Quick Review of the Approaches of Landslide Risk Assessment

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Abstract Landslide prevention and mitigation have a long history. Retaining walls and ground anchors are popular methods for preventing slope failure, as these prevention methods increase the factor of safety against failure. These methods are widely utilised and proven to be effective all around the world. The methods are however very costly, leading to a restricted application only for wide slopes. A landslide early warning system (LEWS) with real-time monitoring system is required to identify appropriate moment for preventive measures in order to handle landslide emergencies. However, depending on the type of landslide, different techniques are required. The approach is frequently used to help determine a set of crucial thresholds that can be used to determine when alerts can be sent, and it is based on LEWS' own theoretical basis. This paper presents a quick review on the three general approaches used in LEWS, namely statistical approach, physical-based approach and monitoring-based approach. This quick review will attempt in discovering more on the strengths and advantages rather than diving into the limitations of each approach.

Keywords Landslide early warning system · Statistical approach · Physical-based approach · Monitoring-based approach

1 Introduction

Due to global climate change, the intensity and frequency of heavy rainfall events in a landslide-prone area have increased, resulting in significant landslides and high-intensity rainfall. Aside from the presence of weathered material on a slope, the

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frequent high-intensity rainfall is a well-known criterion for causing landslides [1–8]. In many countries, the growing number of urban or residential settlements inhabiting mountainous environments has resulted in a vast amount of damage caused by landslides [9]. Affected areas and accompanying annual recovery expenditures have increased dramatically in Korea since roughly 2000, while a locality in Amboori, India, experienced its most devastating landslide incident in 2001 [10–12]. Thus, an early warning system is a necessary prerequisite for places prone to landslides, as it is sometimes referred to as the low-cost option for mitigating the losses and casualties associated with natural hazards [12–16]. However, in order to develop an efficient and optimal landslide early warning system (LEWS), the important first step is to acquire knowledge on risks that the landslides impose. Numerous techniques, plans, frameworks and tactics have been devised and used in response to the social and physical environmental characteristics of the study areas [16]. Geological and meteorological elements, covered area, landslide type, data availability and dependability, local authorities and policy- and decision-makers' concerns are among them. Based on a substantial quantity of literature from prior functional examples or suggested LEWS, the majority of the research has determined that each LEWS requires its unique risk assessment approach according to the area's physical and social characteristics mentioned earlier [17]. The approach is commonly used to help determine a series of crucial thresholds that can be used to determine when warnings and alerts can be given, and it is based on LEWS' own theoretical basis. Park et al. [12] concluded that the methodologies can be divided into three categories: statistical based, physical based and monitoring based. The LEWS that use the same type of risks assessment approaches generally have similar features, advantages, and disadvantages in numerous components of the system. Table 1 displays the common attributes of LEWS based on a statistical-, physical- and monitoring-based approaches, which was partly adapted from Park et al. [12]. This work includes a monitoring-based approach that use contact-sensing methods with ground instrumentation [14, 18], and remote-sensing methods with GB-InSAR [17]. The reason for this inclusion is to also compare statistical- and physical-based approach with the monitoring-based approach with other approaches previously done by Park et al. [12].

2 Discussion on Different Approaches, Its Advantages and Disadvantages

2.1 Basic of Statistical Approach

The method employs statistically studied correlations where the final results were obtained using, almost exclusively, historical landslide data and rainfall data, which later translated into rainfall thresholds. The rainfall threshold usually comprises intensity-duration curves, among various data included. It has been one of the most

Table 1 Common attributes of LEWS based on statistical-, physical- and monitoring-based approaches [12]

