Journal of Critical Global Issues

Volume 1 | Issue 1 Article 5

February 2024

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ISSN:

Journal of CRITICAL GLOBAL ISSUES

SIT SCHOOL FOR INTERNATIONAL TRAINING

Relocating Lubra Village and Visualizing Himalayan Flood Damages with Remote Sensing

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Abstract

As weather patterns change worldwide, isolated communities impacted by climate change go unnoticed and we need community-driven solutions. In Himalayan Mustang, Nepal, indigenous Lubra Village faces threats of increasing flash flooding. After every flood, residual muddy sediment hardens across the riverbed like concrete, causing the riverbed elevation to rise. As elevation increases, sediment encroaches on Lubra's agricultural fields and homes, magnifying flood vulnerability. In the last monsoon season alone, the Lubra community witnessed floods swallowing several agricultural fields and damaging two homes. One solution considers relocating the village to a new location entirely. However, relocation poses a challenging task, as eight centuries of ancestry, heritage, and nuanced cultural complexities exist in both aspects of communal opinion and civil engineering. To investigate this issue further, we utilize remote sensing technologies such as drones and satellite imagery to create unique, highly detailed 3D visualizations and 2D maps to document climate-related impacts in Lubra Village. We also investigate quantifying riverbed elevation trends with digital elevation models to address how the riverbed elevation changes overtime. In tandem, we conduct oral interviews with members of Lubra to understand how flooding and droughts affect their ways of life, allowing us to contextualize these models. Pairing visualized data with personal accounts, we provide an informative story that depicts Himalayan climate change on a local level for supporting Lubra in informing local policy and requesting relief aid.

Resumen

A medida que los patrones climáticos cambian a nivel mundial, algunas comunidades marginadas, impactadas por el cambio climático, pasan desapercibidas, lo que nos lleva a buscar soluciones conscientes de la comunidad. En el Himalaya Mustang, Nepal, la aldea autóctona de Lubra enfrenta crecientes amenazas de inundaciones repentinas. Después de cada inundación, un sedimento lodoso se endurece en el lecho del río, elevando su altura. A medida que dicha elevación crece, este sedimento invade los campos agrícolas y las viviendas de Lubra, aumentando la vulnerabilidad a las inundaciones. Durante la última temporada de monzones, la aldea presenció inundaciones que afectaron varios campos y dañaron dos hogares. Una solución considera la reubicación completa de la aldea en una nueva ubicación, pero esto implica una tarea desafiante, debido a los ocho siglos de ancestros, patrimonio y complejidades culturales en cuestión comunitaria y retos de ingeniería civil. Para investigar más a fondo, se utilizaron tecnologías de teledetección, como drones e imágenes de satélite, para crear visualizaciones 3D y mapas 2D detallados, documentando los impactos climáticos en Lubra. Además, se investigaron tendencias de elevación del lecho del río con modelos digitales cuantitativos para abordar cómo cambia la elevación a través del tiempo. Complementando esto, se llevaron a cabo entrevistas orales con miembros de Lubra para entender cómo las inundaciones y sequías afectan sus formas de vida, permitiéndonos contextualizar esos modelos. Al combinar datos visuales con relatos personales, se pretende ofrecer una historia informativa que represente el cambio climático en el Himalaya a nivel local, para apoyar a Lubra en informar sobre la política local y a solicitar asistencia.

Keywords

Climate change, preservation of indigenous heritage, remote sensing, Himalayas, communal displacement

Introduction

As weather patterns change worldwide, remote Himalayan communities impacted by climate change go relatively underexplored (Uprety et al., 2017). In Mustang, Nepal, indigenous Lubra Village faces threats of increasing flash flooding. After every flood, residual muddy sediment hardens across the riverbed like concrete, causing the riverbed elevation to rise. As riverbed elevation increases, sediment encroaches on Lubra's agricultural fields and houses, magnifying flood vulnerability. One solution considers relocating the village to a new location entirely. However, relocation poses a challenging task, as eight centuries of ancestry, heritage, and nuanced cultural complexities exist between communal opinion and civil engineering.[1] Furthermore, Lubra lacks adequate funding for a swift solution, as some in the Mustang community deny the issue's existence. Insufficient quantitative data of the rising riverbed elevation contributes to this skepticism. Our research aims to combine indigenous knowledge,

[1] Considerable information regarding Lubra and local flooding was obtained from the authors' first-hand experience and will be discussed further in the next two paragraphs.

local experience, and computer-aided surveying to expeditiously and empathetically communicate this issue to garner support and raise awareness.

To investigate this issue further, we spent two months living with the Lubra community in Mustang, learning about communal experiences, and collecting images and GPS data. During this time, we explored remote sensing technology such as hand-held cameras, drones, and satellites to collect aerial and terrestrial imagesets that reflect the current state of Lubra Village. With these imagesets, we created highly detailed 3D visualizations to document climate-related impacts in Lubra Village. To address the lack of elevation data, we constructed digital elevation models with satellite imagery over the last decade and explored their usage for understanding the riverbed elevation trend. To support the architecture and development team in relocating Lubra Village, we mapped the trail and road infrastructure using GPS and satellite data, allowing us to imagine how new locations would exist in the village's current infrastructure. Finally, we conducted oral interviews with community members to understand how flooding and droughts affect their ways of life and contextualize our resulting visualizations. Pairing visualized data with personal accounts, we provide an informative story for depicting Himalayan climate change impact on a local level and demonstrating these impacts to communal leaders, policymakers, and NGOs.

The information regarding Lubra and local flooding was obtained from the authors' first-hand experience. Information in this paper comes from these experiences unless otherwise noted. As for the paper's organization, we will first contextualize the problem space by exploring the cultural significance and identity of Lubra, along with its heritage in preserving Bön[2] religion and tradition. Following this, we will delve into how Himalayan flooding physically displaces Lubra and examine what relocation means for the community. With this context, we will then weave technology into the problem space, laying out our research methods and resulting visualizations. Concluding our paper, we aim to provide local perspectives and perceptions of climate change in Nepal and its impact on indigenous Tibetan livelihoods.

To uphold ethical standards, our research received Institutional Review Board (IRB) approval, as well as consent from all participants to share this information. Overall, this work contributes to the intersection of computer science, environmental conservation, and cultural preservation, and offers valuable insight on empathetically navigating a culturally sensitive space through an engineering lens. This written report intends to consolidate data-driven visualizations with experiential context as a resource for Lubra in communicating this time-sensitive issue to external parties.

Lubra Village

As we walked along the cliffsides of Lubra Valley, the sun radiated through our caps. Stones and loose soil shifted with every step, sending pebbles down the cliff and dust into the air. One misstep along the trails would send us tumbling 700 meters into the valley below us. In the distant west of us, the Dhaulagiri Mountain Range sat, while the Annapurna Mountain Range

[2] Indigenous, pre-Buddhist religion of Tibet.

gently pressed us from the south and east. The further we trekked south from Muktinath in Mustang, the deeper we discussed co-author Gurung's birthplace, Lubra Village.

Considered to be one of the few villages fully practicing Bön in Nepal, Lubra Village sits at the edge of Lubra River in the Annapurna Conservation Area, nurturing over 800 years of cultural and ancestral significance (Shneiderman, 2006). Originally established in the 12th century, it is locally believed that Lama Yangton Tashi Gyaltsen, after crossing many plateaus through Tibet, made the area suitable for settlement by subduing the land's unruly spirits. He then determined that if a planted walnut tree would grow, that the Bön religion would survive here. Soon after the tree's flourishing, the lifeline of Lubra began where the tree still exists today (Ramble, 1983). In the Mustangi dialect of central Tibetan language, *lu* means serpentine naga spirits, and *brak* means rock cliffs. With its uniquely snake-line textured valley cliffs, many consider Lubra as the snake valley (Smith, 2019).

