The Fundamental Role of GNSS in Modern Surveying and Mapping to Support Climate Responsive Land Governance and to Enhance Disaster Resilience

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Key words: GNSS, Positioning, Surveying and Mapping, Land Governance, Disaster Resilience

SUMMARY

The geodetic infrastructure such as terrestrial reference frames and Continuously Operating Reference Station (CORS) infrastructure is fundamental to build and support climate responsive land governance and disaster resilience. Similarly, the surveying and mapping information from modern surveying methods such as Real Time Kinematic (RTK), Light Detection and Ranging (LiDAR) and Unmanned Aerial Vehicle (UAV), etc. is equally important to address climate challenges and disaster management. However, whether it be reference frame or CORS or modern surveying methods; Global Navigation Satellite System (GNSS) is key to provide precise positioning. The role of GNSS is important here because precise and accurate positioning is fundamental. Nowadays, GNSS is the only method that offers precision, accuracy, efficiency, and cost-effectiveness as a precise positioning tool.

Climate-responsive land governance and disaster resilience draw a huge contribution from the surveying and mapping profession as this is closely tied to climate change, disaster risk reduction, tenure security, land governance, geospatial information management, land administration and land management, spatial planning and land valuation. In turn, surveying and mapping get their precise and accurate positioning from GNSS. Thus, in various ways, GNSS has an important role in supporting climate-responsive land governance and disaster resilience. In this paper, we explored how GNSS in the form of reference frame, CORS, and precise positioning tools in modern surveying methods has been directly and indirectly contributing to achieve climate responsive land governance and disaster resilience.

In addition, we discuss both the advantages and challenges of applications of GNSS in various forms and to meet various purposes from technological, policy, existing infrastructure and future perspectives. Also, we present and discuss gaps and limitations in order to find better ways to address climate challenges and disaster management.

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1 Introduction

Global Navigation Satellite System (GNSS) plays a crucial role in surveying and mapping activities due to its capability of providing precise positioning, all-weather suitability, accessibility in any part of the world, versatility across various applications and integration with other modern surveying instruments. GNSS significantly improves upon traditional surveying methods by offering high accuracy, ease of operation, and increased efficiency (Jiang & Zhao, 2023). The continuous advancement in GNSS technology enhances the reliability and accuracy of measurements, making it indispensable in navigation, land governance, disaster risk reduction and other geo sectors (CELMS et al., 2024).

Geodetic infrastructure, such as terrestrial reference frames and Continuously Operating Reference Station (CORS) infrastructure, is fundamental to building and supporting climate-responsive land governance and disaster resilience. This reference frame will be the backbone for all kinds of surveying and mapping works as well as for building climate-responsive land governance and disaster-resilient communities. Climate-responsive land governance generally involves integrating land use and management along with climate considerations to address the challenges of climate change. Disaster resilience generally refers to the ability of communities as well as systems to anticipate, prepare for, respond to and recover from the disasters. GNSS can be seamlessly integrated well with modern surveying instruments such as UAVs, LiDAR, RTK and other geospatial tools to address climate challenges and disaster management.

Precise positioning is vital for enhancing climate-responsive land governance by facilitating accurate spatial-based decision-making processes, significantly improving land administration functions such as land use, value, tenure and development (Pinuji, 2020). Using precise positioning data, urbanization can be better managed through effective land use planning, squatter and informal settlement management, precise cadastral surveys and tenure security. This reduces vulnerability and improves environmental sustainability, particularly in rapidly urbanizing areas susceptible to climate change impacts (Mitchell et al., 2015). Detailed maps prepared using precise positioning help policymakers plan land use to mitigate climate impacts, such as avoiding development in flood-prone areas, near wetlands, or on unstable soil prone to landslides and guide infrastructure development in safe locations. Precise Positioning also plays a crucial role in disaster resilience by aiding in effective decision-making and response strategies. GNSS provides real-time data on ground movements, essential for early detection of seismic activity and land subsidence. This data can be integrated with early warning systems, giving communities time to evacuate and take proactive measures in order to build disaster-resilient societies. Additionally, precise geospatial data helps assess the extent and severity of disasters, which is crucial for planning and prioritizing recovery efforts.

This paper explores how GNSS, through reference frame, CORS, and precise positioning tools in modern surveying methods has directly and indirectly contributed to achieving climate-responsive land governance and disaster resilience. We discuss the advantages and challenges of GNSS applications across various contexts, considering technological, policy, existing infrastructure and future perspectives. Furthermore, we identify gaps and limitations in order to find better ways to address climate challenges and disaster management.

2 Background and Literature Review

2.1 Geodetic Infrastructure in Nepal

The existing current horizontal reference frame in Nepal was established more than four decades ago under the collaboration between MoDUK and the Survey Department using a traditional approach (S. KC & Acharya, 2022). Since 1981, Nepal has gone through multiple major and minor seismic events including the mega earthquake 2015. However, Nepal hasn't been able to update the control stations with the changing times and technology as this is directly related to cost and resources. Having said that, Survey Department has realized the importance of an up-to-date horizontal reference frame and thus has started the establishment of new CORS stations that can be used to update the reference frame. This CORS network will also be used for the adaptation of semi-dynamic datum that will be based on the most current International Terrestrial Reference Frame (ITRF). So far, Survey Department has established 4 CORS stations namely: NAGR, NAPI, PLWA and BRDB and it plans to expand this network in the years to come. Similarly, on the counterpart, the Survey Department has also initiated the integration of the other CORS networks established by other agencies with the ones established by the Survey Department to make a wider and broader network of CORS. Figure 1 shows the recently established CORS station along with its accessories at Piluwa, Bara.

a)

(b)

Figure 1: Recently established CORS station (PLWA). (a) CORS Station Monument (b) CORS Station Accessories

Under the Survey Department's plan to expand the CORS station network, is planning to widen the network so that there is one station in every 30-40 km distance interval. This is being done in different levels, where the proposed first-tier aims to establish one station for each 70-80 km separation which will later be reduced to 30-40 km. The following map in Figure 2 shows the potential locations of the first-tier CORS stations throughout the country and the existing CORS operated by the Survey Department and UNAVCO. This CORS network will be able to maintain an accurate and updated horizontal reference frame leading to accurate cadastral surveys and mapping in the country for climate-responsive land governance and enhancing disaster resilience.