Approach		Statistical	Physical based	Monitoring based
Covered area		Regional scale	Local scale	Regional and local scale
Type		Debris flow, shallow landslide	Shallow landslide, debris flow	Rockslide, shallow landslide, debris flow
Input data		Rainfall data	Rainfall data; hydrological and geotechnical data; and other physical attributes	Measurements from sensor units or monitoring system
Evaluation method		Rainfall thresholds deriving from analysis of rainfall data	A variety of models for analysis purposes	Wireless sensor units, or ground-based synthetic aperture radar interferometry (GB-InSAR)
Time period for risks assessment		A few days ahead	1–24 h ahead	A few days—2 h or 3 h ahead
Resolution of alert level	Update frequency	Twice per day–every 6 min	Daily, twice a day, hourly	60 s, 5 min, 10 min, or 8 h–24 h
	Spatial	Ranging from 1 km grid mesh to regional-scale area	Whole area	Whole area, or 2 × 2 m at 1 km range

popular methods for developing an operational LEWS in recent years. Mandal and Mondal [19] described this method as a method in landslide studies that employ numerical models and procedures that incorporate multiple important variables and inventories of landslide before producing a susceptibility map of a specific area with extreme certainty by utilising statistical, mathematical and GIS software. On the other hand, the quality of the evaluation is contingent upon the inventory's accuracy and completeness [9, 20, 21]. Ordinary statistical models, for instance, logistic regression and linear regression, are only relevant to binary-dependent variables, such as the existence (one) or absence (zero) of a landslide. Nevertheless, the likely landslides in valleys, for example, correspond to multivalent dependent variables with values between zero and one, which will necessitate the employment of statistical models with several classifications [20]. According to Park et al. [12], the evaluation process for landslide early warning uses susceptibility maps to examine the spatial element of landslide hazard. In order to create the map, a statistical approach is applied to various geoproperty variables [22]. Commonly, the statistical approach used is rainfall thresholds that use recorded and forecasted rainfall data to determine landslide warning levels which are considered to be cost-effective, convenient and the preferred tools for years now. Park et al. [12] and other researchers [15, 23–25] have studied various landslide early warning systems that apply statistical approach in order to evaluate different managed area ranging from nation-size area to province-, city- and lastly district-size area. This approach involves the data collection of input factors in real-time and risk assessment calculations. Despite this, the approach has issued relatively high warning level updates over a wide area due to its relatively light requirements [12]. Initially, the influence of different geoproperties (geotechnical, hydraulic, geology and topography properties), that have not been clearly integrated into this method might offer answers for more thorough spatial discrimination in landslide forecasting. Moreover, the accuracy of data obtained in real-time from rainfall is critical to the reliability of an LEWS based on a statistical approach [12]. Hence, because the data sources are dispersed, the statistical approach may not be particularly suitable for regional-scale areas. The geographical variability in rainfall throughout these locations are not adequately captured, particularly localised strong rainfall effects. Alternatively, by using satellite-based precipitation tracking or forecasting techniques as data sources, it may provide higher-resolution rainfall data on a regional scale at reduced update rates.

2.2 Fundamental of Physical-Based Approach

The approach represents the techniques for developing rationales for landslide early warning systems based on analytic interpretations of the physical process underlying landslide events. Marin et al. [26] stated that under normal circumstances, it is the input parameters determine the accuracy of a physical-based landslide risk assessment. Numerous models have been researched and proposed to explain landslide-triggering physics by integrating hydrological and geomechanical theories. A lot of these models have been widely used in the landslide research throughout the world [26–30]. The theories usually range from rainfall drainage into porous soil surface to groundwater flow to changes in underground water state up until to the shear failure due to the loss of mechanical balance between stress and strength of materials. Although, numerical method is the more preferred method to derive the solutions, analytically solved equations have been utilised in many cases of simpler models. While different model designs and implementation research of intermediate prototype systems have been suggested, the system's application has been ignored and the work has not yet proceeded to the degree that solely physical-based LEWS are in use. This approach has been applied in areas such as targeted slopes, valleys and watersheds, as certain level of detail and advancement in investigations and supervisions of landslides are demanded [12]. However, the LEWS has undergone some simplifications in terms of physical-based models, and this kind of implementation is rarely practiced [31]. In contrary to the statistical approach, physical-based approach models incorporate particular characteristics ranging from topographical, geological, meteorological and hydrological aspects to geotechnical issues. This will make it difficult to apply the physically dependent approach to a wide field. In addition, unless intentionally simplified, a coupled hydro-geomechanical models simulating landslide-triggering and hydraulic processes typically require a significant amount of computational time to determine whether a threshold associated with a particular type of safety factor is exceeded [12, 25]. This time-consuming assessment cycle which defines the physical-based approach needs to be refined in order to determine near-future risks with fairly long assessment cycles at a site. This is due to its computational intensiveness. Given the assurance of the precision of anticipated rainfall data is at a certain standard, the nowcasting ability is, according to Park et al. [12], as essential as the forecasting ability. This ensure nowcasting to offer means in identifying current risk levels and also to initiate suitable plans against the imminent landslides. With higher update rate of the alert level than the statistical approach, it can be invaluable in countries with localised extreme heavy rainfall that causes rapid increase of danger level over short period of time. This supported by Park et al. [12] as they stated that Korea can benefit as it has similar weather conditions.

