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A Crypto-Spatial Framework For Landslide Susceptibility Assessment And Decision-Making

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Areas where it rains a lot and the ground is unstable, landslides are quite dangerous for people as well as for buildings. Since they are not very accurate or clear, the conventional methods of determining the probability of a place sliding can slow down the decision-making process. Our response to these problems is a crypto-spatial framework based on blockchain technology meant to provide more accurate landslide risk assessments. Blockchain technology cannot be altered and is distributed rather widely. Together with geospatial data analysis, it has produced a fair and dependable approach to data exchange. Blockchain-based verification systems and geospatial analysis of environmental elements, including landforms and rainfall patterns, allowed one to confirm the accuracy of the evaluation data. Often, in areas prone to landslides, field tests ensure that the system operates as it should and consistently. More sensitivity produced more accurate estimations and improved collaboration amongst stakeholders. The present work addresses geospatial data analysis and blockchain technologies meant to reduce disaster risk. This approach increases the safety and efficiency of landslide-prone areas, so enhancing the data dependability and decision-making capacity.

KEYWORDS: Landslide Risk Assessment; Blockchain Technology; Geospatial Data Analysis; Disaster Risk Reduction; Crypto-Spatial Framework.

(1) Introduction:

In regions prone to heavy rainfall and unstable soils, the threat of landslides to public safety is significant. Extensive property damage, infrastructure disruption and loss of life often result from such disasters. Conventional approaches to landslide risk assessment are inaccurate because they utilize only limited data. Important decisions are often delayed. As climate change and land use policies are expected to increase landslide frequency and severity, a more accurate and efficient risk assessment method is needed. Geospatial data analysis and blockchain technology may accelerate and improve risk assessment [1]. Immutable blockchain technology is combined with geospatial data analysis. Data security and transparency have been improved [2], so the credibility of the assessment is strengthened. Environmental parameters such as landforms and soil stability are analyzed in greater depth. Disaster risk reduction strategies are improved through this crypto-spatial framework. Data reliability and stakeholder cooperation are enhanced. Timely information supports decision-making in landslide-prone areas.

Methods for assessing the likelihood of landslides are evolving to make use of new technological tools. Inaccurate and inadequate data are common in traditional assessments, which contributes to their inherent lack of certainty. To combat this, the data used is protected by utilizing blockchain technology. Blockchain data cannot be changed, making evaluation results more reliable. MCDM, Geospatial, and Blockchain improve landslide risk assessment [3], [4]. Complex geographic data analysis improves with MCDM. This method considers rainfall and soil stability. Government and local communities can verify the analysis's results, reducing risk assessment uncertainty. More accurate and reliable data can improve disaster risk reduction and response times. Technology-based landslide risk assessment is being developed. Traditional evaluations are prone to error due to small sample sizes and faulty data. Blockchain technology protects data. The incorruptibility of blockchain data boosts evaluation confidence. Multiple parties can audit data transparently. This method improves geospatial data usage for more thorough environmental analysis. This allows faster and more accurate decision-making in landslide-prone areas.

Research by [5] mapped landslide vulnerability in Ethiopia using GIS, remote sensing, and AHP. The results showed higher accuracy in the identification of landslide-prone areas, supporting better decision-making in disaster mitigation. Developed a methodology for mapping landslide vulnerability in Turkey by combining fuzzy-AHP and decision trees [6]. This approach improved the accuracy of the assessment and helped manage the complexity of varying geological conditions. Applied AHP to geospatial data to evaluate landslide vulnerability in the Beas River Valley, Himalayas [7]. This study emphasized the importance of accurate geospatial data in supporting risk mitigation in disaster-prone areas. Compared AHP and frequency ratio (FR) methods for landslide vulnerability mapping in Reshun, Pakistan [8]. Both methods provide their own advantages, and the combination of the two resulted in a more accurate vulnerability map. Used AHP for landslide susceptibility zonation in the Bafoussam-Dschang region of Cameroon [9]. The results showed a more detailed and accurate zonation, which is important for disaster risk mitigation in landslide-prone areas.