With the help of the CORS network, we can define the National Terrestrial Reference Frame for Nepal which will be the backbone for all kinds of surveying and mapping works as well as to build climate-responsive land governance and disaster resilient community. In the future, after the establishment of the CORS network, the CORS station will act as a reference station for doing RTK-based cadastral surveys and provide correction services while collecting details of each boundary point. Besides, the CORS network will work as the fundamental station for correction and measurement techniques in all engineering survey works. These precise positioning datasets will be crucial for climate-responsive land governance and disaster resilience, contributing to tenure security, land governance, geospatial information management, land administration, land management, spatial planning and land valuation.

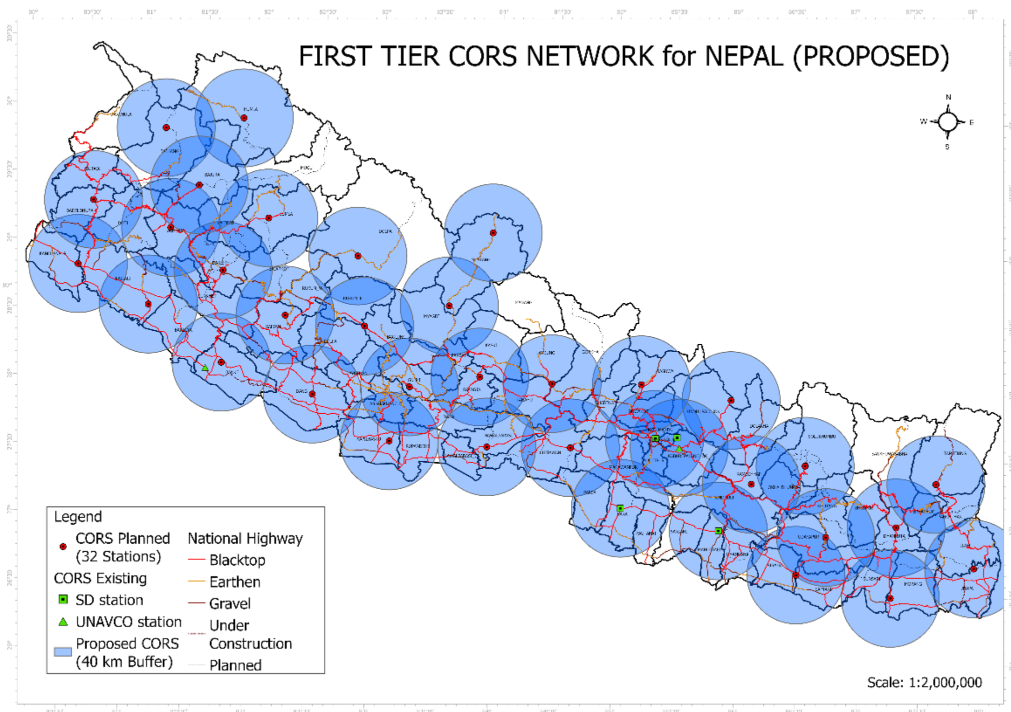


Figure 2: Proposed first-tier CORS Network for Nepal

2.2 Modern Surveying Methods for Disaster Risk Management

Modern surveying methods such as UAVs, LiDAR, and RTK etc. use GNSS in integrated manner in order to provide precise positioning of geospatial data/information. Such precisely positioned geospatial data as an input to disaster risk mitigation models and climate studies promotes the reliability of various disaster resilience efforts as well as climate action.

UAVs, equipped with various sensors and GNSS, have become essential tools in natural disaster monitoring, early warning systems, post-disaster assessment, and ecological restoration (Chen, 2024). For example, UAVs combined with GNSS are used to search for missing persons or locate individuals in need of assistance (Ghosh, 2023). In post-disaster scenarios, UAVs have proven indispensable for rapid, high-resolution surveying of building damage, facilitating efficient disaster response and recovery efforts by assessing affected areas (Nagasawa et al., 2021). This integration not only enhances the efficiency and accuracy of disaster management but also helps address potential threats posed by climate change-induced natural disasters. GNSS provides precise positioning data essential for UAV navigation, data collection, and georeferencing of UAV imagery. Associating precise coordinates with orthomosaic maps helps create detailed and accurate maps necessary for disaster analysis and management. Furthermore, integrating GNSS with thermal sensors mounted on UAVs can detect heat emitted by people and animals, even in low

visibility conditions like fog, underwater, and smoke, making it useful for locating survivors in disasters such as floods, forest fires, and earthquakes (Yeom, 2024).
LiDAR technology has significantly contributed to disaster risk management and climate change adaptation by providing high-resolution 3D point cloud data. Its effectiveness in emergency response is demonstrated through the 3D capture of disaster scenarios (Ghosh, 2023). LiDAR also uses precise positioning from GNSS for georeferencing point clouds. It has been instrumental in quantitatively evaluating the impact of natural disasters like floods and hurricanes on infrastructure such as buildings, roads, bridges, and power lines, aiding efficient disaster response efforts (Mehta et al., 2022). Additionally, the integration of LiDAR data with GNSS allows for the assessment of landscape changes before, during, and after disaster events, enhancing the understanding of terrain features and identifying disaster risks and environmental alterations due to climate change (Bellini et al., 2024).
Another modern surveying method, RTK, has also significantly contributed to disaster risk management and climate challenges. For example, RTK GNSS network systems have been deployed in earthquake-prone areas of Japan to monitor crustal movements and provide early warning signals(KATO et al., 2022). These systems also continuously monitor ocean-bottom crustal movements, enhancing tsunami warning capabilities and enabling forecasting and ionospheric monitoring(KATO et al., 2022). Further research is needed to explore the full potential of RTK GNSS in disaster risk management.

