: Before Melamchi flood (google earth image-2020)

Figure 8: After Melamchi Flood (google earth image-2023)

Many floods occured every year in Sindhupalchok districts but among them Melamchi flood is one of the popular and well-known disaster of Sindhupalchok district. It has completely ruined 259 businesses in the Melamchi municipality, including a hydroelectric plant and trout hatcheries (according to a presentation by the Municipality on 2 July 2021). It has also damaged largely market centers like Chanaute bazaar and Melamchi Bazaar, the effect of which remains to be analyzed. Above all, the flood has converted productive 'khet' (cultivated plots of lands) to riverbanks. The Melamchi Municipality alone lost around 3500 Ropani (one Ropani is equivalent in size to 508.74 m^2) of khet lands, which constituted lifelines for the livelihood of the crop-based farmers. The effect of the flood damage in the Melamchi Drinking Water Project will reach as far away as Kathmandu. This project had only recently begun providing water to households in Kathmandu after a prolonged delay. But now due to extensive damage in its intake locations, the water supply can once more be halted for a prolonged span of time. In general, the upstream communities were comparatively far more vulnerable than the downstream communities. (ICIMOD, 2021) Melamchi flood affects a huge area including Chanaute bazar and Melamchi bazar. Residential houses, buildings, highways, bridges, and essential infrastructure like electricity and drinking water systems was completely destroyed.

7.4 GLACIAL LAKE OUTBRUST FLOOD

Sindhupalchok is highly vulnerable to GLOFs and related flash-floods because of its steep Himalayan catchments, cross-border glacial lakes from Tibet to Nepal, and many communities and hydropower projects in narrow river valleys (Sharma, G. 2025). Due to the high altitude and steep slope mountains, there is a high risk of catastrophic floods in downstream side of Sindhupachok district. In the Bhote Koshi/Sun Koshi basin, 139 glacial lakes and nine lakes have been identified as potentially dangerous shown in Figure 9 (ICIMOD 2011). Time series analysis shows that the number, area, and ice reserves of glaciers in this basin are declining, but that the number of glacial lakes and their area are increasing (Mool et al. 2005).

The Bhote Koshi is a transboundary river originating on the southern slopes of the Himalayas in the Tibet Autonomous Region of China. This river is called the Poiqu (Boqu) in Tibet, the Bhote Koshi in Nepal from the Nepal-China border (Friendship Bridge) down to the confluence with the Sun Koshi at Barhabise, and the Sun Koshi downstream from this confluence. Twenty-four GLOF events have been reported in Nepal, ten of which occurred in the Tibetan catchments of rivers flowing into Nepal (ICIMOD 2011). The Bhote Koshi/Sun Koshi River experienced three such GLOF events: in 1935, 1964, and 1981(ICIMOD 2011). GLOFs have caused fatalities, major infrastructure loss (roads, bridges, hydropower), widespread economic damage, and triggered secondary hazards like landslides and debris flows (Sharma, G. 2025).

Figure 4 Major glacial lakes and potentially dangerous lakes in the Bhote Koshi/Sun Koshi basin (adapted from ICIMOD 2011)

8. DISCUSSIONS

The study reveals that the geology and geomorphology are the most significant factors influencing geohazards. The hilly mountainous region has infrastructures that are ill-equipped for that level of disaster complexity. As a result, preparedness before the disaster is a common-sense approach. Now, we ought to seriously deliberate on the catastrophe mechanism procedure of cascading hazards within the region and invest the right resources not only to learn more about such events but be better equipped to deal with them in an effort to prevent unnecessary loss of human lives and resources comprising early warning systems, relocation of high-risk settlements, and use of geologically vulnerable land-use planning for constructing disaster-resilient communities.

The findings demand for a significant and proper strategies to be applied in disaster risk reduction for Sindhupalchok district.

8.1 POLICY AND PLANNING

Current planning is based on historical records or single-hazard events and is not reflective of the dynamic, cascading nature of risk in the post-earthquake environment. Policy must demand

ISSN: 3021-937X (Print)

that dynamic multi-hazard maps be produced that overlay geological instability with future climate forecasts. Policy must focus funding initiatives on purchasing and preparing Safe Land Banks that are within government ownership. The Safe Land Banks would be utilized for rapid and systematic resettlement of households that are already occupying high-risk locations today, resolving the "households in limbo" issue. Additionally, resettlement packages would need to be accompanied by livelihood support to be economically viable in the new site with a view to promoting durable solutions rather than temporary solutions.

