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Developing an Accessible Landslide Susceptibility Model Using Open-Source Resources

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Abstract: Landslide susceptibility models are important for public safety, but often rely on inaccessible or unaffordable software and geospatial data. Thus, affordable and accessible landslide prediction systems would be especially useful in places that lack the infrastructure for acquiring and analyzing geospatial data. Current landslide susceptibility models and existing methodologies do not consider such issues; therefore, this study aimed to develop an accessible and affordable landslide susceptibility modeling application and methodology based on open-source software and geospatial data. This model used TRIGRS (asc format) and QGIS (Digital Elevation Models (DEMs) extracted from GeoTIFF format) with widely accessible environmental parameters to identify potential landslide risks. In order to verify the suitability of the proposed application and methodology, a case study was conducted on Lantau Island, Hong Kong to assess the validity of the results, a comparison with 1999 landslide locations. The application developed in this study showed a good agreement with the four previous landslide locations marked as highly susceptible, which proves the validity of the study. Therefore, the developing model and the cost-effective approach, in this study simulated the landslide performance well and suggested the new approach of the landslide prediction system.

Keywords: landslide modeling; landslide hazards; susceptibility models; open-source software; satellite imagery; accessible modeling

1. Introduction

Landslides—defined as the displacement of soil and rocks on slopes—are one of the most common natural hazards in many mountainous areas and greatly affect the social sustainability of human beings [1–3]. They can have natural causes, such as heavy rainfall and earthquakes, but also human causes, including urban encroachments and increased surface impermeability to water infiltration. Many international studies have focused on rainfall-induced landslides in the last few decades [4] because it is important for public safety to have a process in place for gauging potential landslide hazards in all susceptible regions [5]. As a consequence, several landslide risk modeling applications have been developed (such as GEOtop [6] and SHETRAN [7]), which are able to calculate risk over large areas using hydrological and mechanical elements. Other applications can evaluate landslide hazards for smaller areas such as catchments of a few square kilometers [8,9].

Although advances in computer modeling of landslide risks have been supported by highly sophisticated risk map analysis at various scales, actual landslide risk prediction can often be a complicated and expensive process. Furthermore, the majority of landslide susceptibility models require the acquisition of geospatial data such as Digital Elevation Models (DEMs) and geospatial statistics such as regional rainfall distributions, making access to these models difficult for places where the geographic data infrastructure is not sufficiently developed. In particular, the key infrastructure for this process such as Light Detecting and Ranging (LiDAR) or Digital Terrain Models (DTMs) is complex and not user-friendly. In addition, most existing modeling applications are scripting-oriented, adding a level of complexity that requires specialists or trained personnel for their operation. Industry-standard GIS software is also costly, an additional barrier to use in these areas. As a consequence, crucial landslide prediction processes are more difficult to implement in many places where people live at high risk of such natural disasters. Therefore, this study aimed to develop an accessible and affordable landslide prediction system using open-source software and publicly-available data, including environmental (e.g., rainfall, soils, and aquifers) and geospatial (e.g., satellite imagery, DEMs, and DTMs) resources. This work also investigated whether landslide susceptibility prediction could be performed using the same applications and data sets. A case study, Lantau Island, Hong Kong, was employed to test the developed model and assess the validity of the application for modeling landslide susceptibility.

The majority of slope instability situations are the result of rainfall; specifically rainfall-induced landslides. Research from many disciplines, including engineering geology, soil mechanics, hydrology, and geomorphology, has focused on this subject; the introduction of Geographical Information Systems (GIS) software has made a significant contribution to landslide risk assessment [4,10–13]. Various deterministic modeling applications are available for use at different scales [14], such as distributed Shallow Landslide Analysis Models (dSLAMs), which employs physical variables [9,15]. Because of the implications of infinite slope stability and soil humidity, a number of research approaches have employed deterministic models for investigating landslide susceptibility, including TRIGRS, SINMAP [14], CHASM, and GEOtop-FS. These are well-known for calculating shallow-depth landslide susceptibility. This study considered a variety of deterministic landslide susceptibility modeling software, listed in Table 1.

Table 1. Deterministic landslide susceptibility modeling applications.