2.3 Use of GNSS for Disaster Management Practices

The application of GNSS technologies plays a crucial role in disaster mitigation. GNSS technology naturally complements disaster management because nearly every aspect of a disaster is tied to a precise location (Westlund, 2010). The value of GNSS in tracking and managing disaster events cannot be overstated. GNSS provides real-time, highly precise location information, which is essential for managing all phases of a disaster i.e. pre-disaster, during the disaster, and post-disaster (Kafi & Gibril, 2018). GNSS technologies are widely utilized in climate and disaster management through various techniques of surveying and mapping.
For instance, accurately determining the ground displacement of the area will yield vital information for understanding the earthquake's structure and scope, ultimately aiding in quicker and more accurate earthquake predictions. In (Lau, 2017), the precise point positioning method was used to measure the displacements of 17 GNSS stations around the epicenter on the day of the devastating earthquake in 2015 in Nepal. The results show that the predominant displacement direction is close to the southwest, with the largest value being approximately 2 meters (Lau, 2017). The affected area extends about 160 kilometers in the southeast direction, centered on the earthquake epicenter (Lau, 2017). Thus, GNSS technology is crucial to monitor the effect and affected area of the earthquake.
Likewise, a static survey method was employed by (Z. Abidin et al., 2004) to investigate landslide displacement. GNSS provided precise coordinates of vulnerable areas at specific intervals, allowing the study of displacement characteristics and rates (Kafi & Gibril, 2018). Dual-frequency receivers measured coordinate differences with millimeter-level accuracy(Z. Abidin et al., 2004).
Similarly, in tsunami monitoring, (Maio et al., 2013) compared GNSS georeferenced ground photos of damaged areas with post-event satellite data. The high-precision kinematic GNSS data was used to pinpoint each damaged building. Post-event satellite imagery was then compared with ground-truth GIS data, and a tsunami damage map was generated by analyzing pre- and post-disaster satellite images. GNSS was crucial in determining the exact locations of damaged structures in this case.
Also, a study (Cova, 2016) examined the impact of the Oakland fire, which destroyed over 2,500 structures. Here, GNSS and survey questionnaires were used to assess each structure's damage. GNSS was instrumental in collecting locational data (Cova, 2016). During the fire, GNSS and GIS were employed to map the fire perimeter and geo-reference damaged or destroyed structures. This data was overlaid with census and parcel maps to evaluate individual losses and support rebuilding loan and grant applications. GNSS plays a vital role in various aspects of forest fire management, from preparedness to suppression (Alkhatib, 2014).

In the same way, Geomatics technologies including GNSS, RS, and GIS, are increasingly used for flood assessment. They integrate inventory mapping, surface structure location, roughness information, and factors like lithology, fault location, slope, vegetation, and land use to provide comprehensive flow emplacement parameters (e.g., rate, velocity, rheology) (Malet et al., 2002). In flood disaster management, (ISLAM & SADO, 2000) utilized GNSS and Synthetic Aperture Radar (SAR) imagery to estimate flood water depth.

3 GNSS for supporting Land Governance

Land Information System (LIS) is a crucial component of land governance. A national land administration system and informal settlement management are two focus areas in the context of Nepal, which requires a robust, geospatially accurate and precise LIS. GNSS is the key to providing precise positional links to geospatial information of LIS. In this section, we elaborate upon how the cadastral surveying and mapping component of the national land administration system is made efficient and timely by GNSS positioning and how this facilitates to achieve the objective of land governance and take climate action. Similarly, we discuss the role of GNSS in informal settlement management and engineering surveying projects in order to support land governance and take climate action and disaster management.

3.1 Cadastral Surveying and Mapping

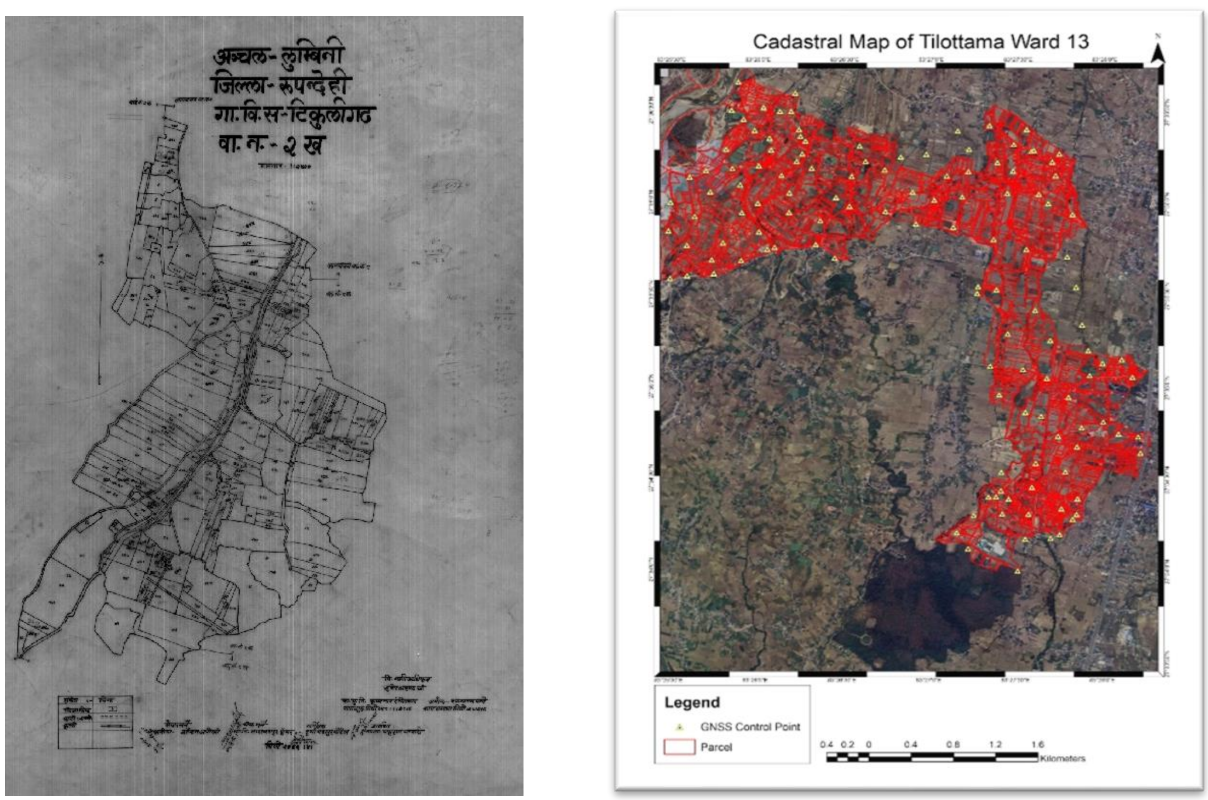
In the pursuit of implementing the Land Reform Act of 1963, SD started a nationwide cadastral survey without any geodetic control points (S. KC & Acharya, 2022). These surveys were mainly concentrated on cadastral mapping and land revenue collection whereas other development projects and cadastral applications on disaster resilience in such projects were not realized by then (Chhatkuli, 2007). However, since the cadastral maps were made in free sheets, this created inaccuracies and misleading as they lacked the georeferenced (spatial) information. Realizing the above-mentioned problem, GSD started preparing for reference control points establishment for cadastral applications to increase the accuracy and precision of produced maps. This network establishment was expected to minimize the spatial inaccuracies in the cadastral data, also making them more reliable and usable for various applications such as disaster resilience, disaster risk reduction, infrastructure development and many more. The use of these control reference stations started in 1972 and was used in the mapping of 37 districts (S. KC & Acharya, 2022).