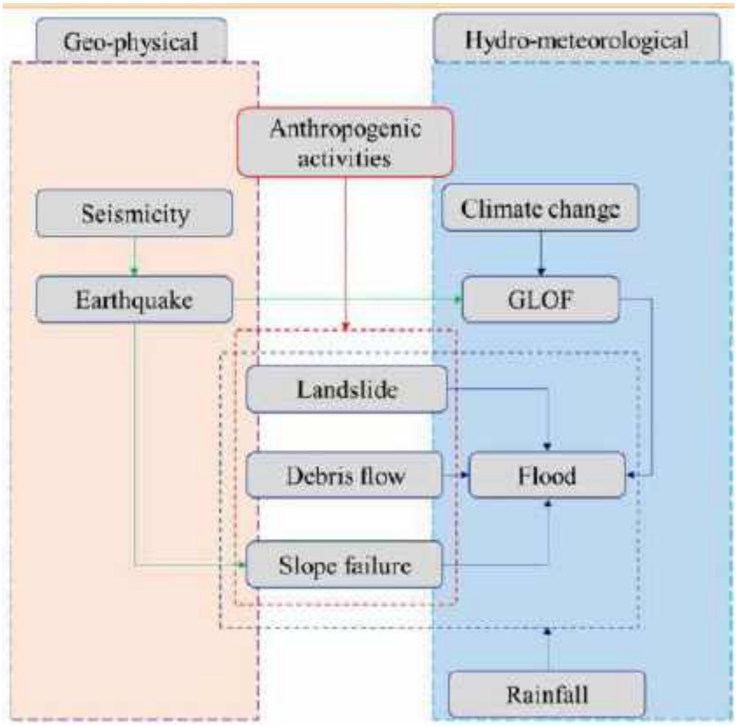

Figure 5: Cause and consequences matrix of geohazards (Lamichhane et al., 2021).

8.2 COMMUNITY-BASED RESILIENCE

The research recommends that implementation of affordable community-based approaches like local early warning systems as well as slope stabilization methods be ensured for short-term safety.

8.3 INSTITUTIONAL ALIGNMENT AND COORDINATION

It is essential that a multi-hazard area be serviced by a special Multi-Sectoral Coordination Body that integrates geological, hydrological, urban planning, as well as socio-economic expertise. The body can be mandated to simplify the bureaucratic procedures, enforce adherence to new zoning regulations, as well as insist on local government units' adherence to the timely practice of risk reduction and resettlement policies.

8.4 CONSTRAINTS AND FUTURE STUDIES

The present research provides a snapshot of disaster impacts. Future research must focus on devising dynamic indexes of vulnerability that include physical (geological instability) as well as socio-economic (education disruption, poverty) parameters. Further research is required on validation of long-term performance of existing reconstruction models along with robustness against future unavoidable cascades of geohazards prompted owing to climate change as well as seismicity.

Table 1: Impact of Geohazards in sindhupalchok district (sources from internet)

Year	Geohazards	Impacts
1982	Balefi Lansdslide	97 people died, 15 houses destroyed
1987	Sunkoshi Flash-flood	98 people died
1996	Larcha Landslide	54 people died, 18 houses destroyed
2014	Jure Landslide	156 people died, 36 people displaced
2015	Gorkha Earthquake	3075people died, 1450 injured
2016	Bhotekoshi Flood	No lives loss but infrastructures damaged
2020	Nagpuje Landslide	14 people died, 62 displaced
2021	Melamchi Flood	5 people died, 20 people missing

9. CONCLUSION

Sindhupalchok district is one of the districts in Nepal that is heavily susceptible to various naturally and human-induced disasters like earthquakes, landslides, floods, fire, and thunderbolts. The topographic, geo-lithological, and climatic condition of the district has placed it at high risk for those hazards and has already witnessed high loss of lives, properties, and infrastructures. The district has seen various disastrous events in the past, for instance, the 2015 earthquake, Jure landslide in 2014, Bhotekoshi flood in 2016, and Melamchi flood in 2021, bearing witness to high exposure to the multiple hazards. As hazards are occurred both by naturally and by anthropogenic activities. We cannot stop the natural ongoing process but we can tackle and reduce the consequences by implementing proper strategies and policy planning in the potential hazard area with well-equipped infrastructure and skilled manpower.