Modeling	Description	License/Open source
CHASM	Hydrological Stability Model	Standalone Software
LISA	Stability Analysis	Scripts, No source
SHALSTAB	Shallow Landslide Stability Model	jgrasstools (Java source), supplied ArchView extension dll
SMORPH	Slope Morphology Model	ESRI ArcScript
iSLAM/IDSSM	Shallow Landslide Model, Dynamic Stability and Shallow Landslide Model	No open source
SINMAP	Stability Factor Method	MW-SINMAP
SHETRAN	European Hydrology System	No open source
TRIGRS	Rainfall Intensity and Regional Slope Stability	USGS TRIGRS, open source, Scripts
PROBSTAB	PCRaster GIS Package (Stability Model)	No open source
PISA	Slope Probability Analysis Model	PISA-m Software
SUSHI	Slope Stability and Water Saturation Simulation	No open source
GEOtop-FS	Hydrological Dispersion Model, Slope Stability Probability Model	No open source

For the landslide susceptibility evaluation, Formetta et al. [1] defined three main components: a hydrological model for soil suction and soil water content estimates, a component for computing the factor of safety (FS) based on the infinite slope hypothesis, and a GIS for visualization and calculation of the outputs. They then employed the GEOtop-FS model in a mountainous area of Italy to analyze the physical and spatial distribution of landslide susceptibility. The main model outputs were soil moisture and water table depth maps at different soil depths as environmental variables. In order to further analyze such processes, one study [16] compared three landslide susceptibility models: TRIGRS (Transient Rainfall Infiltration and Grid-based Regional Slope-stability Models), SINMAP (Stability Index MAPing), and SHALSTAB. Another investigated the addition of tree roots as a landslide variable [17]. Various studies have shown that landslide risk models are able to produce hazard risk maps from mechanical and physical variables [13,18–20].

While each model has different characteristics and its own advantages and disadvantages, most are commercial and script-based, and some are plugins for other CAD or GIS software packages. Standalone applications such as CHASM have better interfaces that improve their ease of use, whereas those based on scripts like TRIGRS (Fortran) are less user-friendly. On the other hand, script-based models are often open-source licensed, resulting in a disparity between user-friendly interfaces and affordable or easily-accessible software.

Many studies have investigated landslide prediction modeling using commercially available software. One recent study [1] employed GEOtop modeling modules using DEMs and soil properties such as moisture, water table depth, and soil depth to analyze landslide susceptibility [21,22]. At the catchment scale, the SHALSTAB model uses steady-state hydrological processes and the infinite slope approach [8], whereas the SINMAP model [16] employs both uncertainty parameters and raster-based GIS images. SHETRAN [10] and TRIGRS [23] performed hydrological and spatial temporal modeling for saturated or unsaturated soil conditions. GEOtop-FS [6] is capable of handling soil layers separately, whereas PROBSTAB [24,25] can be combined with the STARWARS hydrologic model to consider multiple soil parameters.

This study employed Transient Rainfall Infiltration and Grid-based Regional Slope-stability (TRIGRS)—a Fortran-based program produced by the United States Geological Survey (USGS). TRIGRS is a dynamic or real-time dispersion model rather than a hydrological static analysis. The main function of TRIGRS is to calculate the FS by analyzing the run-off phenomenon using slope extracted from the DEM and based on DEM data obtained from stereo images. It is suitable for landslide analysis over time and over a relatively large area, and is a publicly-accessible open-source model. The version chosen in this study (published in November 2009) uses gridded elevation models such as DEMs and DSMs. Process variables can include water, permeability, and slope stability. Moreover, recent studies (listed in Table 2) have also indicated that TRIGRS provides an efficient methodology for analyzing landslide probability with various environmental variables and in different contexts. Most of these studies were conducted in countries with a high risk of rainfall-induced landslides, such as the mountainous areas of Southeast Asia (including Hong Kong and Taiwan), which experience frequent shallow landslides initiated by heavy rainfall in the typhoon season [26].

Table 2. Recent studies using the open source Transient Rainfall Infiltration and Grid-based Regional Slope-stability (TRIGRS) application. DEM: Digital Elevation Model.