However, the survey technique was still inefficient. The establishment and transfer of national reference networks to areas of interest consumed greater time and manpower. This amplified the need for a faster technology for control station establishment that could boost the speed of work while also maintaining the spatial accuracy of the cadastral survey. Thus, GSD started GNSS surveys for reference station densification and re-survey of existing traditional control stations. At the moment, SD is conducting a re-survey using GNSS technology on 38 districts that were mapped on a freesheet previously. The current survey technique has significantly enhanced the accuracy, efficiency and reliability of the data.

GNSS applications for cadastral map updating directly support the United Nations Sustainable Development Goals UN SDG 1 (Zero Poverty) and UN SDG 11 (Sustainable Cities and Communities). In a country like Nepal, secure land tenure enables individuals to access credit, invest in their land and generate income. So, up-to-date Cadastral Maps are directly linked with the Poverty Reduction supporting UN SDG 1. Also, Cadastral Maps updated with GNSS technology are essential for effective urban planning and infrastructure development which contributes to more sustainable cities and communities supporting UN SDG 11. Parcel boundaries are the major cause of conflict and disputes in the society. Inaccurate survey techniques have resulted in fragile parcel boundaries leading to both economic and societal chaos. Thus, the foundational solution is to have an accurate measurement followed by up-to-date tools and policies.

3.1.1 Casework

The map below in Figure 3 (a) shows the free sheet map that was prepared in 1971. This map lacks spatial information as they were prepared on freesheets. Those static maps also made it difficult to demarcate the accurate boundaries later. Back then the sole purpose of preparing cadastral maps was to collect land-related tax. Whereas with the changing times, the use of cadastral information started being useful for real estate, development projects, land pooling, land acquisitions, disaster resilience society, spatial planning and supporting climate-responsive land governance and disaster resilience which required spatial accuracy. Thus, the map below in Figure 3(b) is an example of Tilottama Municipality Ward-13, Rupandehi district of Nepal which was re-surveyed and geo-referenced using GNSS control points spread all over the wards. Current cadastral maps are digital and spatially correct, which is why they can be used for other spatial analysis and land-related analysis purposes. This has also made it easier for Survey offices/professionals to easily communicate with the public on boundary-related matters as the digital cadastral maps can now be accurately overlaid on aerial imageries. Digital and georeferenced cadastral maps have significantly reduced boundary demarcation-related issues and have expedited the demarcation process. Besides mapping and boundary demarcation, the GNSS survey has also technically supported cadastral map updating, spatial record keeping, disaster management and management of an effective land tenure system.



(a) (b)

Figure 3: a) Cadastral Free Sheet Map prepared in 1971 b) Updated cadastral map with GNSS control points.

3.2 In Informal Settlement Management

Informal settlement and management of squatters have been a major issue in land tenure management systems in major developing nations, including Nepal. Management of squatters and informal settlements has been mentioned in the Constitution of Nepal Part 4, Article 50 (J). The Government of Nepal (GoN) had tried to solve this issue through various commissions in the past but none of them could get the job done. The major issue was the commissions were unable to precisely locate the area boundaries which made it difficult to quantify the land required and land being used. Thus, GoN has started using GNSS control points in satellite image rectification and detailed cadastral surveys for accurate cadastral mapping of the area. These precise cadastral maps help in effective land management and ensuring tenure security. Also, GNSS applications for squatters' area boundary demarcation directly support the United Nations Sustainable Development Goals (UN SDG) 1 (Zero Poverty) and UN SDG 11 (Sustainable Cities and Communities).

3.2.1 Casework

The below map in Figure 4 shows a case of using the GNSS control stations for accurate georeferencing of cadastral data to map and quantify the area of informal settlement in Biratnagar Sub-Metropolitan City in Nepal. Initially, the area shown by the cadastral map below was registered as *"Parti Jagga"* meaning "the barren lands". Later, those parcels became settlements informally, but the records were still registered as barren lands. Since the lands were under the barren lands category, their transaction was not possible formally, which created an informal trade of such lands which was not under the land taxation radar. So, it was necessary to update the cadastral information, quantify the area that has changed from Barren to settlement and handover the land ownership to the people who have been using it for a long time now. So, a detailed and precise cadastral survey was conducted in such an area with the help of GNSS control stations. This survey was used to update the cadastral information and map them. In the following map, the parcels are demarcated after the recent survey conducted recently using GNSS control stations.

Figure 4: Cadastral map prepared using GNSS control points used for Informal settlement mapping.

3.3 In Engineering Surveying

Nepal is a developing country with hundreds of development projects going on each day. The major issue with the developing project, like roads, hydropower and transmission lines, is compensating private lands being used under the project area and accurate demarcation of Right of Way. This leads to proxy demarcation, mismatching of identified parcels, and financial issues as well. But now, these problems have almost been eliminated with the use of GNSS technology. For this, precise GNSS control point surveys are performed which will later be used for georeferencing of the survey data and cadastral data. Thus, project designs and corridors can be overlaid on the cadastral data to identify the affected parcels. This simplifies the overall compensation and boundary demarcation process. GNSS for development project demarcations and compensation supports SDG 9 (Industry, Innovation, and Infrastructure)

3.3.1 Casework

The following map shows a section of a road development project in Nepal. In this project, a GNSS survey was conducted at the beginning to support the precise topographical surveying and cadastral analysis process. The GNSS survey was followed by a topographical survey using UAV, where the previously established GNSS control points were used to georeference the orthomosaic and DEM. After the survey and design, it was time to estimate and map the area to be acquired for the project. Thus, cadastral data was overlaid on top of the survey data and was geo-referenced using the same GNSS points established to ensure the consistency and similar accuracy of the data, which was the major issue in earlier techniques of cadastral overlay. The major problem in earlier techniques was that the cadastral data could not be precisely georeferenced, leading to misidentification or false mapping. That could create both technical and financial burdens for the project. But, with the use of GNSS control points to georeference the survey and cadastral data, the overall survey design and execution of development projects along with land demarcation and acquisition has become easy, accurate and hassle-free.