10. ACKNOWLEDGEMENT

I would like to extend my whole-hearted appreciation towards the department of geology, Tri-Chandra Multiple campus for providing me with such a great opportunity and encourage me to write this article. The opportunity did not just make me present my research study, but was also a motivation for me to explore more into the dynamics of the geohazards in Sindhupalchok. The opportunity has been an experience that I cannot forget in my academic career, and I appreciate that you trusted in my research.

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ISSN: 3021-937X (Print)

CRITICAL MINERALS AND RARE EARTH ELEMENTS

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ABSTRACT

Geologically, Nepal lies at the boundary between the Indian and Eurasian plate where the collision has formed the Himalayas. The variations in the landscape from Terai plains to high mountains are naturally rich in minerals. Some minerals such as iron, copper and limestone have been mined for decades. While critical minerals and Rare Earth Elements (REEs) are still in their formative stage. These minerals are crucial in today's technological world. They play an important role in renewable energy as well as industrial applications. This paper discusses the potential of critical minerals and Rare Earth Elements in Nepal and the challenges in developing these resources and highlights future opportunities for sustainable mineral development.

Keywords: *Indian and Eurasian plates, Rare Earth Elements (REEs), Sustainable*

1. BACKGROUND

Rare earth elements (REEs) are a group of 17 metallic elements including the 15 lanthanides plus scandium and yttrium that are essential for modern technologies like smartphones, electric vehicles, wind turbines and advanced defense systems. Even though they are called rare, they are relatively abundant in the Earth's crust but rarely found in the amount that can be mined easily.

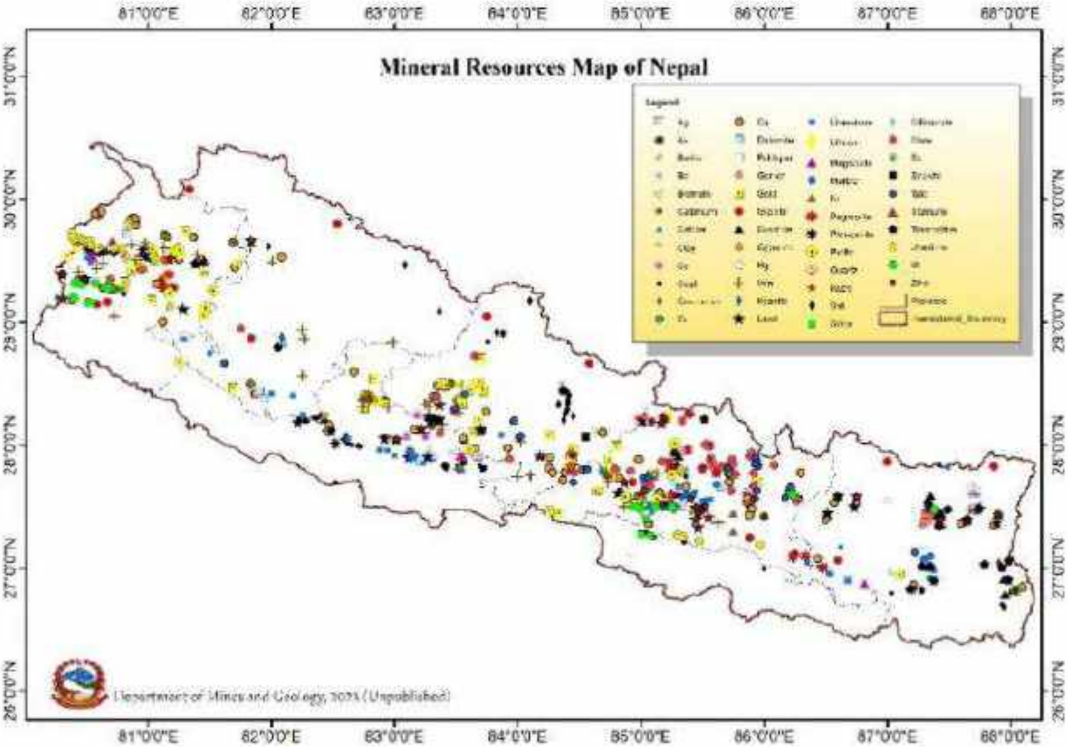

Figure 1: Map of Nepal (Department of Mines and Geology, 2023)

Critical minerals are minerals that are vital for a country's economy, industries or national security but their supply is at risk due to scarcity or import dependence. These include metals like lithium, copper, cobalt and magnesium as well as some REEs. Together, REEs and critical minerals are crucial for electronics, renewable energy, aerospace, and industrial applications making them strategically important resources worldwide.