Study	Case Study	Environmental Variables	Elevation Data and Year
TRIGRS—Assessment of the effects of grid size, rainfall pattern, and groundwater stage on slope stability at Shan-Tsun-Laio landslide [27]	Taiwan, Fu-Hsin village Chihchang Township Taitung County	Grid size, Rainfall pattern, Groundwater stage	DEM (5 m × 5 m, 10 m × 10 m) 2012
Assessment of regional rainfall-induced landslides using 3S-based hydro-geological model [28]	Taiwan, Ta-Chia River Central western Taiwan	Geology, Climatic setting	DTM (40 m × 40 m) 2008
Mapping susceptibility of rainfall-triggered shallow landslides using a probabilistic approach [29]	Taiwan, Route Nantou 71 Bet. Wujai tribe and Fachi village Central Taiwan		DEM (40 m × 40 m, 10 m × 10 m) 2007
Analysis of time-varying rainfall infiltration induced landslide [30]	Taiwan, Tenlio Mountain Northern Taipei County	Climatic antecedent condition	DTM 2005
Rainfall infiltration: infinite slope model for landslides triggering by rainstorm [26]	Hong Kong, Tung Chung East Lantau Island	Soil type	2010
Dynamic characteristics analysis of shallow landslides in response to rainfall event using GIS [31]	Hong Kong, Tung Chung East Lantau Island	Historic rainfall record	DEM 2005
Prototyping an experimental early warning system for rainfall-induced landslides in Indonesia using satellite remote sensing and geospatial datasets [32]	Indonesia, Karnaganyar Java	Rainfall	DEM 2010

The ability of GIS software to acquire and map environmental variables, along with its robust analytical and data-management capabilities, make it an excellent partner for applications like TRIGRS with regard to landslide risk assessment [33]. GIS can use multi-layered analysis and artificial networks in order to evaluate slope stability and landslide risk at various scales [28]. Conventional analyses of rainfall-caused landslide risks have essentially relied on either two-dimensional numerical analyses with limit balances or determinate elements and different analysis systems [30]. The potential of GIS has also been expanded to spatial analysis functions over larger areas. Therefore, not only academics but many engineers and other users have employed GIS applications for landslide prediction.

QGIS is a well-known and equally efficient open-source GIS software package that can also generate multiple maps with multi-layered projections. Compared with other open-source GIS software packages such as gvSIG and GRASS, QGIS has a short start-up time and an easy incorporation with the C/C++ programming [34]. QGIS can not only create maps in different formats and for various purposes, but also allows the creation of plans in both raster and vector layers, while typical GIS applications only allow the saving of points, lines, or polygons for vector data. Various raster images can be used; crucially, QGIS can implement geo-referencing. Finally, as open-source software, QGIS falls under the General Public License (GNU) so that it can be modified to carry out various special tasks. Although the key elements of landslide prediction are ground models such as DEMs, other environmental variables such as soil depth, rainfall intensity, and topographic index can increase the validity of the analytical process. Most of these are now publicly available [20].

2. Method

2.1. Method Outline

Typical approaches to landslide hazard prediction are limited by a number of natural uncertainties [35], such that predictions rely heavily on the amount of available information and can thus be a knowledge-intensive process [31]. Therefore, during the development of this study's landslide risk prediction application, several scenarios were considered to make the developed application more robust. This was another reason for the selection of an open-source approach, which allows for greater customization with regard to the consideration of natural elements. An overview of the methodology using TRIGRS and QGIS for landslide hazard prediction is shown in Figure 1. The satellite imagery came from KOMPSAT-2, a South Korean multipurpose satellite launched in 2006 and orbiting at a height of 685 km (circling the Earth 14 times per day).

TRIGRS is designed to model the timing and distribution of shallow rainfall-induced landslides [36] using sequential computation consisting of infiltration models for wet initial conditions. Some modules within TRIGRS are based on Iverson's linearized methods of Richards' equation and extensions [23,36]. Moreover, TRIGRS also employs a number of Heaviside step functions for rainfall intensity and time-varying sequences for duration [37]. However, because predicting landslide risks is a highly rational process, and requires significant quantities of data to overcome uncertainty, a number of environmental variables need to be taken into account [38,39]. Meanwhile, QGIS offers a variety of vector or raster analysis functionality with certain limits, which can be overcome with plugins and extension packs.