Sitting at an altitude of approximately 2,950 meters, the current day village and its 14 family inhabitants rely heavily on subsistence farming and tourism to survive (Shneiderman, 2006). Each family farms with their own allotted land while carrying the responsibility of communal jobs. Most mud buildings and guesthouses reside on the edge of Lubra River. A school, two monasteries, several stupas, a children's hostel, water tanks, and agricultural fields span the rest of the land. As we imagined Lubra Village, we surmounted the final hilltop from which, five kilometers in the distance, Lubra sat on the valley slope neighboring the towering cliffsides as shown in Figure 1. A map of Lubra's location is shown in Figure 2.

Figure 1: Lubra Village in Lubra Valley with the Annapurna Mountain Range in the Background in 2022

Figure 2: Map of Lubra in the Mustang District of Nepal, Located in the Himalayan Mountain Range

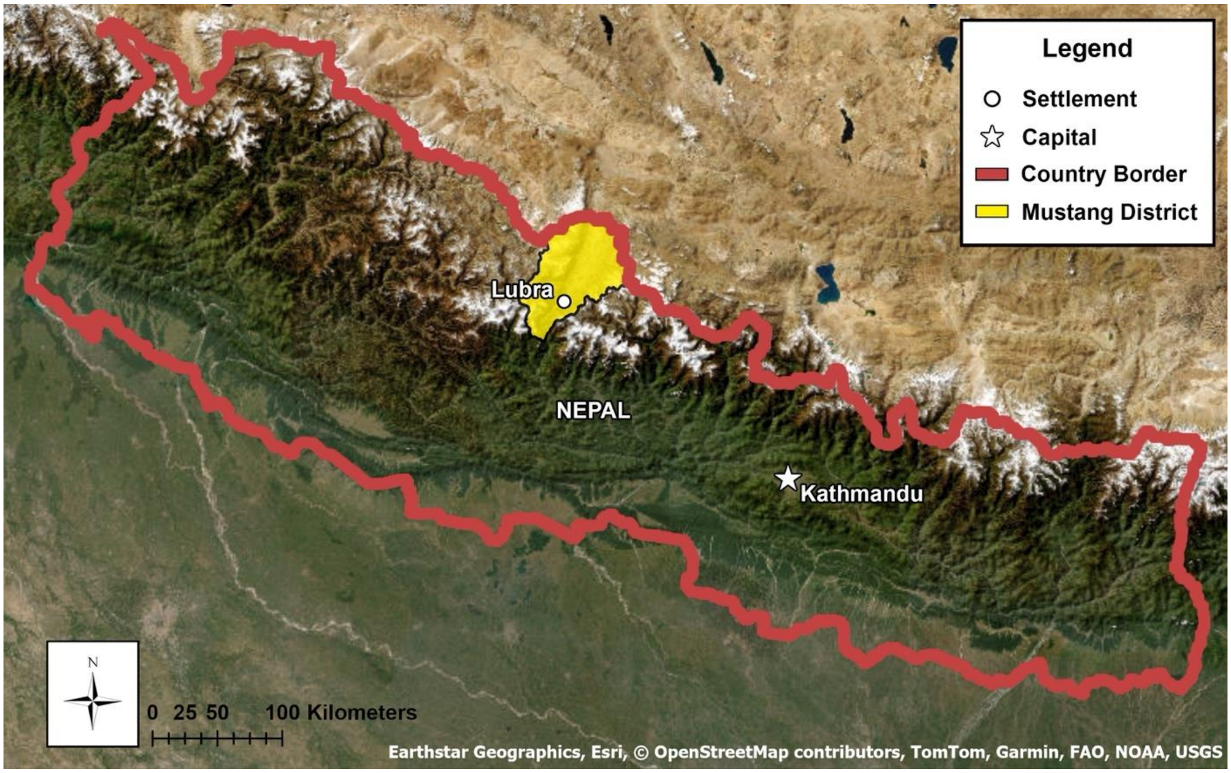

Figure note: Country borders based on the map in the Constitution of Nepal (Survey Department, 2021)

HIMALAYAN FLOODING

Making our descent into the valley, co-author Gurung expressed concern for his home in Lubra. Every year between June and August, Lubra faces flash flooding disasters. What is usually the three- to five-meter-wide Lubra River turns into a creeping 150-meter-wide flood. During these monsoon seasons, water flows through the valley to meet with the Kali Gandaki River, carrying all types of sediments ranging from boulders to clay size fragments with it. With the amount of mud, sub-rounded to rounded boulders, and cobbles from previous deposits on the riverbed, the mudflow transforms this valley into a concrete mixer, stirring the mud-stone-water mixture into a viscous sludge as shown in Figure 3. As this sludge collects high in the valley, water may fail to find passage, causing this muddy water to pool. Eventually, the sludge gives way, bringing down a rush of aqueous concrete. These flood bursts repeat consistently over three months, spanning the entire riverbed as shown in Figure 4 (Community member, personal communication, May 2022).

Looking into the valley, we examined the hardened riverbed as it cradled a glimmering stream, guiding it through the valley. Backed with first-hand knowledge, we acknowledged the river's deceiving disguise. It was March when this thread of water flowed coyly through the riverbed's scattered rocks, spellbinding travelers in its off-season beauty.

Figure 3: Sludge-like Mixture of Mud, Stone, and Water in Lubra Valley (Varrgongwa, 2021)

Figure 4: Flash Floods Spanning the Riverbed Adjacent to Lubra (Varrgongwa, 2021)

As global temperatures increase, Mustang experiences an altering water cycle. Existing in the rain shadow[3] of the Dhaulagiri Mountain Range, the once arid Mustang is turning wet. Rain patterns are changing, and what used to be light rain has turned to destructive, pouring showers over the last six to seven years (Jomsom[4] local, personal communication, April 2022). Specifically, winters are warming, and precipitation has increased in the monsoon months of June and July (Bhadra & Neupane, 2021). Furthermore, a recent report conducted by the International Centre for Integrated Mountain Development (ICIMOD) shows a significant acceleration of glacial mass loss in the Hindu Kush Himalaya region between 2000 and 2019 (ICIMOD, 2023). As Himalayan glacial melting rates and precipitation increase, more water flows through Lubra Valley, contributing to more flash floods at higher intensities.

Other indicators of changing weather patterns are seen through the perspectives of locals. Distinguishing weather patterns from the last 50 years, community members worry about decreasing snowfall. As snowfall patterns change, previously compact glacial snow loosens, leading to more melting. Although snow patterns have not been easily determined, locals are confident that snowfall is decreasing, as they observe previously snow-covered mountains like Mt. Nilgiri as naked without snow.

In parallel, farmers of Marpha, a southern village known for its apples, have halted apple production because their crop cannot survive the rising temperatures. Additionally, Jomsom residents have experienced rising temperatures with rising mosquito populations, as increased temperature lures them to lay and hatch.

FLOOD DAMAGES

For Lubra, this is a fatal disaster. Located on the riverbank edge in Lubra, families are vulnerable to flooding destruction. For decades, floods have occurred in the valley once every three to five years. However, over the last ten years, one or more flash floods have occurred each year. When a monsoon season concludes, newly brought sediment sets and hardens like concrete at the foot of the village, increasing the height of the riverbed. As the riverbed encroaches on the village, Lubra is more susceptible to damage. Over the last decade alone, the riverbed has increased 12 meters in elevation, having already destroyed several fields of crops as shown in Figure 5.

As a direct consequence of climate change, the surge in flash flooding buries the village at a quicker rate, where these changes are recorded by comparing overlayed historical satellite imagery as shown in Figure 6. During the two-month monsoon in 2021, the first homes were damaged, leaving two families to take shelter in another family's guesthouse for three months. One community member's family suffered as mud rushed through their home, filling the lowermost room. Having lived his entire life in Lubra, he felt pain for his family and defenseless at home. "It is what it is," he expressed with sorrow. "If the next monsoon is like the last one, the rest of my house will be gone" (Community member, personal communication, May 2022).