2. GEOLOGICAL ZONES OF NEPAL AND THEIR MINERAL POTENTIAL

2.1 SIWALIK ZONE

It is composed of sedimentary rocks such as sandstone, conglomerates and mudstone. It has low grade deposits of iron, sulfur and copper. Till now no significant Rare Earth Elements deposits have been identified. Due to low grade ores and tectonic instability, large scale mining is not economically viable here.

2.2 LESSER HIMALAYA

It is characterized by metamorphic rocks like schist, phyllite and quartzite. It is known for deposits of iron ore, lead, zinc, copper and gold. The potential for Rare Earth Elements (REEs) in this region is still uncertain. Preliminary studies suggest the presence of minerals such as tantalum, niobium, molybdenum, and other rare earth metals. Detailed exploration and analysis are needed to confirm their distribution and economic viability.

2.3 HIGHER HIMALAYA

It comprises high-grade metamorphic rocks including gneiss and migmatites. It is rich in gemstones, lithium and REEs. The presence of beryllium and aquamarine suggests potential for REE deposits. There is high potential for rare metals, however accessibility and infrastructure challenge the mining and exploration.

2.4 TETHYS HIMALAYA

It is dominated by sedimentary rocks such as limestone, dolomite and marbles. There is limited evidence for rare earth element deposits. Mineral extraction is economically viable for industrial minerals however REEs potential remains underexplored.

2.5 TRANSITIONAL ZONES (LESSER HIMALAYA TO HIGHER HIMALAYA)

These are the areas where metamorphic and sedimentary rocks intersect. It is known for the deposits of copper, iron, and magnesium. There is the presence of rare earth elements and moderate potential for critical minerals however further exploration and infrastructure development are required. Globally, the demand for these minerals has increased rapidly due to the growth of electrical vehicles, solar and wind energy systems and advanced electronics. Nepal comprises complex geological structures which suggest the possibilities of these minerals. However, lack of modern tools for exploration and systematic study are limited, leaving much of this potential unexploited.

3. OBJECTIVES

The major objectives of the study are:

- Distribution of Rare Earth Elements and critical minerals on different tectonic zones of Nepal.
- Highlight the economic importance of these minerals for Nepal and global technology industries.
- To point out areas with potential minerals that are still unexplored.

4. METHODOLOGY

The secondary data was taken into consideration. Related newspapers, articles and journals were reviewed.

5. RESULTS

5.1 GEOLOGICAL CONTEXT OF NEPAL

Nepal's geology is extremely diverse. The country extends from low land Terai plains to the rocky Himalayas, covering sedimentary, metamorphic and igneous rock zones. This variation has made it possible where different minerals deposit can be formed. Currently, most of the mining in Nepal focuses on industrial minerals such as magnesite, talc and limestone. Small scale deposits of metals such as copper, iron, lead zinc and gold have also been reported. While evidence of critical minerals and REEs exists in some studies, detailed mapping, sampling and exploration are still lacking. Some river sediments may contain heavy minerals like monazite and zircon which are sources of rare earth elements.

5.2 CHALLENGES IN DEVELOPMENT

The challenges in development of REEs are:

- Geological surveys are insufficient due to the varied landscape due to which systematic exploration has not been conducted widely.
- The extraction and processing of these minerals require advanced technologies which are not yet available locally.
- The current government regulations make it hard to attract investment for mining important strategic minerals.
- Mining in the fragile Himalayan ecosystem can lead to several disasters such as landslides and water contamination and it affects the whole ecosystem if not managed responsibly.

5.3 IMPORTANCE AND BENEFITS OF DEVELOPMENT

The importance and benefits of development of REEs are:

- The mining and processing activities could create jobs for the locals, support infrastructure development and increase government revenue.
- Domestic access to REEs and other critical minerals would support renewable energy projects and electronics development.
- Production of key minerals on a local basis could reduce reliance on imports, strengthening Nepal's role in global supply chains.

5.4 RECOMMENDATIONS FOR NEPAL

Some of the recommenations for Nepal in the field of REEs development are:

- Detailed mapping, sampling, and lab testing are needed to know the amount and quality of minerals.
- More investment in research, mining technology, and processing plants is important for sustainable use.
- Clear and supportive policies should attract private and foreign investors while protecting nature and society.
- Every mining project must include environmental care, proper waste control, and community involvement.