2.3 Monitoring-Based Approach

The monitoring-based approach is not a new methodology that needs introduction. Even though, the approach may not receive similar preference as the statistical approach or even the physical-based approach, this approach should be considered for future LEWS. It is impractical and expensive to develop a LEWS appropriate for all landslide types. Due to the variation of precursors and monitored parameters, the LEWS is designed specifically for the designated area, whether it is local-scale or regional-scale area [14]. Though, Uchimura et al. [18] previously have focused more on the small-scale slope disaster. Their work observed the behaviour of the soil implementing a minimal number of measurement points on a slope using low-cost and advanced wireless sensor network, so that the residents occupying near the landslide-prone areas can use it. In order to monitor the parameters, a number of at least three measurement points are set up. Numerous LEWS utilize a wireless sensor network (WSN), which comprises extensometers, thermometer, rain gauge and camera, while others are using ground-based synthetic aperture radar interferometry (GB-InSAR) and also microelectromechanical systems (MEMS) tilt sensor as reported by Uchimura et al. [18], Intrieri et al. [14] and Casagli et al. [17]. The benefit from using the tilt sensor as proposed by Uchimura et al. [18] is that the installation and maintenance become straightforward and low-cost, due to absence of long wire from an extensometer. This means that the transfer of measurement data was mostly done through Wi-Fi or radio communication. However, the downside of using the tilt sensor is that it incapable of determining the slope surface displacement directly [18]. Additionally, the power supply is a key component of an LEWS that must be considered, since disruptions in monitoring leading to a shortage of electricity may be extremely detrimental at times of high landslide activity [14]. Another option of power source is the AAA alkaline batteries, which performed for more than a year at the site remarkably well, according to Uchimura et al. [18]. From the monitoring activities, the researcher can determine whether to decide where it is required to install new sensor units by analysing the information gathered by LEWS monitoring units in terms of the displacement velocity of the soil. This is convenient for planning the expansion of the covered area in the future.

Intrieri et al. [14] stated that the presence of rain events throughout this campaign had no apparent effect on landslide behaviour, at least in the near term. Therefore, most monitoring-based approach LEWS decided to exclude rainfall thresholds attributed to a tenuous link between them and probable failure and insisted on using displacement velocity as thresholds in issuing warning levels. If thresholds using records of rainfall and other additional parameters, then the number of thresholds could be considered as too many and thus would increase the frequency of false alarm produced. This may have more serious implications than the landslide itself, as it will undermine the population's credibility, and the LEWS would be less conservative [14]. Moreover, a large number of thresholds defined would defeat the purpose of a low-cost, simple and straightforward design that many of the studies of monitoring-based LEWS are aiming for [18]. Intrieri et al. [14] have stated the solution for counter-measuring the false alarm, which is to have experts as the last resort to produce a much-thought judgement and decision in issuance of warning levels. Uchimura et al. [18] suggested a criteria for the judgment before issuing the warning, which was based on the combination of data obtained by the monitoring system of LEWS and the complementary sensors, such as volumetric water content sensors. In addition to experts' decision, redundancy and data averaging were used by most studies to minimise the chance of false alarms. In a study by Intrieri et al. [14], they considered ground water content calculations and weather forecasts before issuing warning levels. As for the frequency of warning update, the approach may be related to the frequency of measurements update obtained from the monitoring system. According to Uchimura et al. [18], Intrieri et al. [14] and Casagli et al. [17], the frequency ranging from 60 s to a maximum of 10 min, while the lowest warning level, the monitoring system would produce measurements in the range of 8–24 h cycle [17]. In terms of warning levels, Intrieri et al. [14] stated that further deriving or defining more alert levels would almost certainly necessitate the development of additional thresholds. In this case, the previously mentioned high frequency of false alarms would become a problem. Moreover, lowering the alert levels would be more economically viable [14].