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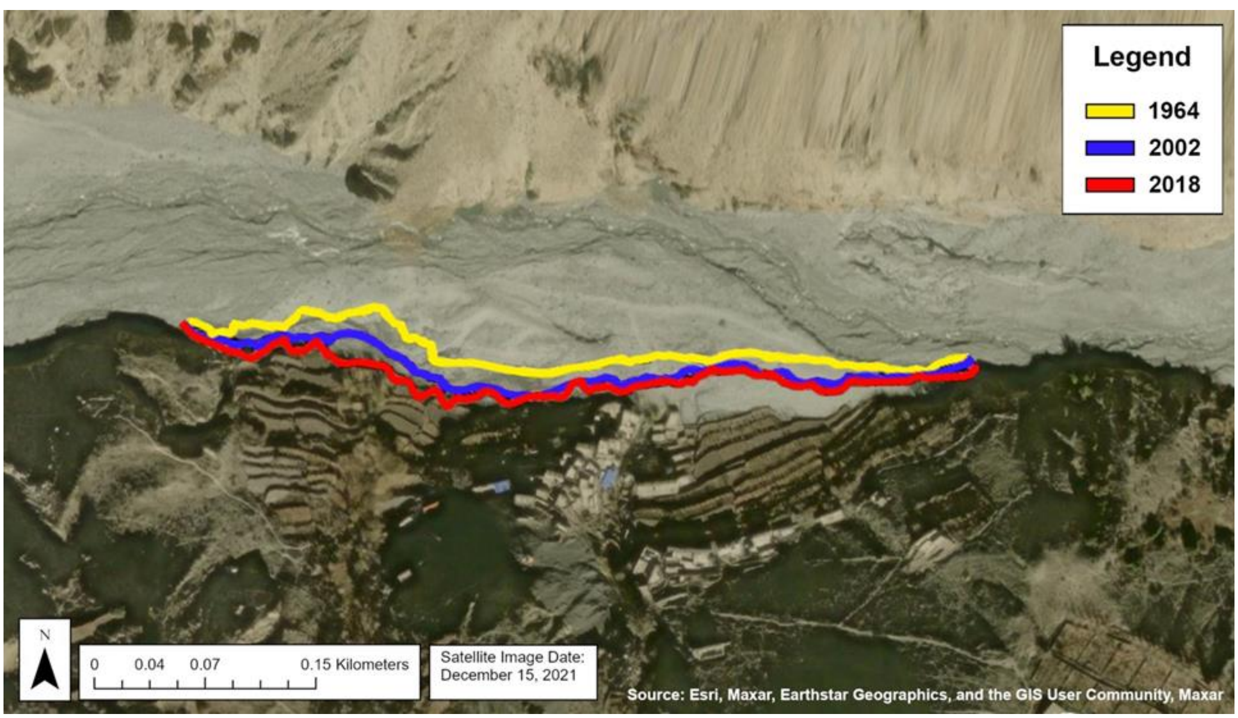
[3] A region of reduced rainfall due to an orographic barrier such as a mountain range.

[4] A neighboring town in Mustang.

Figure 3: Agricultural Fields in Lubra Destroyed by Flooding in 2021

Because multi-level buildings are stacked upon each other up the valley slope, the main village stands as one entire building. Each building depends on one another for structural and foundational strength. Because of this architecture, damage to one home immediately threatens the structural integrity of the building majority, threatening the safety of several families. The next two monsoon seasons alone could leave families homeless. The community member looked on: “In ten years if the monsoons continue as they do, the entire village will be gone” (Community member, personal communication, May 2022).

Figure 4: River Erosion Shifting Towards Lubra, Recorded in 1964 (Yellow), 2002 (Blue), and 2018 (Red) (Carlson, 2021)



With increased flooding and rainfall, traditional mud homes have more trouble in the winter and monsoon season. In the last three years, mud roofs leak more due to rain damage, and mud fences and walls wear away from monsoons of increasing intensity, contributing to communal insecurity. Additionally, roads have been entirely wiped out. For example, before the monsoon of 2021, a road was built from the Kali Gandaki River across the riverbed to reach Lubra Village. With a budget of 30 lakh,[5] road construction finished after three months of work. Only two months later, the entire road was washed away during the following monsoon. Along with roads and residential homes, the community's livelihood is further threatened as flooding consumes agricultural fields, rendering them unusable. Furthermore, during the monsoon in 2017, a 70-year-old chorten[6] of religious significance once standing 25 meters tall (as shown in Figure 7) now finds itself submerged in debris, destined to fossilize in the riverbed.

Figure 5: Chorten at the Entrance of Lubra Prior to Destruction (The Base is Covered in Hardened Mud) (Community Member, 2015)

[5] 1 lakh is 100,000 Nepalese Rupees and is approximately equivalent to 800 US dollars. In US dollars, a budget of 30 lakh is approximately $24,000.
[6] Tibetan for an important religious monument (also known as *stupa* in Sanskrit).

As their spiritual livelihood faces the consequences of flooding, the community connects these damages with their spiritual beliefs. Some members believe that flooding and climate change are due to disturbed spirits and rely on traditional knowledge over scientific data and conclusions. For example, for a good supply of water, rituals are performed near the primary water source or near the home of a spirit related to the water source. When examining this issue, it is crucial to understand how all members of the community feel and try to understand their belief system, as spirituality and religious belief are integral in creating solutions that work best with the community's needs.

Flood damages in recent years show that the riverbed continues to rise, and the need for a solution is evident. Increasing flooding threatens the community's livelihood and security of culture and traditions. Decades of culturally significant land are disappearing, and some fear their ancestral heritage and traditions will go with it.

CULTURE UNDER THREAT

Cultural and traditional ways of living remain in Lubra as one of the only few fully Bön practicing villages in Nepal. Although other Bön monasteries exist in Lower Mustang, none compare to the authenticity of how the Lubra is traditionally and religiously maintained (Smith, 2019). One issue, however, is its survivability in a cultural revolution followed closely by varying social changes. In search for a more prosperous life along with reputation in their village, younger generations migrate out of Lubra at a young age, leaving their community and elders behind. Spending most of their youth in culturally foreign cities or countries, these children learn the ways of other cultures and rarely settle in their village during adulthood. For those that do, they are subject to relearning their culture and traditions (Amburgey & Gurung, 2021). Now, little remains in Lubra to sustain their culturally significant traditions, making preservation that much more important.

Before we considered any aspect of computer science, we explored current solutions implemented by the community. One initiative is redirecting flooding through man-made intervention. For example, for the last 20 years, gabion wire boxes[7] have been built as flood barriers as shown in Figure 8. However, these barriers have not always been effective. As an alternative, the community has been experimenting with digging trenches to control the flow of flooding as shown in Figure 9. Unfortunately, these adaptation strategies fall short as the riverbed elevation continues to rise regardless. Now, the community considers relocating the village entirely to a new settlement area to ensure the physical and cultural safety of Lubra.

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[7] A wired cage, cylinder, or box filled with rocks, concrete, or sand and soil.

Figure 6: A Wall of Gabion Boxes Built to Protect a Road from Flood Damage and Control Flood Flow in 2022

Figure 7: Trench and Gabion Boxes Guarding the Main Village in 2021

Relocating Lubra Village

As elevation trends show little sign of plateauing, the Lubra community considers relocating the village to a new settlement area. However, relocation is no easy task, as several aspects must be considered in planning. The architecture and development team must understand how the village is structured, along with how community members interact with their land. Understanding these nuances through the community's perspective is paramount. In terms of planning, the community identifies four potential areas for resettlement, which we will call location A, B, C, and D.

CHOOSING A LOCATION

Differing in size and distance from the main village, each location area is divided equally among the 14 families by the heads of the community. When comparing resettlement locations, factors include but are not limited to soil strength and integrity, access to utilities (water, electricity, roads, agricultural land), closeness to the main village and monasteries, access to materials, trail infrastructure, and spiritual beliefs. To understand how these factors influence communal opinions, we examine the children's hostel as an example.