ISSN: 3021-937X (Print)

6. CONCLUSION

Nepal has many types of rocks and landscapes, from the flat Terai to the high Himalayas, which makes it rich in different minerals. Lately, minerals like lithium, cobalt, graphite, and rare earth elements (REEs) are gaining attention because they are important for technology and renewable energy. Until now, Nepal mainly worked with magnesite, talc, and limestone, but studies hint that REEs could also be present in granites, pegmatites, and riverbeds. If used properly, these resources could bring jobs, better infrastructure, and good income for the country, while also reducing dependence on imports. But there are still problems like less research, old technology, weak rules, and risks to the environment. To move forward, mining must be done in a careful way with proper environmental care and local people's involvement so that development is useful without harming nature.

7. ACKNOWLEDGEMENT

I sincerely thank the Department of Geology for giving me the opportunity to write this article. I would also like to express my gratitude to all my respected teachers for their continuous guidance and encouragement.

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International articles on rare earth elements and critical minerals for global context.

ISSN: 3021-937X (Print)

TECTONIC ZONE AND INVERSE METAMORPHISM AROUND THE HIGHER HIMALAYA

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ABSTRACT
This article focuses on the Higher Himalaya of Nepal, located between the Main Central Thrust (MCT) and the South Tibetan Detachment System (STDS). The study was done through desk research and a field visit along the Pokhara–Muktinath route in the Kali Gandaki Valley. The Higher Himalaya is made up of old, high-grade metamorphic rocks like gneiss and schist. One important feature is inverse metamorphism, where higher-grade rocks are found above lower-grade ones—opposite of the normal pattern. Two models, the Hot Iron Model and the Channel Flow Model, help explain this unusual phenomenon. The study aims to understand how tectonic activity and heat flow shaped the rocks in this region.

Keywords: *Higher Himalaya, Main Central Thrust (MCT), South Tibetan Detachment System (STDS), Migmatite, Mylonites, Phyllonites*

1. INTRODUCTION

1.1 BACKGROUND

The Higher Himalaya is bounded between north of the Lesser Himalayan zone separated by the MCT and south of the Tibetan-Tethys Himalaya separated by the STDS, consisting of the high-grade crystalline rocks including various kinds of gneiss, schist and migmatite extends continuously along the entire length of the country. This zone consists of about 10km thick succession of crystalline rocks and also known as the Tibetan Slab (Le Fort 1975). Le Fort (1975) has studied the rocks of Higher Himalayan zone in detail and described the lithostratigraphy in three Formation as shown in Table 1.

Table 1: Lithostratigraphy of Higher Himalaya after Le Fort 1975

Litho Unit	Main Lithology	Thickness (m)	Age
South Tibetan Detachment System (STDS)			
Formation III	Augen Gneiss	3000	Pre-Cambrian
Formation II	Banded Gneiss, Quartzite, Marble	1700	
Formation I	Gneiss, Schist	5000	
Main Central Thrust (MCT)			

1.2 AIM

The main aim of this article is to understand a portion of Nepal Himalaya ie. Higher Himalaya

1.3 OBJECTIVES

The main objectives are as follows:

- To gain an understanding of the tectonic zone around Higher Himalaya
- To comprehend inverse metamorphism in context of Higher Himalaya

1.4 RESEARCH QUESTIONS

The following research questions signify the study:

- Why is inverse metamorphism common in the MCT?
- How does tectonic zone control the structural evolution of the Higher Himalaya?

2. MATERIALS AND METHODS

The article has been structured around two major stages of study: desk study and field excursion. The desk study phase involved an extensive review of existing academic resources including textbooks, research papers, articles and online sources. This stage provided a strong theoretical foundation and helped to synthesize previous findings related to Higher Himalaya.

The second stage, field excursion was carried out along the Pokhara-Muktinath route in the Kali Gandaki valley, which enabled direct observation, documentation and interpretation of lithological variations, structural features and metamorphic patterns in relation to the tectonic zone.

3. RESULT AND DISCUSSION

3.1 TECTONIC ZONE

3.1.1 MCT

The MCT is the principal tectonic boundary separating the Lesser Himalayan Sequence from the Greater Himalayan Crystalline Complex and is widely recognized as a major shear zone associated with inverted metamorphism (Le Fort, 1975).

For long, one of the most controversial topics in the Himalayan geology has been the nature and position in the evolution of the mountain range. Different researchers have different prospective regarding this issue.