Aside from the normal framework of monitoring-based approach by Uchimura et al. [18], Intrieri et al. [14] and Casagli et al. [17] choose to combine the landslide displacement data with rainfall data to obtain the spatial information. This is for purpose of detecting acceleration on the surface which can determine imminent event of a structural failure of slope. They stated that monitoring-based approach through in situ instrumentation is insufficient in representing the whole area information. They proposed a remote sensing to obtain a two-dimensional deformation maps using the GB-InSAR. According to Casagli et al. [17], GB-InSAR is able to obtain displacement evidence in the observed area, enabling information to be collected from hazardous and rapidly moving areas where no in situ equipment can be mounted.

In the end, the monitoring-based LEWS was trying to achieve a LEWS that is low cost and simple, and in addition to that, the monitoring activities can be maintained for a long time. With less thresholds defined, this approach can be lightweight as the statistical approach, which means that the system is simple and easy to use. Other criteria added from Casagli et al. [17] is data reliability and quick availability. All the studies seem to describe monitoring-based approach as the suitable approach for landslides with high slope acceleration, especially the study by Casagli et al. [17].

3 Conclusion

In summary, the statistical approach is a practical approach for implementing an LEWS and addressing landslide hazards on a regional scale using relatively straightforward evaluation techniques for generating early alerts. Physical arguments and geographically accurate discriminations derived from complex analytical techniques enable the physical-based approach to provide early alerts. Given the complementary nature of the two approaches, various earlier research have presented a method for assessing landslide risks at a regional scale that incorporates and utilises both the statistical and physical-based methodologies. However, this review lacks the findings of a method combining the three approaches or the combination of either one mentioned before with the monitoring-based approach.

Moreover, the physical-based assessment has the advantage of determining higher alert levels with a greater degree of certainty related to physical explanations determined from comprehensive investigations of landslide-triggering occurrences. Meanwhile, due to the frequent updates to the alert level, the statistical approach exhibits a wide range of temporal success in landslide early detection. Lastly, the monitoring-based approach is found to be low-cost approach, simple, and has the potential of a long-term successful investment. With less thresholds defined, this approach can be as simple as the statistical approach. Moreover, it offers data reliability, fast availability and suitable approach for landslides with high slope acceleration.