When Lama Yangton Tashi Gyaltsen founded Lubra, he meditated in caves atop one of the western hills about a kilometer from what is now Lubra. Because of the caves' sacred significance, the Lubra community built the Gonpuk[8] Monastery to protect them. Then, about 20 years ago, the community had built a children's hostel adjacent to the monastery for deepening Bön religion, an integral part of the children's education. Although chosen for its wide space, flatness, and nearness to the monastery, the area consisted of loose, fine-grained topsoil, making for a weak foundation. When the children first moved in, some of the building collapsed due to the shifting soil underneath, forcing students to take shelter elsewhere for more than a year. An alternative site existed near a newly built school on the eastern side, but the community deemed it unsafe for children as it bordered the ceremonial burning grounds. In this example, cultural and geophysical factors intertwine in deciding location suitability, demonstrating how varying factors may influence the community's decision.

COMMUNAL OPINIONS

Location Choice

To choose a final location, all families must unanimously agree. With varying opinions, however, agreement is extremely difficult. For example, one community member believes that location A is better suited, for he finds importance in staying near the Yungdrung Phuntsok Ling monastery to care for it. Furthermore, location A does not require any road development (Community member, personal communication, May 2022). Other families, however, believe that location D is the better suited choice for its vast space.

Building Design

Once a location is chosen, community members seemed to agree that traditional mud homes should be built. These mud buildings are constructed with combined techniques of stacked stones

[8] Tibetan for cave.

for the foundation, rammed earth[9] for the walls, and topped with earthen roofs (Smith, 2019). Maintaining traditional styles is important not only for cultural preservation but also for attracting tourists. Tourists want to see these traditional homes, bringing more money into the community (Community member, personal communication, May 2022). One issue with maintaining traditional homes is leaking from damaged roofs. One proposed solution is to keep traditional mud buildings while incorporating modern design in the roof using concrete. However, concrete has lower heat retention, a crucial aspect during winters and must be taken into consideration (Community member, personal communication, May 2022).

Relocation Reluctance

Even if unanimous agreement about a location is achieved, some Nepali communities are reluctant to relocate regardless of the circumstances. For example, the earthquake in 2015 damaged Laprak village in the Gorkha district, leaving the community in dire need of support. After a new village was constructed nearby, some community members refused to move from their damaged village. Regardless of the destruction, some preferred to live with the disaster until they die with their village than relocate (Lead architect, personal communication, April 2022). A similar situation is occurring in Lubra. If community members nurture this mindset, then those who carry knowledge to revive dying traditions will die with it.

Another issue contributing to this reluctance is land insecurity. Although Lubra has existed on their land for centuries, the lack of government-issued land certificates leaves families in fear. Withholding land certificates, the government may invalidate any land claims and remove community members. Having guaranteed land ownership certificates in a new location could sway opinions on resettlement. Other issues include the vast complexities of village development and the negative disturbance of spirits (Lead architect, personal communication, April 2022). Exploring these nuances, we considered computer science as a support in communal efforts and examined how technology could fit into this complex problem space.

Remote Sensing to Support Lubra

After spending two months in Lubra, we identified a lack of funding, time, and data that needs to be addressed. In the Mustang community, Lubra is considered a minority as they practice Bön in a Buddhism-dominant district, contributing to limited governmental funding. Furthermore, since access to Lubra's remote location is extremely limited during the monsoon season, many fail to witness the flooding first-hand and remain skeptical. Other communities contribute their disbelief as they experience climate change in terms of drought and reject the idea of flooding, further limiting Lubra's funding. Lastly, a lack of data visualizing flooding in Lubra deepens disbelief.

As the riverbed elevation rises, some believe that the village will be wiped out in 10 years. With limited time, the community needs swift, low-cost solutions for making informed plans and decisions. Considering these problems and contexts, we asked: how can we use computer science to support the Lubra community? From our investigation, we made strides in three main problems: relocating Lubra; visualizing flood damages; and quantitatively recording riverbed elevation. Using remote sensing technology, we visualized flood damages, rising riverbed

[9] A combination of gravel and mud, rammed with a wooden post to create a compact and lasting structure.

elevations, and village infrastructure for relocation. Incorporating these visualizations in future development proposals may assist in decreasing disbelief, increasing funding, and improving village development.

Research Methods

We used ethnographic field methods and remote sensing techniques to conduct our research. Because co-author Gurung's family resides in Lubra, we were able to navigate the community with ease and develop communal trust regarding our research objectives. Employing a co-design process, we iteratively shared our visualizations with community members for their opinions and feedback to ensure that our research produced tangible value to the community. Communal feedback shaped our end results. In the following sections, we discuss how we collected data using remote sensing and ethnographic interviewing, and how we processed our data to create 3D digital models, digital elevation models, and 2D maps.

DATA COLLECTION

Remote sensing is the science of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation (Lillesand et al., 2004). To obtain information on flooding in Lubra, we used a drone,[10] phone, GPS-tracking watch, satellites, and open-source images from the internet.[11] A summary of the tools used to collect all relevant data for this paper is shown in Table 1. Using these tools, we compiled a large dataset of aerial and terrestrial images of Lubra and the riverbed. A summary of the data collected for this paper is shown in Table 2. With these imagesets, we can create 3D models, digital elevation models, and 2D maps to visualize village relocation, flooding damages, and riverbed elevation.

Table 1: Summary Table Showing the Data Collection Tools Used

Tool	Model/Brand	Data Type Collected
Drone 1	Holy Stone HS720E	Aerial Images
Drone 2	SJRC F11 4K Pro	Aerial Images
Phone	Google Pixel 3A XL	Terrestrial Images
Satellite	Planet Labs PlanetScope	Aerial Images
GPS Watch	Suunto Ambit3 Peak	GPS Points

[10] Permits and drone registrations were obtained from the Civil Aviation Authority of Nepal prior to flight.
[11] For best results, the drone and phone should be capable of capturing imagery at a resolution between 1920x1080 to 4096x2160 pixels.

Table 2: Summary Table Showing the Data Collected

Data Type	Data Amount	Resolution	Tool Used	Year
Aerial Image	1600*	3840x2160 px	Drone	2022
Terrestrial Image	3500*	3840x2160 px	Phone	2022
Terrestrial Image	40*	1080x1920-3840x2160 px	Phone	2022
Archived Image	224	360x640-1080x1920 px	Phone	2006-2022
Satellite Image	20	3-7 meter/px	Planet Labs Satellites	2022
GPS Point	2000*	0.1-1 point/second	GPS Watch	2022
Interview	14	N/A	Oral Interview	2022

Note. *px = pixel.* * *= approximate.*

Creating 3D digital models, digital elevation models (DEMs), and 2D maps allow us to visualize and observe areas of interest (AOI) across Lubra without having to be there in person. If we have a detailed 3D digital model of an AOI along with DEMs and 2D maps, we can share them with our collaborators and support them in making informed decisions and plans without in-person site visits. These visualizations are needed for the information and insight they provide (Lead architect, personal communication, April 2022).

3D Digital Modeling

To create 3D digital models, we used photogrammetry. Photogrammetry is the method of obtaining reliable information about physical objects and the environment through processes of recording, measuring, and interpreting photographic images. It is primarily concerned with making precise measurements of 3D objects and terrain features from 2D photographs from either aerial (airborne) or terrestrial (on-ground) perspectives. Applications include measuring coordinates, quantifying distances, heights, areas, and volumes, mapping 3D topography, extracting 3D point clouds for surface reconstruction, and generating digital elevation (Doggett, 2020a, 2020b).