Figure 5: GNSS-based cadastral mapping in development project.

4 GNSS for Disaster Resilience

GNSS has been used to build a national geodetic control network which is the fundamental geodetic infrastructure of any nation. Similarly, the nationwide GNSS CORS network is another fundamental backbone infrastructure of the country. GNSS CORS network is distinct from geodetic control network, however, they both serve a few similar functionalities as both are different arrangements for implementing GNSS technology. The geodetic control network has passive geodetic control points of different orders while in the GNSS CORS network, every CORS station acts as active control points. Both are the realization of the national reference frame, supporting various survey and mapping activities and disaster risk reduction activities (Abidin & Syafii, 2022). However, the GNSS CORS network is modernized and advanced form that it supports real-time positioning activities; it is compatible with modern surveying methods such as RTK, UAV, and LiDAR, etc. GNSS CORS network being modern, robust, and flexible, it plays a vital role in disaster management, disaster risk mitigation, and post-disaster rehabilitation and reconstruction activities (Abidin & Syafii, 2022).

Nepal faces disasters such as floods and landslides due to heavy rainfall during the monsoon season. Nepal is also an earthquake-prone zone. The 2015 Gorkha earthquake of magnitude 7.8 is a recent devastating disaster that heavily caused the loss of lives in central and eastern Nepal. These earthquakes substantially disturb the stability of hills and mountains due to which landslide such as Langtang landslide and Melamchi flood have occurred. The earthquake has become the cause of land subsidence in Kathmandu Valley in addition to human activities e.g. massive groundwater extraction (Bhandari, 2022). Land subsidence-related disasters are another category of potential disasters we might face in the future.

GNSS can be effectively utilized for monitoring, modeling, and determining characteristics of these disasters in order to support disaster risk reduction management. GNSS has been used to monitor landslides in two ways: campaign observation with the GNSS static survey method and the GNSS CORS method. In the GNSS static survey method, the position of the control station before and after the landslide event is determined and used for further landslide characteristics. The GNSS CORS method provides the time series position which subsequently provides subtle motion of land landslide potential area (Abidin & Syafii, 2022). Landslides have been high-frequency disasters with more than 2100 events in a decade between 2011 and 2020 that caused more than 1200 deaths, 1000 missing and hundreds turned homeless (R. KC et al., 2024). These landslide-prone areas should be mapped in local, provincial and national level land use zoning as natural hazard zones. Many researchers (Hu et al., 2024), (Huang et al., 2023), (Zeybek et al., 2014) have concluded that landslide events can be very accurately monitored, modeled and predicted with GNSS and machine learning algorithms. Modeling and prediction can help in creating a climate-resilient development activity and can help in the early detection of high-risk zones so that the inhabitants of the region can be moved to a safe place.

GNSS CORS has become a widely used technique of earthquake risk assessment. The subtle crustal motion of Earth's crust can be determined using long-term GNSS observation. The landmass of Nepal lies above the converging boundary zone of two active tectonic plates: the Indian and Eurasian plate (Upreti, 1999). International research institutes have deployed the strategic CORS infrastructure (S. KC & Acharya, 2022) in order to get insights on nature of crust motion, fault line, earthquake hazardous zone, potential earthquakes. Communities, professionals, and organizations should properly take account of earthquake related risk to achieve disaster resilience. High-rate GNSS CORS data have been used to determine dynamic ground displacement during the earthquake; precise 3D positioning in near real-time has been used to infer the underlying geology of the earthquake region (Galetzka et al., 2015). Having insights into underlying geology from ground displacement eventually helps to decision-making and policy formulation in context of disaster risk mitigation.

The sinking of human settlement areas and infrastructures are a disasters related to land subsidence. The Kathmandu metropolitan have experienced such a sinking of infrastructure during the Gorkha earthquake in 2015. Research has shown that land subsidence is due to heavy groundwater extraction in the Kathmandu metropolitan (Bhandari, 2022) (Bhattarai et al., 2017). The subsidence rate have been determined by time

series observation form GNSS CORS. Such land subsidence-associated disaster areas can be pre-identified using GNSS methods for disaster-resilient infrastructure and human settlement.
Geospatial products such as base maps, DEM and satellite image products combined with GNSS-supported positioning, surveying, and mapping are used to prepare various thematic mapping products that help during a) prevention and mitigation, b)preparedness, c)emergency response, d)rehabilitation and reconstruction (Abidin & Syafii, 2022).

4.1 Casework

Academia has been conducting multiple research each year in the disaster and climate resilience domain, while the industry has been executing the academic research outcomes. One of the major projects was to map and model the landslide activities in the Gorkha District (Location of landslide zones is shown in Figure 6). The project used GNSS control points, and LiDAR Survey to monitor the movement of the earth mass in pre and post-monsoon scenarios. The GNSS control points were established in highly susceptible zones identified prior and a UAV LiDAR survey was conducted to understand the 3D position of the surface. The advantage of GNSS control points is that we can have a temporal dataset of the same point over time to precisely examine the spatial changes. Control points were re-measured with the GNSS every month while also the UAV flights were carried out for the point cloud generation. Each dataset was compared with each other temporally, statistically and spatially to measure the spatial movement and to understand the movement direction of the earth mass. This temporal analysis of these six major landslides and susceptible areas in the district helped to understand the effect of monsoon, the pattern of slides, and early forecasting if we see any abnormalities in the velocity of earth mass. Among the six zones, three were highly reactive to monsoon and thus road construction through those belts was re-routed to geologically safer routes to avoid future loss. Besides, those identified monsoon responsive areas were further investigated by the team of geological experts to suggest methods to enhance the soil stability and minimize the landslide risks.