The final output of the landslide modeling application is based on TRIGRS, QGIS, and Geospatial Data Abstraction Library (GDAL) software (Figure 2). GDAL is a translator library for raster and vector geospatial data formats that is released under an X/MIT style Open Source license by the Open Source Geospatial Foundation. It presents a single raster abstract data model and vector abstract data model to the application for all supported formats. The development process can be summarized in three phases: DEM creation for topographical analysis, height and slope analysis using DEMs/DSMs, and landslide susceptibility map rendering using TRIGRS.

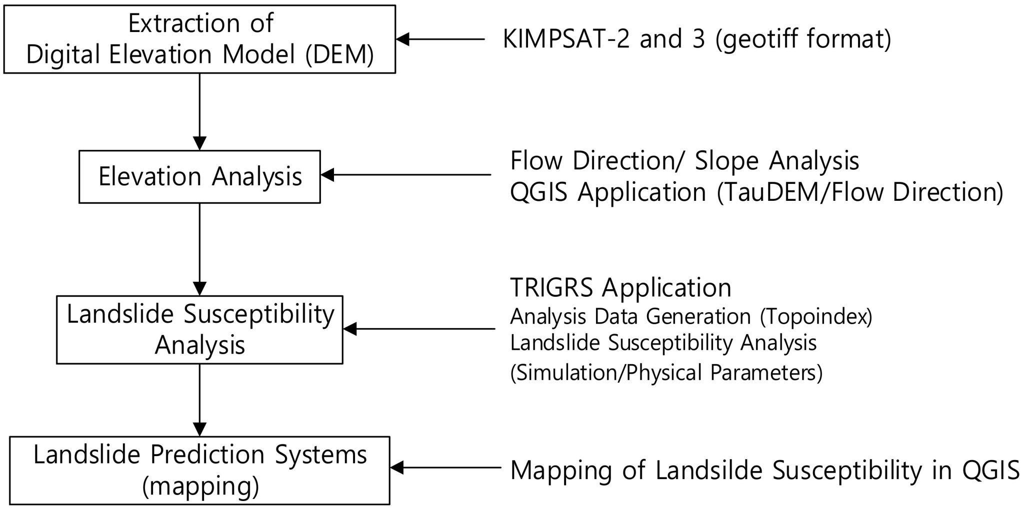

Figure 1. Flow chart of model development procedure.

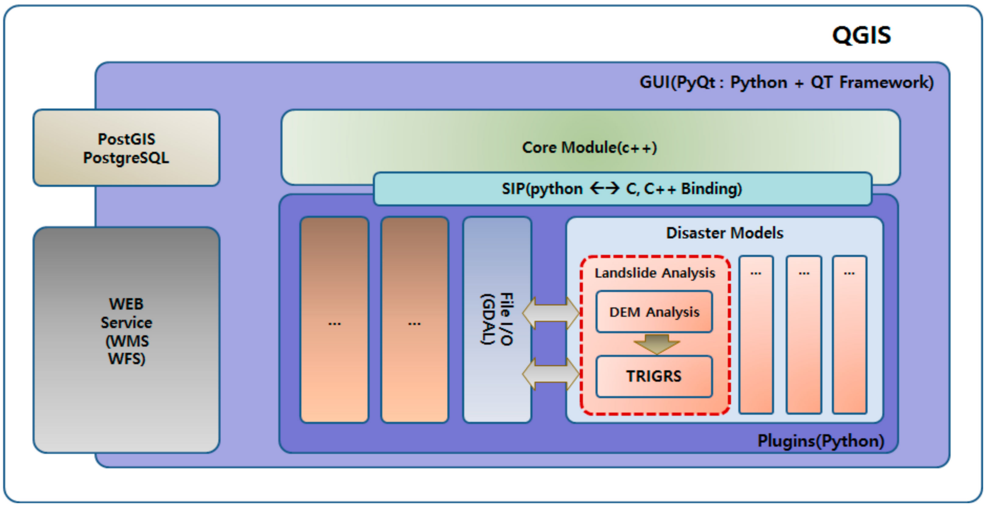

Figure 2. Modeling programming frameworks.