For every AOI, we needed a collection of aerial and terrestrial images. To accomplish this, we flew our drone 50 to 100 meters above every AOI, capturing 4K aerial images in the morning when sunlight and wind conditions were optimal. When a drone was not viable, we used a phone for terrestrial images. For example, the aerial view of one home's flooding damage was obscured by a tree. If we flew the drone near the tree, we would risk crashing the drone and endanger the safety of nearby community members. Instead, we maneuvered around the tree by foot, and collected images from a terrestrial perspective with a phone. Then using Agisoft Metashape,[12] we processed our imagesets to generate point clouds[13] and create highly realistic, 3D digital representations of each AOI (Vasilyan, 2019).

Digital Elevation Modeling

To understand flooding further, we investigated quantitative elevation trends of how the riverbed has changed over the last 20 years. These trends are important as they show how homes and agricultural land have been affected over time. With no record of quantitative elevation measurements, current riverbed elevation trend analyses are based solely on qualitative conversations with community members, and we needed a formal dataset for analyzing elevation trends. To address this, we explored creating digital elevation models with satellite data over the last 20 years to compare riverbed elevation (Agisoft, 2022a, 2022b; Ghuffar, 2018). Our experience with generating DEMs is discussed in-depth in our results.

2D GPS Mapping

To understand the current village infrastructure, we created 2D maps detailing trails, roads, and village locations. To create these maps, we used a combination of satellite imagery and GPS tracking data. With the GPS watch activated, we walked every main trail and road in Lubra to build a map of the village's trail infrastructure, where the watch recorded GPS points once every second to 10 seconds, depending on the accuracy we required. After hiking several hours, we imported the GPS data into ArcGIS Pro,[14] where we plotted these points on a coordinate grid overlaying a satellite image of Lubra (Esri, n.d.).

Oral Interviews

We conducted 14 interviews[15] to conceptualize the main issues Lubra faces. These conversations are critical in contextualizing our resulting visualizations. Although we understood the main story, many nuances and intricacies are left untouched, and require further exploration. We have merely grazed how this issue intertwines with the culture, traditions, and livelihood that exists in Lubra.

Results

With the described methods, we created 3D digital models, DEMs, and 2D maps for village relocation, flood damage visualization, and riverbed elevation quantification. Throughout this section, we will look at the visualizations created, the data underlying them, and the logistics involved in creating them.

RELOCATING LUBRA VILLAGE

To understand each AOI, we surveyed the village, its surrounding land, and new locations by creating 3D digital models and 2D maps from collected imagery and GPS points. These 3D

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[12] Professional 3D modeling software for processing images and creating models.
[13] A set of data points in space that represent a 3D shape or object.
[14] Professional geographic information system software for mapping and geospatial analysis.
[15] 30-to-60-minute conversations in Tibetan, translated into English by co-author Gurung.

models and 2D maps assist the architecture and development team when planning the new village.

LUBRA VALLEY MODEL

The Lubra Valley model represents the entire south valley side and supports the architecture and development team in understanding the valley's topography and village infrastructure. In place of our crashed drone, a phone camera sufficed for creating this model by hiking along the entire valley cliffside edge, taking photos with a phone and binoculars.[16] On subsequent visits, we utilized a second drone purchased in Kathmandu. The Lubra Valley 3D Model is shown briefly in Figure 10 with its corresponding summarized data in Table 3. The rest of this 3D model is shown in Figure A1 in Appendix A, located in this article's supplemental materials.

Table 3: Summary Table of Data Used to Create the Lubra Valley 3D Model

Model Name	Number of Photos	Resolution	Photo Type	Tool	Time Needed
Lubra Valley	463	3840x2160 px	Terrestrial	Phone	12 hours

Figure 10: Lubra Valley – Angled Perspective of the 3D Digital Model Representing the Valley Side in 2022

[16] We do not recommend doing this, for this method is too dangerous and can lead to death without proper training.

RELOCATION MODELS

The three relocation models visualize the terrain and layout of locations A, B, and C. We did not survey location D due to time constraints. With these models, the architecture team can visualize land development for a new settlement. The relocation 3D models are shown briefly in Figures 11, 12, and 13 with their corresponding summarized data in Table 4. The rest of these 3D models are shown in Figures A2 through A7 in Appendix A.

Table 4: Summary Table of Data Used to Create the Relocation 3D Models

Model Name	# of Photos	Resolution	Photo Type	Tool	Time Needed
Location A	177	3840x2160 px	Aerial	Drone	4 hours
Location B	195	3840x2160 px	Aerial	Drone	6 hours
Location C	183	1080x1920 - 3840x2160 px	Aerial	Drone	3 hours

Figure 11: Location A – Aerial View of the 3D Digital Model Representing Location A.

Figure 12: Location B – Aerial View of the 3D Digital Model Representing Location B

Figure 13: Location C – Aerial View of the 3D Digital Model Representing Location C

HOME CONSTRUCTION MODEL

The Home Construction model visualizes co-author Gurung's new home as it is under construction after floods damaged his previous home. Representing one month of construction, this model provides the type of structures expected in a new village, as well as required build time. The Home Construction 3D Model is shown briefly in Figure 14 with its corresponding summarized data in Table 5. The rest of this 3D model is shown in Figures A8 and A9 in Appendix A.

Table 5: Summary Table of Data Used to Create the Home Construction 3D Model

Model Name	# of Photos	Resolution	Photo Type	Tool	Time Needed
Home Construction	464	3840x2160 px	Terrestrial	Phone	3 hours

Figure 14: Home Construction – Aerial View of the 3D Digital Model Representing Co-author Gurung's Home

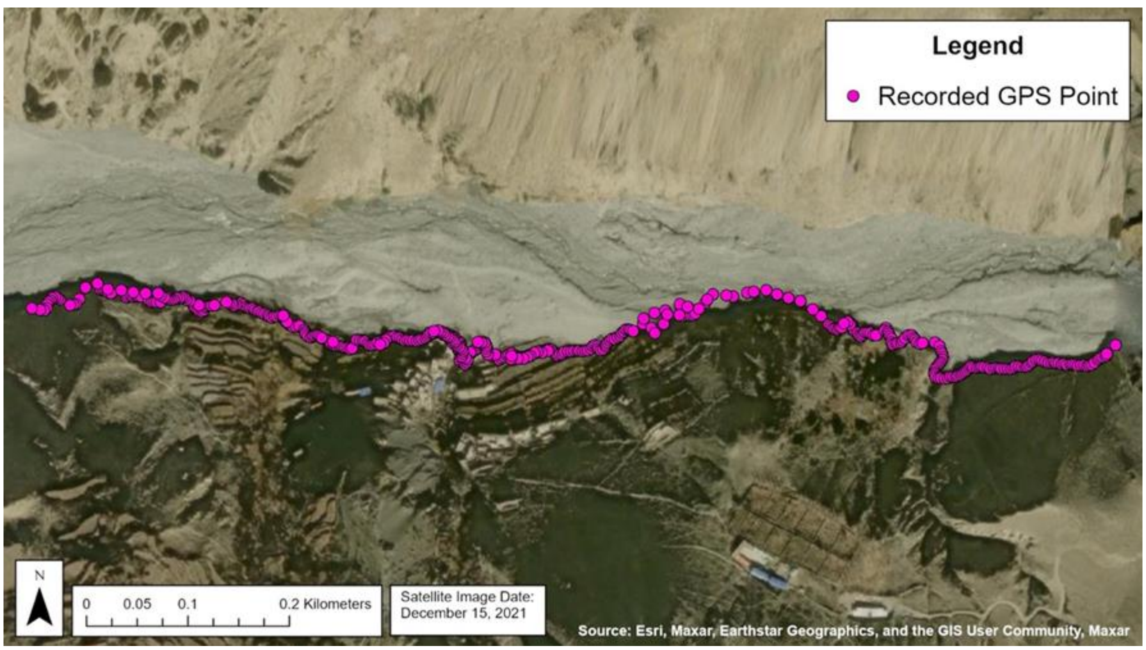
NEW FLOOD LINE MAP

Using the collected GPS data as shown in Figure 15, we plotted a new flood line in 2022 using ArcGIS Pro and Adobe Photoshop.[17] To merge the flood lines onto one satellite image, we first aligned the two satellite images of Figure 6 and Figure 15. Then, we traced over both the GPS points and previous flood lines onto one satellite image. With our flood lines merged onto one satellite image as shown in Figure 16, we observe the erosion of the toe area of the valley slope for 58 years and how the flood line shifts southward towards Lubra.