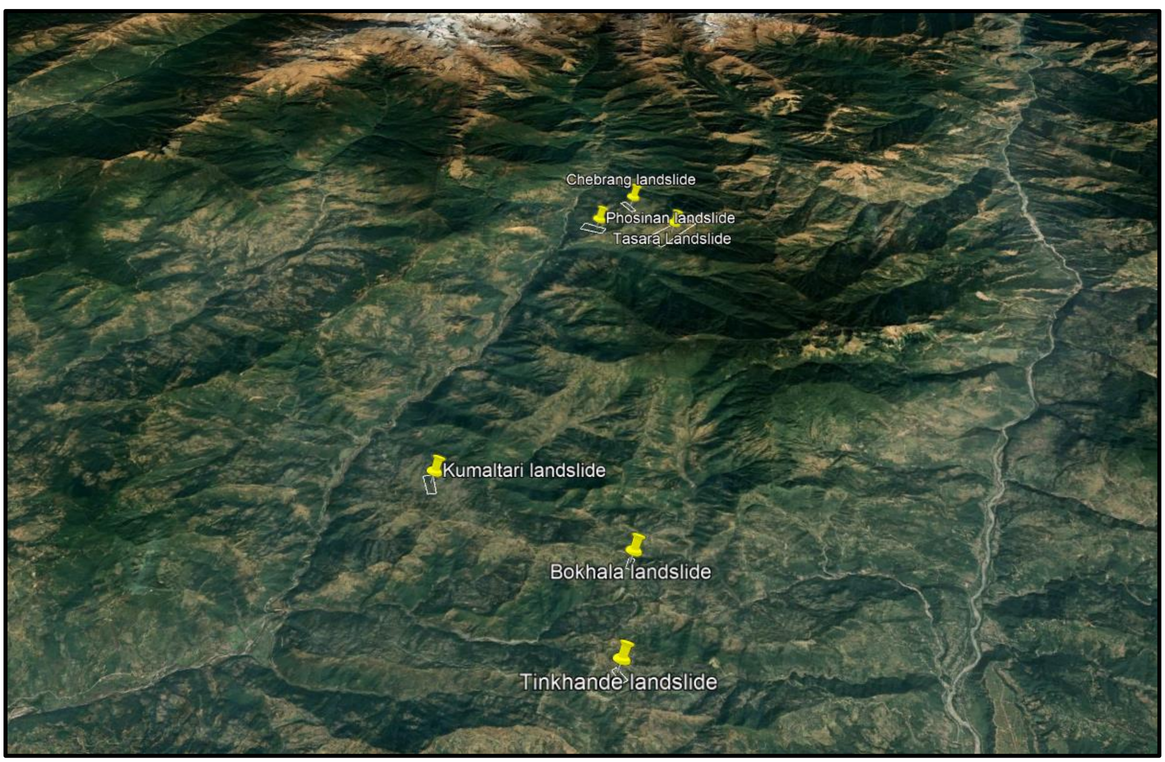


Figure 6: Location of Landslide Zones for study in Gorkha District

5 Discussion and Conclusion

GNSS have been key technology for land governance, disaster management, and climate resilience. In section 3, we discussed the GNSS precise positioning assisted surveying and mapping activities whose end products (e.g. cadastral maps of LIS) are the component of land governance and climate-responsive land governance. While in section 4, we discussed the utilization of GNSS to achieve disaster resilience by highlighting exploitation of GNSS technology in various natural and human-induced disasters.

GNSS provides accurate location information, crucial for tracking the movement and impact of various disasters such as earthquakes, floods, and landslides. It can also be integrated into early warning systems to detect changes in tectonic plates or sea levels, signaling impending disasters. GNSS is utilized at every stage of a disaster i.e. pre-disaster, during the disaster, and post-disaster through integration with other geospatial technologies. For effective land use planning and management, GNSS provides accurate spatial information. It helps resolve land disputes and safeguard land rights, as discussed in section 3. Additionally, GNSS supports the creation of precise cadastral maps and land records, essential for land registration, land valuation, and the transfer of legal rights. By providing precise geographical data, GNSS aids in planning and managing urban and rural areas, contributing to achieving Sustainable Development Goals. GNSS can be combined with UAVs, LiDAR and other geospatial technologies for comprehensive disaster monitoring, response and enhanced disaster management capabilities. Also, GNSS helps in assessing the impact of climate-related events on various infrastructures like bridges, dams, roads, etc. and natural landscapes.

GNSS faces several technological, policy, and infrastructure challenges in its application for disaster management, climate resilience, and land governance. One of the major challenges faced is the errors associated with GNSS such as multipath, satellite clock errors, signal bias, tropospheric and ionospheric delay. The troposphere and ionosphere can delay GNSS signals, causing errors in signal timing and reducing positioning accuracy (Yamada et al., 2023). These delays vary with weather conditions, which can be unpredictable during disasters. In urban areas with tall buildings, GNSS signals can be blocked or reflected causing a multipath effect, leading to reduced positional accuracy. This affects disaster management operations that rely on GNSS data for urban response efforts.RTK and Differential GNSS method work with additional base stations. Building and maintaining base stations requires huge cost. GNSS performs poor in tunnel and indoor settings. Similarly, GNSS signals are vulnerable to spoofing and jamming. This poses a risk in disaster management where accurate location is critical.
In countries like Nepal, there is a lack of policies for GNSS data acquisition, integration, and management. This makes it challenging to implement coordinated disaster management efforts and climate resilience initiatives involving multiple stakeholders (Hashim et al., 2023). The absence of standardized protocols for GNSS data sharing and integration with other technologies hinders effective collaboration and interoperability. Also, there is often insufficient government support for encouraging innovation and providing resources for the adoption of GNSS technologies in disaster management, climate resilience, and land governance.

Building nationwide CORS network and maintaining can be challenging for developing countries like Nepal. Regular maintenance and upgrades are essential to ensure continuous and reliable GNSS service. This can be resource-intensive. Addressing these challenges requires coordinated efforts, adequate funding, and robust policies to fully leverage the potential of GNSS in disaster management, climate resilience, and land governance.

As GNSS has found its application in almost all domains ranging from navigation, forestry, agriculture, communication, disaster risk reduction, land management, etc., future advancements in GNSS technology for disaster management, climate resilience and land governance have huge potential. Establishment of a

base CORS network becomes very essential to create a precise national reference network to support all the survey and mapping activities. GNSS RTK survey can be introduced in the cadastral survey to make precise measurements faster. Only small efforts are seen in utilizing advanced geospatial techniques like UAV, LiDAR and GNSS for disaster preparedness, risk reduction, mitigation and post-disaster response.
Leveraging multi-GNSS technologies with advanced signal processing techniques like multi-constellation and multi-frequency processing, along with adaptive algorithms, can enhance navigation resilience in GNSS-denied areas during disasters (Jangral et al., 2024). Collaborative efforts in research and technological solutions such as the development of accurate low-cost GNSS receivers can revolutionize land management applications, contributing to the modernization of the land management sector (Ta et al., 2021). GNSS technology can be combined with Artificial Intelligence to enhance and support decision-making during and after disasters. Low-cost GNSS can be installed in disaster-prone areas for monitoring disasters and provide valuable information on time for nearby people regarding disaster.