The suggested study would increase landslide vulnerability assessment by means of blockchain technology combined with the Multi-Criteria Decision Making (MCDM) approach. Though this integration could improve openness and safety in decision-making, there is little debate on the application of blockchain technologies in the above-mentioned literature. Although AHP and geospatial techniques are effective, no vulnerability mapping system makes advantage of blockchain smart contracts. This research will cooperate by verifying the accuracy and authenticity of geospatial data using blockchain technologies. Blockchain and multi-criteria decision-making (MCDM) can offer secure and open geospatial data, so improving the speed and quality of decision-making. The goal is a stronger and more useful crypto-spatial framework to reduce the effect of disasters. This study helps us to better know how to prevent tragedies.

This work aims to create a framework combining blockchain technology with the Multi-Criteria Decision Making (MCDM) approach in landslide risk assessment so enhancing dependability, openness, and accuracy in decision-making. This study intends to demonstrate how blockchain integration guarantees security and integrity of geospatial data, so enabling faster and more effective application of the landslide risk assessment process. Furthermore, this study aims to demonstrate how smart contracts used in MCDM might improve cooperation among disaster mitigating stakeholders. By means of this research, an original crypto-spatial framework is expected to enable more informed and timely decision-making in areas prone to landslides.

The research questions to be answered by this study are:

1. How can combining blockchain technology with the MCDM method improve the reliability and security of geospatial data in landslide risk assessment?
2. Can the integration of smart contracts in the crypto-spatial framework accelerate and improve the decision-making process in landslide-prone areas?
3. How effective is the use of a crypto-spatial framework in supporting collaboration between stakeholders in landslide risk mitigation compared to conventional methods?

2) Methods and Methodology:

The researcher gathered geospatial data about places prone to landslides by means of several techniques. Data were collected from topographic maps displaying finely detailed area contours. To further have a picture of the surface conditions of the earth, scientists also made use of satellite images. The team verified the information gathered from satellites and maps by means of field studies. Every zone of the territory was examined according to the land slope influencing landslide risk. Every area's soil was determined since soil stability depends on its properties. Furthermore, rainfall records were gathered by researchers and could cause local ground movement. To assess the degree of disaster vulnerability for the nearby populations, land cover and population density were noted around places prone to landslides. The method can be seen in Figure 1

The geospatial data that has been collected is processed by researchers using Geographic Information Systems (GIS). The researcher used QGIS software to perform complex data analysis and mapping. In this process, regional zones were classified based on geospatial parameters such as slope and soil type. The hill was analyzed to determine the level of landslide vulnerability in each zone. Researchers also identified the soil type in each area because soil characteristics affect land stability. In addition, historical rainfall was analyzed to identify rainfall trends that could trigger landslides. Researchers also identified population density and land cover type to determine the impact of disasters on densely populated areas.