After a decade of research nearly covering the whole country, the Japanese research group (Hashimoto et al., 1973) came up with the idea of two thrust which they called MCT I (corresponds with the MCT of Heim and Gansser, 1939) and MCT II (equivalent to the MCT of French workers, Le Fort, 1975a, b: Pecher, 1989). The intervening zone between the MCT I and MCT II was called the MCT zone. Along Kali Gandaki section, MCT equivalent to French begins just north of Dana at the base of Upper Crystalline Nappe.

3.1.2 STDS

The south Tibetan Detachment System (STDS) is a regionally extensive, low to moderate-angle normal fault system separating high-grade metamorphic rock of Higher Himalaya to the south & low-grade metamorphic and sedimentary rock of Tethys Himalaya to the north. (Burchfield et al., 1991).

It is particularly well-exposed in central Nepal (e.g., Annapurna, Manaslu, Everest regions). Tens to hundreds of meters of mylonitic rocks are found where mylonite, phyllonites and highly sheared granites are common.

The STDS is interpreted as the upper bounding fault of the ductile channel in the channel flow model. Together with MCT at its base, the STDS facilitated the extrusion of the Higher Himalaya leading to the inverted metamorphic sequence observed in the Himalaya.

3.2 INVERSE METAMORPHISM

Inverse metamorphism results from over thrusting of high-grade metamorphic rocks of the Greater Himalayan Sequence over the lower-grade Lesser Himalayan units (Pecher, A. 1989). The inverted metamorphism has become one of the distinctive aspects of the Himalaya (Harison et al. 1999). A steady increase in the Lesser Himalayan (i.e., the footwall of the MCT) to the lower end of the Higher Himalaya (i.e., the hanging wall of the Main Central Thrust). Chlorite from the lower section of the Lesser Himalaya to the kyanite + staurolite approaching to the MCT, kyanite and staurolite bearing rocks with intermediate Pressure-Temperature condition at the basal part of Higher Himalaya, sillimanite + cordierite containing upper amphibolite to granulitic facies metamorphic rocks at the upper part of Higher Himalaya.

There are basically two models explaining inverse metamorphism:

3.2.1 HOT IRON MODEL FOR INVERSE METAMORPHISM -DEVELOPED BY P.G. ENGLAND AND A.B. THOMPSON IN 1984

This model describes the isograde distribution. The hotter Higher Himalaya diffuses the heat to the cooler Lesser Himalaya during the movement of the MCT resulting the paleothermal inversion, i.e. grade of metamorphism gradually decreasing from garnet-kyanite-staurolite grade to the biotite and chlorite grade rocks, respectively to the lower section of the Lesser Himalaya (Le Fort 1975).

3.2.2 CHANNEL MODEL FOR INVERSE METAMORPHISM -DEVELOPED BY R.L. ROYDEN AND B.C. BURCHFIEL (1987- 1989) AND FORMALIZED BY BEAUMONT ET AL. (2001, 2004)

This model explains that channel flow is a process in which a viscous fluid moves in a channel between two rigid plates provocating deformation by shear stress and a pressure gradient in the channel (Grujic et al. 1996; Daniel et al. 2003). In this model, the Higher Himalayan Crystalline was channeled by the viscous fluid produced by the deformation due to shear stress and pressure difference. The heat from viscous fluid transfers to both the Lesser Himalaya and Tibetan-Tethys Himalaya resulting decrease of the metamorphism.

4. CONCLUSION

The Higher Himalaya is an important geological zone containing high-grade metamorphic rocks. It is bounded by the MCT in the south and the STDS in the north. The rocks show inverse metamorphism, where high-grade metamorphic rocks are above low-grade metamorphic ones. This happened due to strong tectonic movements and heat transfer during mountain building. Two main models—the Hot Iron Model and the Channel Flow Model help explain this process. Overall, the Higher Himalaya shows how deep rocks can move upward and how mountain belts evolve over time.

5. ACKNOWLEDGMENT

I would like to express my sincere gratitude to the Department of Geology, Tri-Chandra Multiple Campus for providing us with the opportunity to write an article on a topic of our academic interest. This platform has been instrumental in encouraging our research and enhancing our understanding in the field of geology.

I am also thankful to the editorial team for their valuable support and understanding throughout the preparation of this article. My heartfelt appreciation goes to the supervisory team for their constructive feedback, encouragement and continuous assistance which greatly contributed to the successful completion of this work.

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