VILLAGE TRAIL INFRASTRUCTURE MAP

With the GPS points collected (shown in Figure 17), we created maps to visualize the village infrastructure and demonstrate how each location would fit in the community's current infrastructure as shown in Figure 18. We drew the trails and roads by tracing our GPS points in Adobe Photoshop.

Figure 15: GPS Points Recorded while Walking the New Flood Line in 2022 and Plotted in ArcGIS Pro



[17] Professional photo editing software.

Figure 16: New Flood Line in 2022 (Pink) Overlayed with Previous Flood Lines

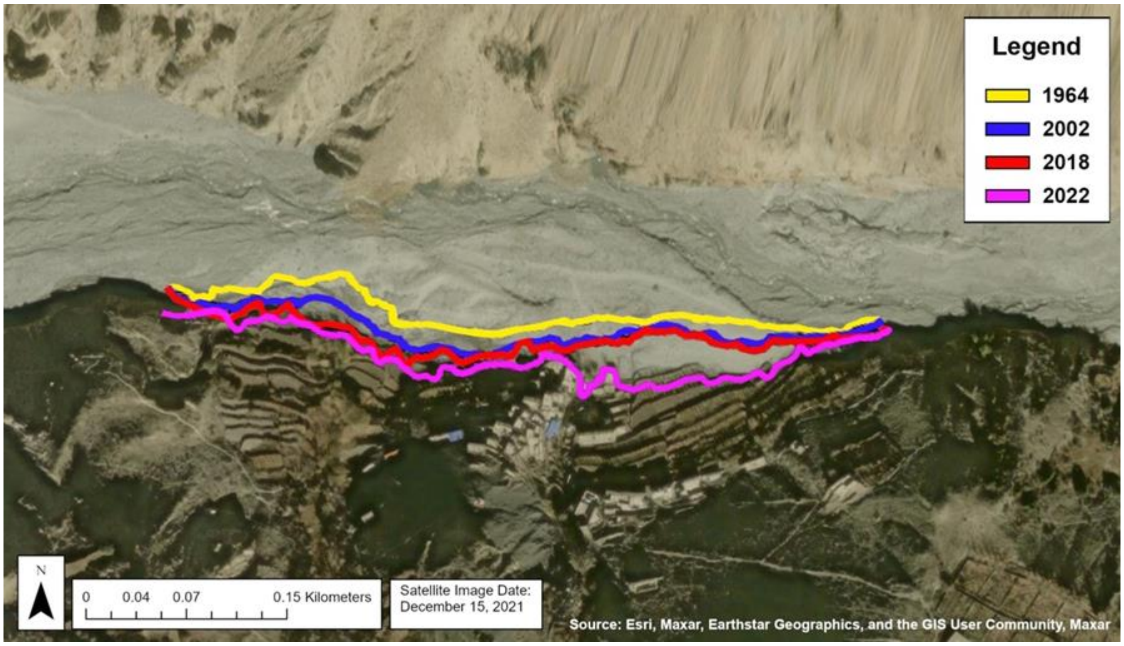


Figure 17: GPS Points Recorded while Walking all Main Trails and Roads across Lubra in 2022 and Plotted in ArcGIS Pro

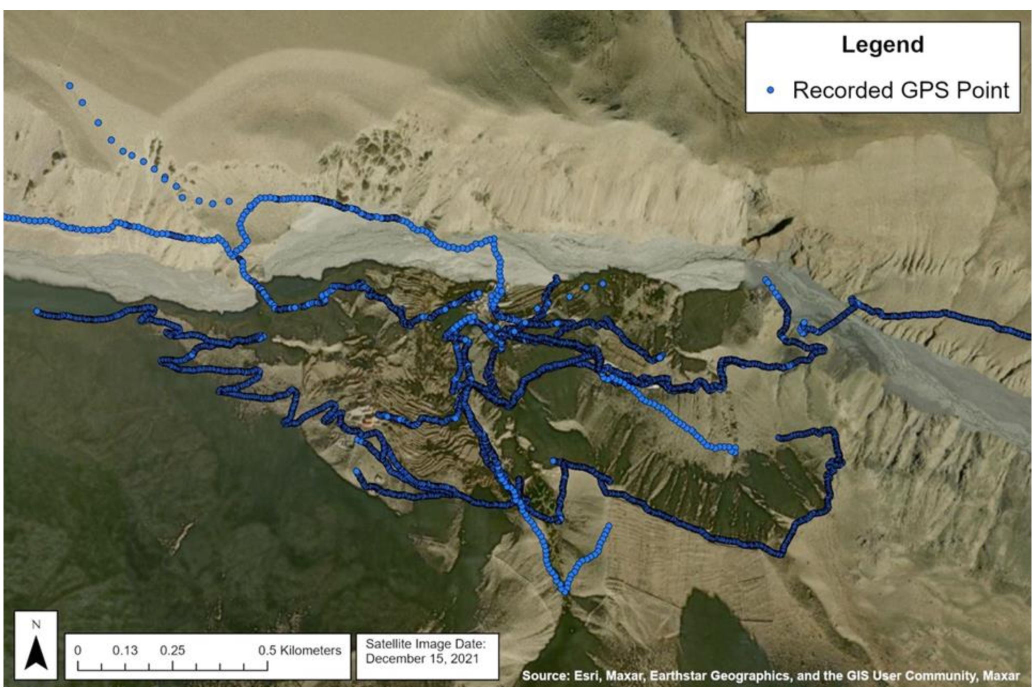
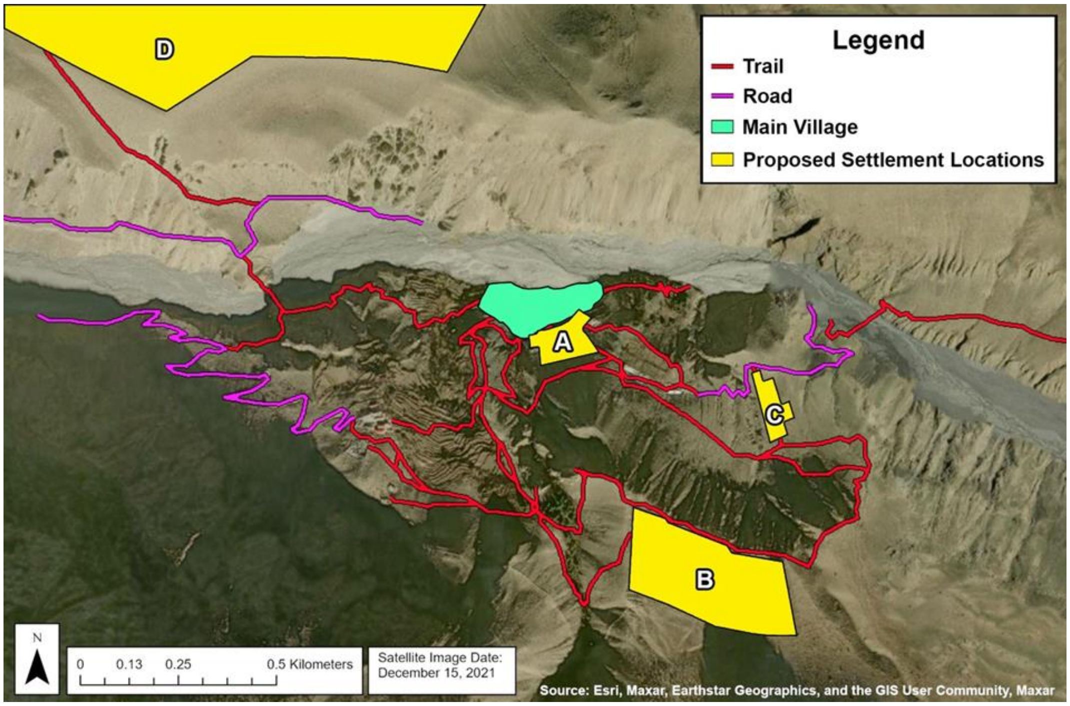


Figure 18: Trail Infrastructure Map of Lubra with Proposed Settlement Locations in Relation to the Main Village



Visualizing Flood Damages

To communicate flood damages effectively, efficiently, and accessibly, we modeled flood damages of homes and agricultural fields.