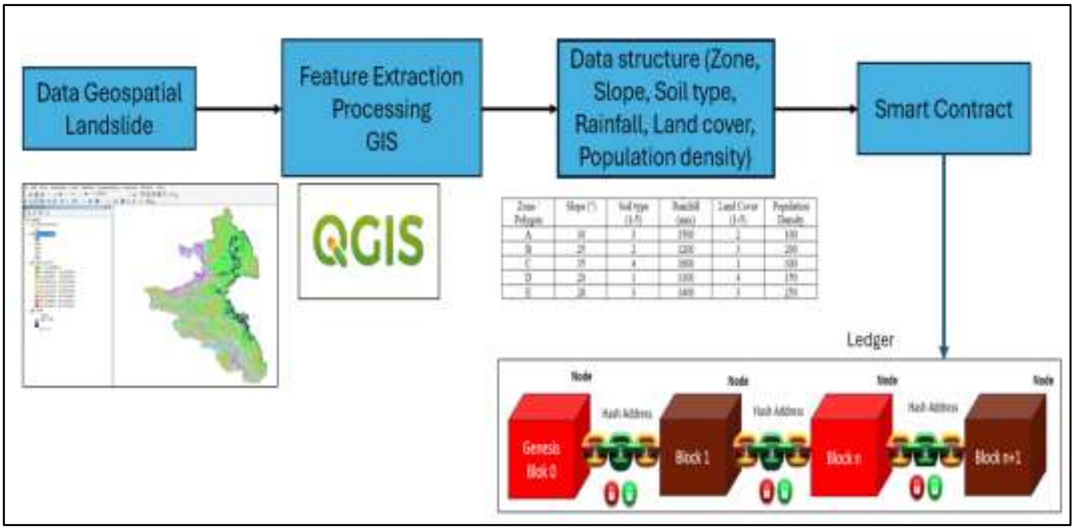

Figure 1. Methodology Research Feature Extraction to Ledger

Researchers working with Geographic Information Systems (GIS) handled the gathered geospatial data. The researcher mapped and examined many geospatial criteria using QGIS program. Zonal classification was done in this stage depending on criteria including land cover, type of soil, and land slope. In every zone, researchers also examined the hill to determine the degree of landslip vulnerability. The type of soil was determined since the stability and movement of soil in sensitive areas are much influenced by its physical characteristics. Researchers looked for strong rainfall trends that might raise landslip risk using past rainfall records. After that, the degree of disaster risk is categorized using the basis of every zone under analysis.

Apart from zone classification, we also investigated area population and land cover elements. Examining the population density, the researcher sought to ascertain the possible effects of the disaster on the nearby society around the sensitive area. Along with mapping the type of land cover—such as forest, plantation, or open land—which influences the area's susceptibility to erosion and landslides in this process is Potential disaster victims are calculated considering population density elements in case of a landslide. Every one of these feature studies offers necessary data for designing disaster prevention strategies in sensitive areas. A more accurate landslide prediction model was developed by researchers using the outcomes of this feature extraction. By means of the integration of all these criteria, scientists can make better choices to lower disaster risk in sensitive regions.

After that, the blockchain platform incorporates the created structural data by researchers. To automatically monitor and control geospatial data concerning landslide risk, researchers developed a smart contract. This smart contract detects sensitive areas depending on previously found criteria including land slope and rainfall. Furthermore, in case a region is classified as high risk for landslides, the smart contract will trigger an early warning. Furthermore, useful for additional research is the smart contract, which keeps past information about parameter adjustments. Researchers can examine long-term changes in risk by means of this storage. The smart contract guarantees transparent and safe access to all landslide-related data via the blockchain and well-management of it.

The blockchain ledger stores securely kept data under management through a smart contract. Every modification or update to the data—such as adjustments in geospatial parameters or rainfall—is automatically noted in a fresh block on the blockchain. This logging gives all those engaged complete transparency, so enabling data tracking and validation at any moment. Since every block in a blockchain is guarded by an unchangeable hash address that cannot be manipulated, blockchain also guarantees the security of kept data. These hash addresses guarantee data integrity over time, so the accuracy and unchangeable nature of the kept data is maintained. Blockchain network nodes help to securely distribute data so that only consensus among all the nodes will allow data to be changed. Blockchain is thus a dependable way for the management of private geospatial data since it offers strong data continuity and auditability.

By applying this methodology, an automated monitoring system for landslide mitigation is expected:

1. Able to detect high-risk areas
2. Improves accuracy in disaster management through the utilization of blockchain technology and smart contracts

The methodology also ensures that data can be tracked and verified through the blockchain ledger, which makes the disaster mitigation process more transparent and reliable.