The creation of a DEM is the first step to building the landslide model. Elevation data, the critical element, can be provided from LiDAR or optical and radar imagery from KOMPSAT 2 and 3 satellites. For a wider regional analysis, non-commercial data from Shuttle Radar Topography Mission (SRTM) or Global Digital Elevation Model (GDEM) can be freely acquired with 90 m and 30 m accuracy levels (within the US). However, for detailed analysis, KOMPSAT 3 satellite imagery is required because it has 4 m resolution in multiple bands and 0.7 m resolution in color bands, from which 8 m and 1.4 m resolution DEMs can be developed, respectively. Although there is no specific reason for choosing a 4-m resolution DEM, the authors' previous attempts to use higher resolutions resulted in serious time consumption and inefficiency. Such detailed elevation data is highly efficient for localized and accurate results where terrain is variable, and a number of environmental variables need to be taken into account. DEMs were extracted from the satellite imagery using another open-source software package, Orfeo ToolBox (OTB), which is a C++ library for remote sensing image processing distributed under the CeCILL-v2 license. In this study, the Stereo Framework command within OTB was used.

Next, using the produced DEM, additional data can be created in accordance with the spatial information. At this stage, TauDEM, an expansion of QGIS, was implemented to produce flow direction and slope analyses. Lastly, landslide susceptibility maps were produced using TRIGRS. TopoIndex was used to create the files associated with runoff routing from flow direction information, then TRIGRS was used with QGIS to visualize landslide hazard maps with regard to slope, runoff routing, physical parameters of infiltration (soil, water table, and infiltration speed), and rainfall intensity.

2.2. Landslide Susceptibility Modeling

As summarized in Figure 1, model development requires the following processes: display of satellite imagery, production of colored imagery, landslide analysis, sensor modeling of raw data, production of a DEM from stereo imagery, calculation of areas previously damaged by landslides, prediction of future landslides, production of slope and flow direction based on TauDEM, production of landslide risk maps based on TRIGRS, implementation of analyzed results, display and overlay of analyzed results, saving of analyzed results, and output/mapping of analyzed results. A standard format, GeoTIFF, was used to save and analyze imagery within QGIS, and the entire program was based on the Python scripting language for analysis modules as an expansion to QGIS.

KOMPSAT-2 and -3 stereo imagery was obtained from the Korea Aerospace Research Institute. This imagery can be converted into DEMs using the time gap between the two images. This study tested the use of four applications (Aster GDEM, ENVI, ERDAS, and Orfeo Toolbox) for creating DEMs, all of which produced appropriate results (Figure 3). Spatial resolution of four applications are 30 m (1″). However, as Orfeo Toolbox is open-source software, it was chosen for further conversion of stereo imagery to DEMs due to the combination of credible results and better public access to the program.

Height analysis was performed (including Flow Direction and Slope Analysis) using TauDEM within QGIS. After extraction, landslide analysis and risk susceptibility were visualized using TRIGRS, in which the TopoIndex command was used to create input data (this creates and performs Runoff Routing files in conjunction with DEM and Flow Direction). TRIGRS also produces landslide prediction maps in combination with slope, runoff routing, soil properties, aquifers, permeability, and rainfall intensity. TRIGRS is a dynamic or real-time dispersion model rather than a hydrological static analysis. Using the DEM data obtained from stereo images makes it suitable for landslide analysis over time and a relatively large area.