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References

1. Bíl, M., Andrášik, R., Zahradníček, P., Kubeček, J., Sedoník, J., Štěpánek, P.: Total water content thresholds for shallow landslides. Outer Western Carpathians. Landslides **13**(2), 337–347 (2016). https://doi.org/10.1007/s10346-015-0570-9
2. Fell, R., Corominas, J., Bonnard, C., Cascini, L., Leroi, E., Savage, W.Z.: Guidelines for landslide susceptibility, hazard and risk zoning for land use planning. Eng. Geol. **102**(3), 85–98 (2008). https://doi.org/10.1016/j.enggeo.2008.03.022
3. Guzzetti, F., Peruccacci, S., Rossi, M., Stark, C.P.: Rainfall thresholds for the initiation of landslides in central and southern Europe. Meteorol. Atmos. Phys. **98**(3), 239–267 (2007). https://doi.org/10.1007/s00703-007-0262-7
4. Montrasio, L., Valentino, R.: Experimental analysis and modelling of shallow landslides. Landslides **4**(3), 291–296 (2007). https://doi.org/10.1007/s10346-007-0082-3
5. Petley, D.: Global patterns of loss of life from landslides. Geology **40**(10), 927–930 (2012). https://doi.org/10.1130/G33217.1
6. Segoni, S., Piciullo, L., Gariano, S.L.: A review of the recent literature on rainfall thresholds for landslide occurrence. Landslides **15**(8), 1483–1501 (2018). https://doi.org/10.1007/s10346-018-0966-4
7. Smith, D.M., Oommen, T., Bowman, L.J., Gierke, J.S., Vitton, S.J.: Hazard assessment of rainfall-induced landslides: a case study of San Vicente volcano in central El Salvador. Nat. Hazards **75**(3), 2291–2310 (2015). https://doi.org/10.1007/s11069-014-1422-y
8. Thiery, Y., Terrier, M., Colas, B., Fressard, M., Maquaire, O., Grandjean, G., Gourdier, S.: Improvement of landslide hazard assessments for regulatory zoning in France: STATE–OF–THE-ART perspectives and considerations. Int. J. Disaster Risk Reduction **47**, 101562 (2020). https://doi.org/10.1016/j.ijdrr.2020.101562
9. Guzzetti, F., Gariano, S.L., Peruccacci, S., Brunetti, M.T., Marchesini, I., Rossi, M., Melillo, M.: Geographical landslide early warning systems. Earth Sci. Rev. **200**, 102973 (2020). https://doi.org/10.1016/j.earscirev.2019.102973
10. Naidu, S., Sajinkumar, K.S., Oommen, T., Anuja, V.J., Samuel, R.A., Muraleedharan, C.: Early warning system for shallow landslides using rainfall threshold and slope stability analysis. Geosci. Front. **9**(6), 1871–1882 (2018). https://doi.org/10.1016/j.gsf.2017.10.008
11. Park, J., Lee, S., Son, D.: Safety of elevation from superficial fascial plane versus traditional deep fascial plane for flap elevation in a porcine model. Arch Hand Microsurg. **23**(2), 99–109 (2018). https://doi.org/10.12790/ahm.2018.23.2.99
12. Park, J.Y., Lee, S.R., Lee, D.H., Kim, Y.T., Lee, J.S.: A regional-scale landslide early warning methodology applying statistical and physically based approaches in sequence. Eng. Geol. **260**(October 2018), 105193 (2019). https://doi.org/10.1016/j.enggeo.2019.105193
13. Chen, M., Jiang, Q.: An early warning system integrating time-of-failure analysis and alert procedure for slope failures. Eng. Geol. **272**(April), 105629 (2020). https://doi.org/10.1016/j.enggeo.2020.105629
14. Intrieri, E., Gigli, G., Mugnai, F., Fanti, R., Casagli, N.: Design and implementation of a landslide early warning system. Eng. Geol. **147–148**, 124–136 (2012). https://doi.org/10.1016/j.enggeo.2012.07.017
15. Osanai, N., Shimizu, T., Kuramoto, K., Kojima, S., Noro, T.: Japanese early-warning for debris flows and slope failures using rainfall indices with radial basis function network. Landslides **7**(3), 325–338 (2010). https://doi.org/10.1007/s10346-010-0229-5
16. Pecoraro, G., Calvello, M., Piciullo, L.: Monitoring strategies for local landslide early warning systems. Landslides **16**(2), 213–231 (2019). https://doi.org/10.1007/s10346-018-1068-z
17. Casagli, N., Catani, F., Del Ventisette, C., Luzi, G.: Monitoring, prediction, and early warning using ground-based radar interferometry. Landslides **7**(3), 291–301 (2010). https://doi.org/10.1007/s10346-010-0215-y
18. Uchimura, T., Towhata, I., Anh, T.T.L., Fukuda, J., Bautista, C.J.B., Wang, L., Seko, I., Uchida, T., Matsuoka, A., Ito, Y., Onda, Y., Iwagami, S., Kim, M.S., Sakai, N.: Simple monitoring