Smart Contract Implementation Methodology with PROMETHEE

1. Integration of Geospatial Data into Blockchain. Geospatial data related to landslide risk, which has been processed using GIS, is integrated into the blockchain platform. This data includes geospatial parameters such as land slope, soil type, rainfall, land cover, and population density. Each of these parameters is collected from various reliable sources, including topographic maps and satellite images. This data is then processed by a blockchain-based system to ensure its integrity and security. Once integrated, the data is processed by smart contracts that automatically execute rules related to risk mitigation. These smart contracts are responsible for identifying high-risk areas and triggering early warnings if certain thresholds are exceeded. This entire process is carried out in a secure and transparent blockchain environment, ensuring the data cannot be altered without consensus.
2. Using many criteria, smart contracts evaluate landslide-prone areas using the PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) approach [10]. Among the noted risk factors that one can assess and rank depending on preferences are slope, type of soil, rainfall, land cover, and population density using PROMETHEE. Based on the researcher's criteria, the PROMETHEE algorithm assigns a value to each region. The impact of each criterion on landslide risk is balanced. The ranking results allow the researcher to prioritize high-risk areas based on importance and inclination. This method enables scientists to make better decisions about landslide

avoidance. Using PROMETHEE in smart contracts, the system can automatically classify areas based on the objectively calculated risk level.

3. The smart contract employs the PROMETHEE algorithm in a predetermined criteria-based decision-making sequence [11]. The PROMETHEE algorithm is directly integrated into the smart contract and calculates zone preferences based on risk factors such as slope, soil type, and rainfall. Geospatial data is entered into the smart contract first. The smart contract employs the PROMETHEE algorithm to calculate zone preferences based on predefined weights. Following calculation, the smart contract will return a risk rating for each zone analyzed. Researchers use this risk ranking to determine disaster mitigation priorities. The rankings' results are also stored on the blockchain to ensure data security and transparency. Smart contracts can automatically run these algorithms, allowing for faster and more accurate decisions. This process is systematic and efficient for mitigating the risk of landslides.
4. The smart contract prioritizes landslide-prone areas using PROMETHEE [12]. Each zone will be carefully examined using pre-processed geospatial data on land slope, soil type, and rainfall. If a zone exceeds the system-set risk level, the smart contract will send an immediate warning. For the authorities to immediately take the necessary measures to ensure the safety of the people, this alert is being sent out. In addition, important messages will be communicated through pre-arranged means of contact to guarantee timely receipt by all parties involved. No human intervention is needed because it's automated. Issues can be identified faster and addressed more proactively. Smart contracts also store alert data on the blockchain. This ensures transparent and responsible risk management. This system will reduce human error and improve disaster management. This automated system aims to prevent and mitigate landslides.
5. For data security and transparency, PROMETHEE analysis results, including risk ratings and criteria preferences, are permanently recorded on the blockchain ledger. Rainfall or soil type changes will automatically re-execute the smart contract to update the risk rating of the affected area. This ensures the system's data is accurate and current. Blockchain records can be traced back at any time, providing a complete audit trail. This system lets interested parties track risks in real time without manipulation or data loss. Each block of data has a unique hash address, ensuring analysis results integrity on the blockchain. Whatever big changes happen, the smart contract will go through the PROMETHEE calculation and risk rating again to make sure the right response is made. This stored data makes it possible to make more accurate predictions about future risks. So, using blockchain to store and manage analysis results helps people make better decisions about how to prevent landslides.
6. Blockchain technology provides security for all data transactions and updates, including the PROMETHEE method evaluation results, by preventing changes that do not have network approval. Each blockchain block contains a unique digital signature that safeguards the analysis results and risk ratings. The transparency of the blockchain enables researchers and relevant institutions to access real-time, accurate information. The blockchain offers a comprehensive audit trail for all modifications. Changing critical data necessitates the consent of the entire distributed network of nodes, which serves to prevent manipulation or omission. Cryptographic mechanisms protect data from external threats. With the blockchain, all risk ranking, and data analysis decisions can be made.