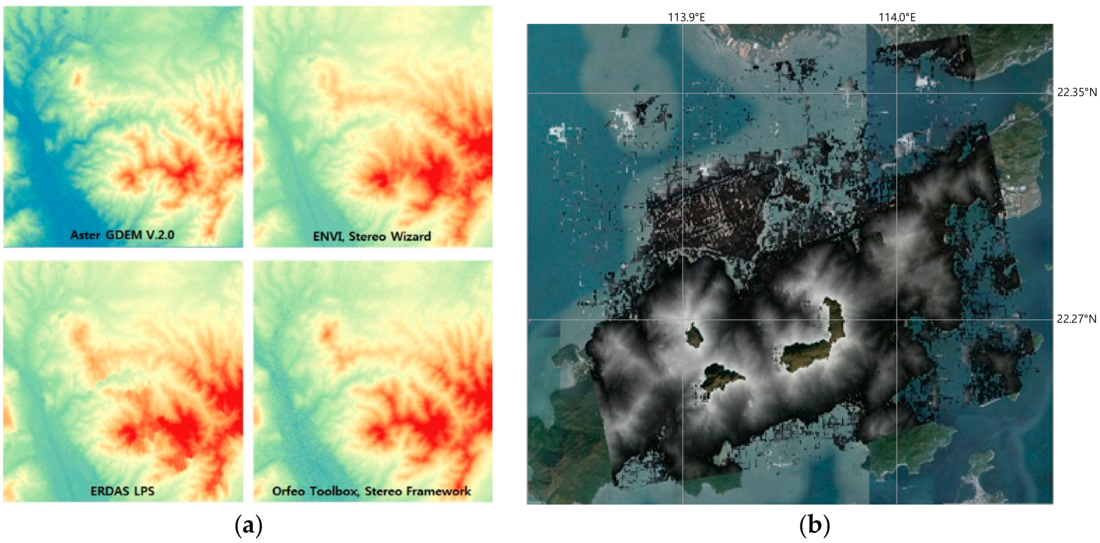

Figure 3. (**a**) Comparison of DEM processing options and (**b**) DEM of case study location created by Orfeo ToolBox.

In the TRIGRS model, slope stability using an infinite-slope stability [23,36,37] is represented as below:

$$FS = \frac{tan\psi}{tan\theta} + \frac{c - \varphi(Z,t)\gamma_w tan\psi}{\gamma_s Z sin\theta cos\theta} \quad (1)$$

where c is soil cohesion, φ is the ground-water pressure head, Z is the vertical depth, t is time, ψ is the soil friction angle, γ_w is the unit weight of groundwater, γ_s is the soil unit weight, and θ is the slope angle. A more detailed TRIGRS model was described by Baum et al. [23] and Park et al. [37]. In this study, FS < 0.7 denotes unstable conditions because too many sites exhibited FS below 1 in the experimental area, and it was necessary to show more susceptible areas.

With regard to the accuracy of landslide prediction systems, environmental variables were considered within the TRIGRS process using the parameter settings shown in Figure 4. Within TRIGRS, some key commands are critical for the generation of DEMs, such as UnitCover (changes image data grid size, controlling input/output image grid size), GridMatch (matches image grid numbers to no-data cell locations, critical for matching vertical and horizontal grid numbers with no-data locations), TopoIndex (calculates image sizes, creates data related to water in downslope cells), and TRIGRS (performs landslide analysis). Furthermore, various environmental variables were considered to increase the accuracy of landslide susceptibility models, such as soil depth (Zmax, Depthwt, Rizero), rainfall intensity (Ri), and other topographic indices (flow accumulation, soil moisture, distribution of saturation zones, depth of water table, evapotranspiration, thickness of soil horizons, organic matter, pH, silt/sand content, and plant cover distribution) using commands such as TldscelGrid, TlcelidxList, TldscelList, and TlwfactorList. The command TauDEM was used to analyze flow direction and slope. In particular, the Pit Remover module was used to amend (fill) the DEM for efficient slope analysis.