method for precaution of landslides watching tilting and water contents on slopes surface. Landslides **7**(3), 351–357 (2010). https://doi.org/10.1007/s10346-009-0178-z
19. Mandal, S., Mondal, S.: Concept on landslides and landslide susceptibility BT. In: Mandal S., Mondal S. (eds.) Statistical Approaches for Landslide Susceptibility Assessment and Prediction, pp. 1–39. Springer International Publishing (2019). https://doi.org/10.1007/978-3-319-93897-4_1
20. Du, J., Glade, T., Woldai, T., Chai, B., Zeng, B.: Landslide susceptibility assessment based on an incomplete landslide inventory in the Jilong Valley, Tibet, Chinese Himalayas. Eng. Geol. **270**, 105572 (2020). https://doi.org/10.1016/j.enggeo.2020.105572
21. Reichenbach, P., Rossi, M., Malamud, B.D., Mihir, M., Guzzetti, F.: A review of statistically-based landslide susceptibility models. Earth Sci. Rev. **180**, 60–91 (2018). https://doi.org/10.1016/j.earscirev.2018.03.001
22. Piciullo, L., Dahl, M.-P., Devoli, G., Colleuille, H., Calvello, M.: Adapting the EDuMaP method to test the performance of the Norwegian early warning system for weather-induced landslides. Nat. Hazard. **17**(6), 817–831 (2017). https://doi.org/10.5194/nhess-17-817-2017
23. Calvello, M., d'Orsi, R.N., Piciullo, L., Paes, N., Magalhaes, M., Lacerda, W.A.: The Rio de Janeiro early warning system for rainfall-induced landslides: analysis of performance for the years 2010–2013. Int. J. Disaster Risk Reduction **12**, 3–15 (2014). https://doi.org/10.1016/j.ijdrr.2014.10.005
24. Jakob, M., Owen, T., Simpson, T.: A regional real-time debris-flow warning system for the district of North Vancouver, Canada. Landslides **9**(2), 165–178 (2012). https://doi.org/10.1007/s10346-011-0282-8
25. Segoni, S., Battistini, A., Rossi, G., Rosi, A., Lagomarsino, D., Catani, F., Moretti, S., Casagli, N.: Technical note: an operational landslide early warning system at regional scale based on space-time-variable rainfall thresholds. Nat. Hazard. **15**(4), 853–861 (2015). https://doi.org/10.5194/nhess-15-853-2015
26. Marin, R.J., Velásquez, M.F., Sánchez, O.: Applicability and performance of deterministic and probabilistic physically based landslide modeling in a data-scarce environment of the Colombian Andes. J. South Am. Earth Sci. **108**, 103175 (2021). https://doi.org/10.1016/j.jsames.2021.103175
27. Aristizábal, E., Vélez, J.I., Martínez, H.E., Jaboyedoff, M.: SHIA_Landslide: a distributed conceptual and physically based model to forecast the temporal and spatial occurrence of shallow landslides triggered by rainfall in tropical and mountainous basins. Landslides **13**(3), 497–517 (2016). https://doi.org/10.1007/s10346-015-0580-7
28. Mergili, M., Marchesini, I., Alvioli, M., Metz, M., Schneider-Muntau, B., Rossi, M., Guzzetti, F.: A strategy for GIS-based 3-D slope stability modelling over large areas. Geosci. Model Dev. **7**(6), 2969–2982 (2014). https://doi.org/10.5194/gmd-7-2969-2014
29. Mergili, M., Marchesini, I., Rossi, M., Guzzetti, F., Fellin, W.: Spatially distributed three-dimensional slope stability modelling in a raster GIS. Geomorphology **206**, 178–195 (2014). https://doi.org/10.1016/j.geomorph.2013.10.008
30. Reid, M.E., Christian, S.B., Brien, D.L., Henderson, S.: Scoops3D—Software to Analyze Three-Dimensional Slope Stability Throughout a Digital Landscape. US Geological Survey Techniques and Methods, p. 14 (2015)
31. Montrasio, L., Valentino, R., Corina, A., Rossi, L., Rudari, R.: A prototype system for space–time assessment of rainfall-induced shallow landslides in Italy. Nat. Hazards **74**(2), 1263–1290 (2014). https://doi.org/10.1007/s11069-014-1239-8