The entire data history is transparent, so the results of the analysis can be reviewed easily if needed. All parties who depend on the evaluation results for crucial risk mitigation decisions can now have more faith in the system.

7. Because PROMETHEE's risk ranking gives an objective basis for prioritizing actions, the system allows for better decision-making in disaster mitigation [13]. These risk ratings are developed after extensive analysis of multiple parameters, giving authorities clear instructions on how to take precautions. With smart contracts in place, there is full transparency in every process because every decision can be traced through a transparent audit trail on the blockchain. Automating processes is another benefit of smart contracts, which allows for better and faster responses to potentially dangerous situations. Every decision is based on the most current and accurate information because all data used for decision-making is updated in real-time. All actions are based on valid data since interested parties can verify decisions taken at any time. Furthermore, blockchain guarantees that decision-making data is immutable, which adds another safeguard to the process. Because the system can record and account for every action or change, it also makes people more accountable. Consequently, this data-driven decision-making aids in the more precise and efficient reduction of disaster risk.

3] Results:

This research produced some critical findings related to the use of the PROMETHEE method in blockchain-based smart contracts for landslide risk mitigation. The PROMETHEE calculation results show that areas with steep slopes and high rainfall have a higher risk ranking than areas with more stable geospatial conditions. Geospatial data integrated through GIS and processed by smart contracts automatically identifies high-risk zones, with ranking results reflecting a direct relationship between geospatial parameters and landslide potential. In addition, the blockchain system successfully records every transaction and data change transparently and securely, enabling a complete audit trail for all interested parties. To make sure the data is always up to date, the smart contract updates the risk rating automatically whenever data parameters, like soil type or rainfall, go through major changes.

This demonstrates that the created system is capable of correct early warnings for catastrophe mitigation and efficient management of geospatial data. The implementation of intelligent contracts also reduces the time and effort required to monitor disaster-prone areas due to automation in data processing and PROMETHEE algorithm-based decision-making [14]. These results prove that blockchain technology and PROMETHEE can be well integrated to support a more transparent, accurate, and accountable risk mitigation system. To make calculations that match the findings of the research using the PROMETHEE method in blockchain-based smart contracts, we need specific data regarding the geospatial parameters used (land slope, rainfall, soil type, etc.) and the preference weights given to each parameter.

The following are the general steps that can be used to calculate the risk ranking using the PROMETHEE method:

1. Setting Criteria and Their Weights
   Let's say we set three main criteria for determining landslide risk:
   - Slope: K1, weight = 0.4

- Rainfall: K2, weight = 0.3
- Soil Type: K3, weight = 0.3

2. Determining the Rating Scale
   Each criterion is assigned a value based on actual geospatial data:
   - Slope: 0° - 90° (measured in degrees)
   - Rainfall: 0 - 500 mm (measured in millimeters per month)
   - Soil Type: Classification 1 - 5 (from most stable to most vulnerable soil type)

   Example of area data for 4 different zones:

Zone	Land Slope (°)	Rainfall (mm)	Soil Type (1-5)
A	45	300	4
B	20	150	2
C	60	400	5
D	10	200	3

3. Normalizing the data makes sure each parameter is given the same weight, which puts all the criteria on the same scale. The initial values of each criterion are transformed into values that fit into a predetermined range, typically ranging from 0 to 1, to achieve this normalization. This process allows for a fairer comparison between different criteria, such as slope, rainfall, and soil type, which may have very different ranges of values. The minimum value within each criterion will be converted into the lowest value, while the maximum value will be the highest value within the range. In this way, all requirements become uniform and can be used together for further analysis. Normalization ensures that no criterion has a more significant influence just because its value scale is different from the others. Once normalization is done, the data is ready to be processed for further calculations using the PROMETHEE method.