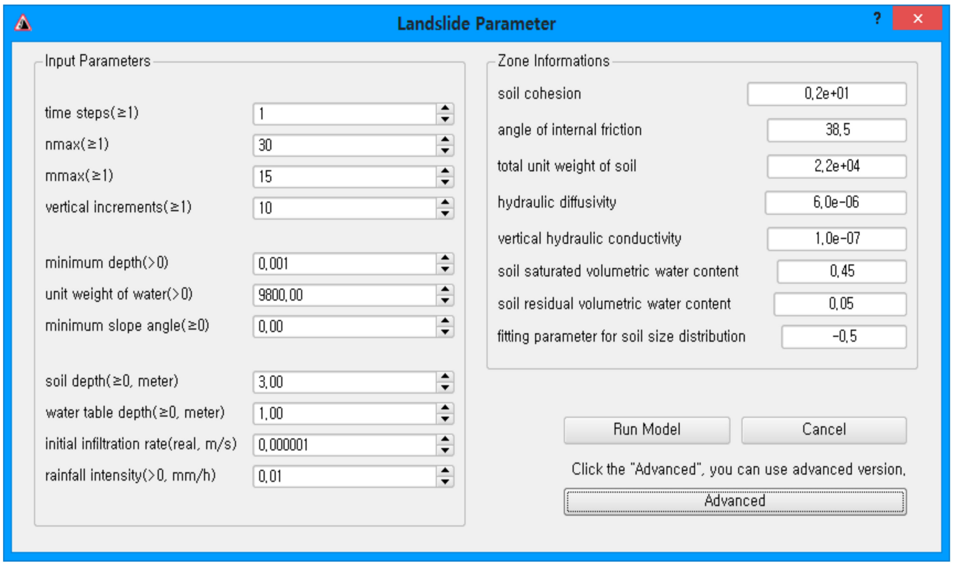

Figure 4. TRIGRS environmental parameter input window showing the settings used in this study.

Information on soil properties is freely available from the Digital Soil Map of the World (worldmap.harvard.edu/data/geonode:DSMW_Rdy). The effective soil depths were obtained from the UN Food and Agriculture Organization (data.fao.org/map?entryID=c3bfc940-bdc3-11db-a0f6-000d939bc5d8). Ground water table data were obtained from the University of Tokyo's Hirabayashi Lab (hydro.iis.u-tokyo.ac.jp/~sujan/research/ongoing/parameter-estimation.html) and ArcGIS's Water Table Depth (www.arcgis.com/home/item.html?id=6030e985be8b483c802376c63c956ca6). Initial rainfall infiltration rates (xpsolutions.com/webhelp/section_11_globals/11_4_infiltration/max_infiltration_rate_h1_wlmax.htm) and rainfall intensity information (http://www.geog.ucsb.edu/-bodo/trimm/) (TRMM data: 90th percentile rainfall threshold) were also freely available for download. Rainfall intensity data were acquired from the University of Santa Barbara Geography Department (http://www.geog.ucsb.edu/~bodo/TRMM/) as the 90th percentile rainfall threshold; these data were then integrated with the DEM. Finally, the user interface was designed with QT Designer, a cross-platform application development framework for desktop, embedded, and mobile platforms; this is also available as free software under several versions of the GPL and LGPL.

2.3. Case Study Application

A case study was employed to verify the validity of the landslide modeling application developed in this study. The study area was a mountainous area near Chek Lap Kok International Airport, Lantau Island, Hong Kong (Figure 5), located at 22°16′28.5492″N latitude, 113°56′16.5192″E longitude, and 102.540 m above sea level. Encircled by mountains and roads, this area is predominantly covered by various species of forest.

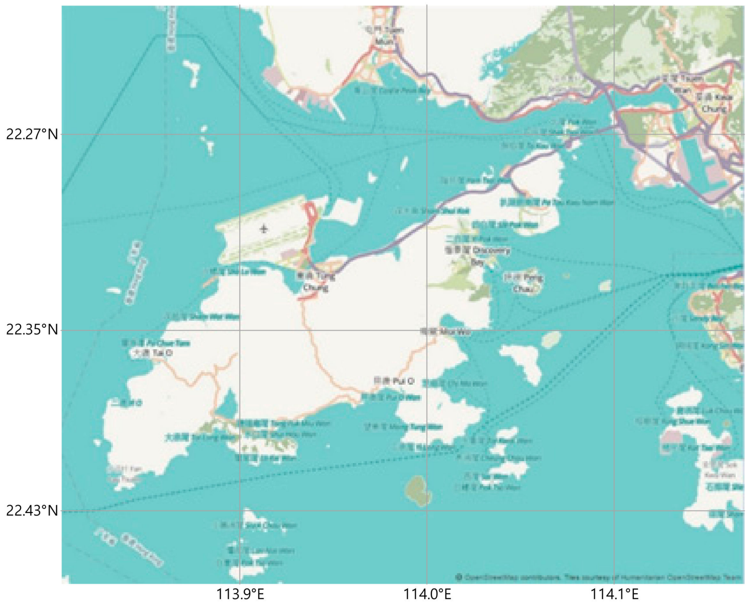

Figure 5. General location of the case study site on Lantau Island, Hong Kong.