MAIN VILLAGE 2022 MODEL

The Main Village 2022 model represents the main village structures and fields before further damage occurs. This is the best model because it captures visual details of the village before further destruction from flooding. This model serves as digital documentation before permanent disappearance. The Main Village 2022 3D model is shown briefly in Figure 19 with its corresponding summarized data in Table 6. The rest of this 3D model is shown in Figures A10 through A19 in Appendix A.

Table 6: Summary of Data Used to Create the Main Village 2022 3D Model

Model Name	# of Photos	Resolution	Photo Type	Tool	Time Needed
Main Village 2022	916	3840x2160 px	Aerial	Drone	12 hours

Figure 19: Main Village 2022 – Aerial View of the 3D Digital Model Representing Lubra Village in 2022

RIVERBED MODEL

The Riverbed model represents the riverbed, covering about $10km^2$ of riverbed surface. With this model, we have an accurate reference as to what the riverbed looks like visually. With this dense model (over 7,000,000 generated points), potential applications may involve generative machine learning for 3D model generation, something we will discuss briefly in the Future Research section. The Riverbed 3D model is shown briefly in Figure 20 with its corresponding summarized data in Table 7. The rest of this 3D model is shown in Figures A20 through A22 in Appendix A.

Table 7: Summary of Data Used to Create the Riverbed 3D Model

Model Name	# of Photos	Resolution	Photo Type	Tool	Time Needed
Riverbed	250	3840x2160 px	Aerial	Drone	12 hours

Figure 20: Riverbed – Aerial View of the 3D Digital Model Representing the Lubra Riverbed Adjacent to the Main Village in 2022

MAIN VILLAGE 2016 MODEL

The Main Village 2016 model represents the main village of Lubra as it was in 2016. We must be clear that this model is an outlier and a result of luck. As trekkers pass through Lubra, some fly their drone for commercial or personal use. In this case, we found drone footage uploaded to video-hosting platform Vimeo by an anonymous trekker (Anonymous Trekker, 2016). Furthermore, we were lucky as the angling of the footage captured perspectives needed to generate a 3D model of the main village. The Main Village 2016 3D Model is shown briefly in Figure 21 with its corresponding summarized data in Table 8. The rest of this 3D model is shown in Figures A23 through A25 in Appendix A.

Table 8: Summary Table of Data Used to Create the Main Village 2016 3D Model

Model Name	# of Photos	Resolution	Photo Type	Tool	Time Needed
Main Village 2016	162	1080x1920 px	Aerial	Drone	6 hours

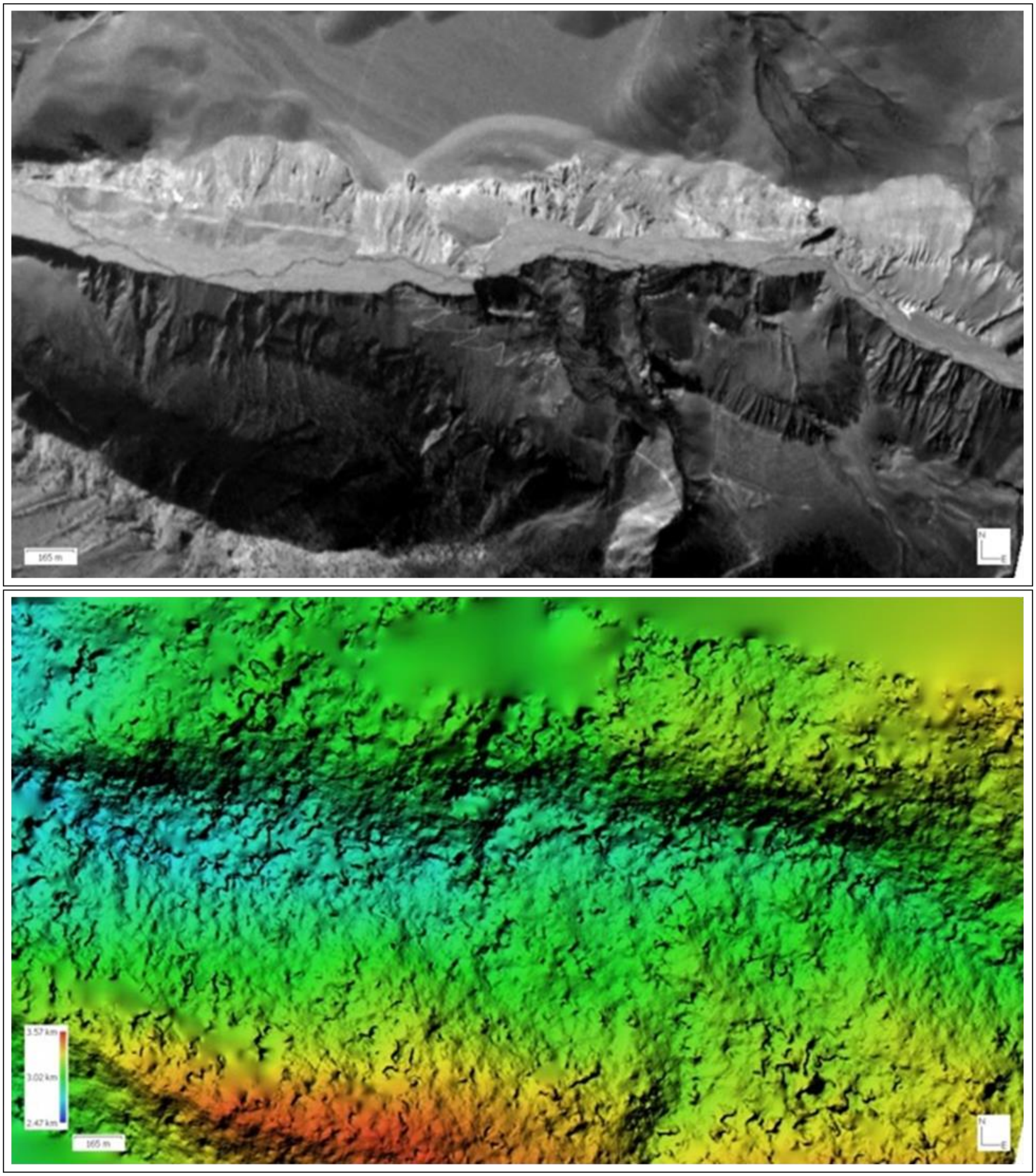
Figure 21: Main Village 2016 – Aerial View of the 3D Digital Model Representing Lubra Village in 2016

Quantifying Riverbed Elevation

To address the lack of quantitative data, we explored generating DEMs to capture elevation trends. In this section, our goal was to compare multiple DEMs across 2015-2022, calculating elevation differences between each model. To create these DEMs, we used two satellite images that are unrectified, and captured the same day within minutes of each other, have little to no cloud cover, and a resolution of at least 3-7 meters/pixel. With these specifications, we took advantage of PlanetScope data, a set of satellite images collected by Planet Labs' satellites (Planet Labs PBC, n.d.).

For example, to visualize the riverbed elevation four years ago, we use two unrectified satellite images taken on October 24, 2018, captured 10 minutes apart, and performed photogrammetry with Agisoft Metashape. With the resulting DEM shown in Figure 22, a lot of bumps, or noise, exist throughout the valley space. This noise is an issue, as it leads to false measurements. To mitigate this issue, one option is smoothing out noise using software like RStudio.