   Normalized Value = $\frac{X - \min(X)}{\max(X) - \min(X)}$

   Suppose the normalization result is as follows:

Zone	Land Slope (°)	Rainfall (mm)	Soil Type (1-5)
A	0.625	0.75	0.75
B	0.25	0.25	0.25
C	1	1	1
D	0	0.5	0.5

4. Preference Calculation
   After the data is normalized, we multiply the normalized value by the weight of each criterion:
   P(Zona A) = $(0.625 \times 0.4)+(0.75 \times 0.3)+(0.75 \times 0.3)=0.25+0.225+0.225=0.7$

P(Zona B) = (0.25×0.4)+(0.25×0.3)+(0.25×0.3)=0.1+0.075+0.075=0.25
P(Zona C) = (1×0.4)+(1×0.3)+(1×0.3)=0.4+0.3+0.3=1
P(Zona D) = (0×0.4)+(0.5×0.3)+(0.5×0.3)=0+0.15+0.15=0.3

5. Final Rating
   After calculating the preference scores, a risk ranking is assigned based on the total score obtained:
   - Zone C: 1 (highest risk)
   - Zone A: 0.7 (high risk)
   - Zone D: 0.3 (medium risk)
   - Zone B: 0.25 (low risk)

The PROMETHEE method ranks the zones based on the weights of the predetermined criteria. The zone with the highest preference value (Zone C) indicates that this area has the highest risk of landslides due to steep slopes, high rainfall, and vulnerable soil type.

4] Discussion

Using the PROMETHEE method to make a risk ranking has helped us understand the study's results in more depth. Based on factors like land slope, rainfall, and soil type, the zones with the highest risk have been found [14]. It means that the area is more likely to have landslides than other areas if it has a higher ranking. The addition of geospatial data to the blockchain system has made risk assessment more open and accurate. Smart contracts have an automated process that makes sure that any changes to data can be made in real time without any help from a person. This has made early detection more accurate, which means that disaster warnings can be sent out more quickly. When it comes to preventing disasters, this system has made it easier to make decisions based on data.

The outcomes of this research highlight how well the PROMETHEE approach might be used in blockchain-based smart contracts to simplify the process of disaster risk assessment. A major development in the system is its capacity to automatically combine geospatial data from several sources and offer risk ratings. The clear audit trail guarantees that analysis findings and data can be checked, so improving openness. Moreover, choices grounded on this analysis have clearly raised the effectiveness of landslide risk reduction in sensitive regions. Blockchain's application has improved the dependability of the system even more since it guarantees that every action is recorded and so improves coordination of disaster management. All taken together, this study has prepared the ground for a more ordered and combined method of disaster prevention.

The study also revealed some of the difficulties applying the system. Further development will help to solve technical challenges including data management in the blockchain and interface with GIS program. Although the outcomes show great promise, real-time data processing and geospatial data coverage still need work. Future studies will help to improve the responsiveness of smart contracts to changing geospatial conditions and maximize the PROMETHEE algorithm. Fortifying this system depends on cooperation among geospatial analysts, blockchain developers, and local governments. This will help the system to be more extensively applied in reducing other calamities, such floods or earthquakes. The studies have opened doors for more technological-based disaster prevention innovations.

5] Conclusion – Summarize the main outcomes and their significance**.**

According to this study, blockchain-based smart contracts employing PROMESHEE can spot and rank areas prone to landslides. Geospatial data was meticulously handled and included in blockchain to guarantee openness and security. Geospatial parameters, including land slope, rainfall, and soil type, automatically determine the risk rating of every zone. The blockchain-based recommendation system has dramatically depended on decisions about disaster prevention. The blockchain's secure and unchangeable character means that the data kept there cannot be changed or manipulated. Using this ledger-based approach improves decision-making transparency and organization. Its strength resides in providing recommendations that are impossible to change yet also secure. The integration of real-time data is one of the technical challenges that still needs improvement. But thanks to blockchain technology, this study has made significant progress toward disaster mitigating techniques, so increasing accuracy and process confidence.

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9] Conflict of interest:

The authors declare that there are no potential conflicts of interest related to this research.

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