Future policy directions and necessary infrastructure improvements in the field of GNSS should enhance geodetic infrastructure to support GNSS data acquisition, integration, and management for implementing coordinated disaster management efforts and climate resilience initiatives involving multiple stakeholders. Policies and standards regarding GNSS geodetic infrastructure and its implementation regarding data acquisition, integration, interoperability and management should be made as soon as possible.

More research work needs to be carried out for the improvement of geodetic infrastructure, which is a base for any surveying and mapping activities and should ensure timely updates of that geodetic infrastructure. International collaboration regarding the use of GNSS geodetic infrastructure and promoting data sharing between different stakeholders for disaster management and climate resilience-related policies should be made and implemented effectively as soon as possible. Similarly, collaboration between government agencies, academic institutions and private companies should be increased in order to maximize the resources and expertise in the field of GNSS research works.

In the future, Artificial Intelligence (AI) and Machine Learning (ML) techniques must be utilized to process and analyze GNSS data for enhancing predictive capabilities for disaster management and climate resilience. Similarly, highly accurate GNSS should be integrated with LiDAR and UAVs for high-resolution mapping and monitoring of land use changes, disaster-prone areas, infrastructures, rivers and forests. Also, more exploration of the fusion of GNSS, AI and ML with satellite imagery for accurate and comprehensive environmental monitoring and disaster assessment should be done. More study and research works should be focused on how GNSS can be utilized to improve disaster risk reduction strategies by enhancing real-time monitoring, early warning systems and decision-making processes related to disasters. Similarly, research can be focused on integrating GNSS with the Inertial Navigation System (INS) such that GNSS can be effectively used under tunnels and inside buildings during disaster response activities. Thus, understanding the challenges of GNSS in disaster management is crucial for future research to address gaps and improve the application of GNSS in climate-responsive land governance and disaster resilience efforts.
GNSS technologies have been used for a wide range of applications while the application area has been getting wider day by day. GNSS technology has contributed to geodetic infrastructure, surveying and mapping, disaster management, urban planning, LIS and land governance, modern geospatial data acquisition techniques and various stages of disaster management.
Despite its advantages, GNSS technology has challenges in terms of technique, cost, policy and standards, and management. Addressing these challenges requires coordinated efforts, adequate funding, and international collaboration. Looking forward, future advancements in GNSS technology hold immense

potential for further improving disaster resilience and climate-responsive land governance. Establishing comprehensive CORS networks, integrating GNSS with AI and ML, and enhancing international collaboration are essential steps toward realizing this potential. By overcoming current challenges and embracing technological innovations, GNSS can significantly contribute to sustainable development and the creation of resilient communities in the face of climate change and natural disasters.

REFERENCES

Abidin, H. Z., & Syafii, M. A. (2022). *The Utilization of GNSS for Disaster Risk Reduction Management in Indonesia : Status and Challenges*. *January*. https://doi.org/10.13140/RG.2.2.12634.47045

Alkhatib, A. A. A. (2014). A Review on Forest Fire Detection Techniques. *International Journal of Distributed Sensor Networks*, *10*(3), 597368. https://doi.org/10.1155/2014/597368

Bellini, L. S., Spanò, A., Bellini, M. C., & Tonolo, F. G. (2024). *A heterogenous-source Geoinformation System to manage landscape modifications from a climate- change resilience perspective*. https://doi.org/10.21203/rs.3.rs-4142910/v1

Bhandari, S. (2022). Detecting Surface Displacement in Kathmandu Valley with Persistent Scatterer Interferometry. *Journal on Geoinformatics, Nepal*, 23–29. https://doi.org/10.3126/njg.v21i1.50878

Bhattarai, R., Alifu, H., Maitiniyazi, A., & Kondoh, A. (2017). Detection of Land Subsidence in Kathmandu Valley, Nepal, Using DInSAR Technique. *Land*, *6*(2), 39. https://doi.org/10.3390/land6020039

CELMS, A., TREVOHO, I., KOLODIY, P., RATKEVICS, A., LIDUMNIEKS, T., & BRINKMANIS-BRIMANIS, M. (2024). Development of GNSS measurement models with the use of base stations and radio modules. *Modern Achievements of Geodesic Science and Industry*, *1*(47), 69–75. https://doi.org/10.33841/1819-1339-1-47-69-75

Chen, Z. (2024). Application of UAV remote sensing in natural disaster monitoring and early warning: an example of flood and mudslide and earthquake disasters. *Highlights in Science, Engineering and Technology*, *85*, 924–933. https://doi.org/10.54097/zak5hp77

Chhatkuli, R. R. (2007). From Cadastral Survey Plan to Geographic Information Infrastructure: Fifty Years of Evolution of Geo-spatial Data Policy in Nepal. *Journal on Geoinformatics, Nepal*, 57–61. https://doi.org/10.3126/njg.v6i1.51227

Cova, T. (2016). *GIS in Emergency Management*. *December 1999*.

Galetzka, J., Melgar, D., Genrich, J. F., Geng, J., Owen, S., Lindsey, E. O., Xu, X., Bock, Y., Avouac, J.-P., Adhikari, L. B., Upreti, B. N., Pratt-Sitaula, B., Bhattarai, T. N., Sitaula, B. P., Moore, A., Hudnut, K. W., Szeliga, W., Normandeau, J., Fend, M., … Maharjan, N. (2015). Slip pulse and resonance of the Kathmandu basin during the 2015 Gorkha earthquake, Nepal. *Science*, *349*(6252), 1091–1095. https://doi.org/10.1126/science.aac6383

Ghosh, C. (2023). GIS and Geospatial Studies in Disaster Management. In *International Handbook of Disaster Research* (pp. 701–708). Springer Nature Singapore. https://doi.org/10.1007/978-981-19-8388-7_214

Hashim, H., Hashim, I. C., Abdulah, S., Mohammad, A. A., & Pugi, N. A. (2023). The Role of Geospatial Technologies in Disaster Risks Assessments: A Review of Recent Research. *International Journal of Business and Technology Management*, *5*, 402–420. https://doi.org/10.55057/ijbtm.2023.5.S2.39