Figure 22: Aerial View of Lubra Village (Top) and Corresponding DEM (Bottom) in 2018.



One limitation of photogrammetry is that we could only make DEMs after 2015 due to the limited number of high-resolution images prior. To create DEMs prior to 2015, we used freely available Sentinel-1 data (Copernicus Open Access Hub, n.d.), where two satellites (Sentinel-1A and Sentinel-1B) perform C-band synthetic aperture radar imaging. Although a great resource for generating DEMs, the process of generating these are different from our photogrammetric workflow. Instead, we used interferometry, a technique that uses the interference of superimposed waves to extract information (Braun, 2021). Due to its difficult 20-step process, we focused on using photogrammetry with the high-resolution data that we do have. Lastly, searching for riverbed elevation data that already exists from previous studies or institutions remains a continued effort.

Future Research

Moving forward, quantifying riverbed elevation trends and numerically recording the progression of flood damages will be beneficial. This objective will include acquiring measurements of how the flood line has shifted towards Lubra in meters and acquiring measurements of how the riverbed elevation has risen over time in meters. One data visualization that would be effective for demonstrating riverbed elevation rise over time is a cross-section of the riverbed. This 2D graphic would show different elevations with their associated year relative to the elevation of residential homes. Additionally, a graph demonstrating the riverbed elevation's rate of change over time would be beneficial.

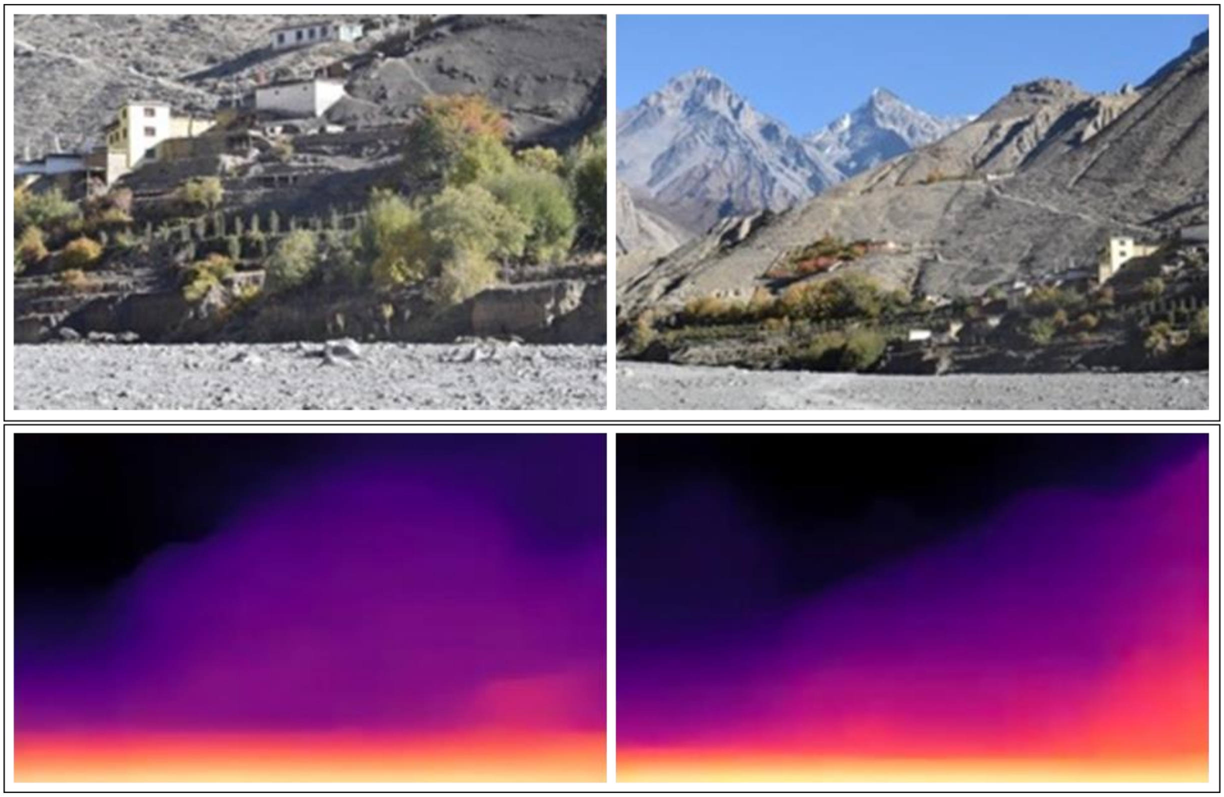
In terms of visualizing flood damages, one experimental approach that would be worth exploring is deep learning as a tool for creating historical 3D models of Lubra from sparse imagesets. With our 224 archived photos of Lubra spanning a two-decade period, we wonder about generating historical 3D models of Lubra from a single image. Creating these 3D models would help in visually comparing flood damages over the last two decades, further establishing a timeline for flood damages. Generating depth maps from our single archived images using monocular depth estimation (shown in Figure 23) would be an interesting first step towards this (Hristova et al., 2022; Song & Kim, 2019).

Whether through DEMs, 3D modeling, or an experimental approach, quantitatively recording flood damages supports Lubra in informing local policy and requesting relief aid. For example, our data-backed visualizations and analyses strengthen communal arguments by integrating them into grant proposals for funding a new settlement. Furthermore, our visuals and analyses act as a resource for Lubra when interfacing with communal leaders, policymakers, and NGOs. Lastly, our visual resources support the architecture team in planning and developing a new settlement. We believe future iterations of our research will support Lubra and other Himalayan communities by further exemplifying remote sensing and community-driven narrative for documenting climate-induced damages.

Conclusion

The issue that Lubra faces is intertwined through hundreds of years of cultural heritage and ancestry, which must be carefully considered when introducing western engineering perspectives. Through thoughtful collaboration, we strived to use non-invasive methods that supports the community in communicating their story. Briefly assessing the effectiveness of these techniques, photogrammetric 3D modeling allows swift creation of highly detailed models for understanding the community from a structural view. Additionally, the resulting models digitally document the current state of Lubra Village before complete destruction and visualizes on-going flood damages. The digital elevation models offer the ability to quantitatively record riverbed elevation changes. However, no quantitative assessments are made at this time because each DEM must be refined for accurate measurements, and we need more DEMs to compare. Before making further judgments about settlement relocation, a slope stability analysis should be carried out.

Figure 23: Testing Depth Estimation on Two Archived Images (Top) with their Corresponding Depth Map (Bottom) (Poggi et al., 2018)



Working closely with the community, we gain a deeper understanding of communal perspectives in the planning and development of a new village. Pairing visualized data with personal accounts, we provide an informative story that depicts Himalayan climate change on a local level in Lubra Village. Pairing personal accounts is imperative, as our work is guided by the community's needs and cannot be done any other way. Through our work, we hope to empathetically shed light on Lubra's story and demonstrate how to combine remote sensing and community-driven narrative to support them.

Acknowledgements

We would like to thank several parties who were integral in this work's success. First, we thank the families in Lubra for offering their time in answering our multitude of questions. Their insights were crucial in understanding flooding from their perspective, and what steps we can best take to support them. We also thank all other interviewees for their time and for supporting our research. Second, we thank the medical team at Jomsom District Hospital for their care, ensuring quick recovery from unexpected altitude sickness and food poisoning. Third, we thank Dr. Isabelle Onians, Nazneen Zafar, Patricia Owens, Dhichen Wangmo, and Rinzi Sherpa of the School for International Training, assistant professor Dane Carlson of Principia College, architect Sonam Lama, and Amalia Rubin for their in-country support and mentorship. Fourth, we thank staff engineer Nathan Hui and Dr. Curt Schurgers of University of California San Diego, and Dr. Susan Fox of Macalester College for their mentorship in engineering and remote sensing. Finally, we thank our friends and family for their unwavering support. We cannot express our gratitude enough. Thank you!

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