Hu, M., Ren, Y., Xiao, L., Liu, X., Tan, Q., Han, H., & Guo, J. (2024). Landslide monitoring based on GNSS and automated inclinometer systems and dynamic modeling using SPH: a case study in Qinghai, China. *Environmental Earth Sciences*, *83*(6), 170. https://doi.org/10.1007/s12665-024-11463-y

Huang, G., Du, S., & Wang, D. (2023). GNSS techniques for real-time monitoring of landslides: a review. *Satellite Navigation*, *4*(1), 5. https://doi.org/10.1186/s43020-023-00095-5

ISLAM, M. M., & SADO, K. (2000). Development of flood hazard maps of Bangladesh using NOAA-AVHRR images with GIS. *Hydrological Sciences Journal*, *45*(3), 337–355. https://doi.org/10.1080/02626660009492334

Jangral, A., Bodade, P. R. M., G, K., & Ghuman, J. K. S. (2024). Multi-GNSS Assisted Navigation for Disaster Management: A Comprehensive Review. *International Journal for Research in Applied Science and Engineering Technology*, *12*(5), 5752–5758. https://doi.org/10.22214/ijraset.2024.62945

Jiang, S., & Zhao, B. (2023). Application Analysis of GPS Surveying and Mapping Technology in Engineering Surveying and Mapping. *Journal of Theory and Practice of Engineering Science*, *3*(11), 7–13. https://doi.org/10.53469/jtpes.2023.03(11).02

Kafi, K. M., & Gibril, M. B. A. (2018). *GPS Application in Disaster Management : A Review*. *August*.

KATO, T., TERADA, Y., TADOKORO, K., & FUTAMURA, A. (2022). Developments of GNSS buoy for a synthetic geohazard monitoring system. *Proceedings of the Japan Academy, Series B*, *98*(2), PJA9802B-01. https://doi.org/10.2183/pjab.98.004

KC, R., Sharma, K., Dahal, B. K., Aryal, M., & Subedi, M. (2024). Study of the spatial distribution and the temporal trend of landslide disasters that occurred in the Nepal Himalayas from 2011 to 2020. *Environmental Earth Sciences*, *83*(1), 42. https://doi.org/10.1007/s12665-023-11347-7

KC, S., & Acharya, T. D. (2022). Advancements of Geodetic Activities in Nepal: A Review on Pre- and Post-2015 Gorkha Earthquake Eras with Future Directions. *Remote Sensing*, *14*(7), 1586. https://doi.org/10.3390/rs14071586

Krishna Samalla, & P. Naveen Kumar. (2024). Global Navigation Satellite System in the Civil Surveillance. *ACS Journal for Science and Engineering*, *4*(1), 1–10. https://doi.org/10.34293/acsjse.v4i1.100

Lau, N. N. (2017). Determination of ground displacement of 25 April 2015 Nepal earthquake by GNSS precise point positioning. *VIETNAM JOURNAL OF EARTH SCIENCES*, *40*(1). https://doi.org/10.15625/0866-7187/40/1/10876

Maio, C. Di, Vassallo, R., Vallario, M., Calcaterra, S., & Gambino, P. (2013). Surface and Deep Displacements Evaluated by GPS and Inclinometers in a Clayey Slope. In *Landslide Science and Practice* (pp. 265–271). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-31445-2_34

Malet, J.-P., Maquaire, O., & Calais, E. (2002). The use of Global Positioning System techniques for the continuous monitoring of landslides: application to the Super-Sauze earthflow (Alpes-de-Haute-Provence, France). *Geomorphology*, *43*(1–2), 33–54. https://doi.org/10.1016/S0169-555X(01)00098-8

Manandhar, N., & KC, S. (2018). Geoid Determination and Gravity Works in Nepal. *Journal on Geoinformatics, Nepal*, *14*(2072), 7–15. https://doi.org/10.3126/njg.v17i1.23003

Mehta, S., Peach, J., & Weinert, A. (2022). *To Expedite Roadway Identification and Damage Assessment in LiDAR 3D Imagery for Disaster Relief Public Assistance*. https://doi.org/https:// doi.org/10.3390/infrastructures 7030039

Mitchell, D., Enemark, S., & van der Molen, P. (2015). Climate resilient urban development: Why responsible land governance is important. *Land Use Policy*, *48*, 190–198. https://doi.org/10.1016/j.landusepol.2015.05.026

Nagasawa, R., Mas, E., Moya, L., & Koshimura, S. (2021). Model-based analysis of multi-UAV path planning for surveying postdisaster building damage. *Scientific Reports*, *11*(1), 18588. https://doi.org/10.1038/s41598-021-97804-4

Pinuji, S. (2020). *CLIMATE CHANGE, SUSTAINABLE LAND MANAGEMENT AND RESPONSIBLE LAND GOVERNANCE*. *6*(2), 188–200.

Ta, T. H., La, V. T., Van Hoang, H., Vannucchi, M., Povero, G., & Belforte, G. (2021). *Collaborative RTD for Precise and Reliable GNSS Based Positioning for Land Management* (pp. 83–94). https://doi.org/10.1007/978-3-030-51260-6_8

Upreti, B. . (1999). An overview of the stratigraphy and tectonics of the Nepal Himalaya. *Journal of Asian Earth Sciences*, *17*(5–6), 577–606. https://doi.org/10.1016/S1367-9120(99)00047-4

Westlund, S. (2010). The Use of Geospatial Technology in Disaster Management. *International Journal of Applied Geospatial Research*, *1*(3), 17–30. https://doi.org/10.4018/jagr.2010070102

Yamada, F. K., Tarelho, L. V. G., & Lima, M. V. (2023). *Ionosphere characterization using GPS P3 method by measuring ionospheric delay in Southeast of Brazil and considering geomagnetic storms*. *April*. https://doi.org/10.22541/essoar.170612430.06713740/v1

Yeom, S. (2024). Thermal Image Tracking for Search and Rescue Missions with a Drone. *Drones*, *8*(2), 53. https://doi.org/10.3390/drones8020053

Z. Abidin, H., Andreas, H., Gamal, M., Surono, S., & Hendrasto, M. (2004). Studying Landslide Displacements in Megamendung (Indonesia) Using GPS Survey Method. *ITB Journal of Engineering Science*, *36*(2), 109–123. https://doi.org/10.5614/itbj.eng.sci.2004.36.2.2

Zeybek, M., Sanlioglu, I., & Genc, A. (2014). *Landslide Monitoring with GNSS measurements and prediction with Linear Regression Model : a case study Ta ş kent (Konya , Turkey) Landslide*. *July 2019*.

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