In the past, two powerful rainfall events have caused landslides in this area. From 22–24 August 1999, Typhoon Sam produced an extremely heavy 24-h rainfall event of 310.5 mm and total rainfall of 616.5 mm. The peak rainfall intensity was 54 mm/h during the major rainfall period. Large-scale landslides subsequently occurred. Other landslides were produced elsewhere on the island due to another severe rainfall event in 2001. A comparison of the 1999 and 2001 rainfall events indicated that no single element such as rainfall intensity could account for landslide initiation. For instance, in 1999, a landslide was initiated by a rainfall intensity of 54 mm/h, whereas in 2001, a rainfall intensity of 82.5 mm/h did not initiate any such event. Therefore, landslide risk predictions need to consider other spatial information in order to produce a credible risk analysis [31]. After the DEMs were set up (Figure 6), appropriate environmental variables for the site were also input (Table 3) before the analysis to produce more accurate landslide hazard risk maps.

Table 3. Summary of applied values for Lantau Island, Hong Kong.

Parameter	Units	Value
Water Unit Weight (γ_ω)	kN/m^3	9.8
Soil Cohesion (c)	kPa	2
Friction Angle (ψ)	degree	38.5
Soil Unit Weight (γ_s)	KN/m^3	19
Initial Infiltration rate (I_z)	Ms^{-1}	0
Rainfall Period (h)	hours	48

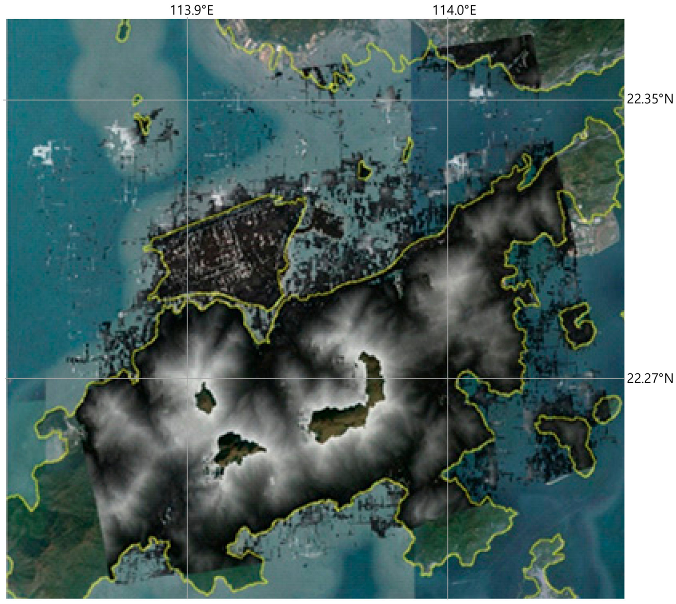

Figure 6. DEM extracted from satellite imagery for further analysis. The DEM was tilted in accordance with the aerial photograph orientation. Yellow lines show administrative borders.

3. Results

The infiltration and slope stability response to rainfall for a portion of the case study site are shown in Figure 7 for the TRIGRS model, which clearly illustrates the potential landslide risk for the area. Figure 7 is reclassified from 0 to 10 FS values from the TRIGRS model with five classes. The spatial resolution in Figures 7 and 8 is 30 m (1″) due to the resolution of Figure 3. As shown in Figure 7, the main strength of the TRIGRS model is allowing quantitative estimated FS. However, the TRIGRS contains the problem such as the high degree of simplification and the applicability limitation due to the intricate data requirements. The poor quality of data together with the high spatial variability in the TRIGRS model resulted in results of limited accuracy. Most of the important limitations at a reasonable cost/benefit ratio are the poor quality of environment data together with the high spatial variability. Thus, the results of the TRIGRS model depends on the type, resolution, and quality of data [35]. Highly susceptible landslide sites are represented as red pixels, for which the FS is below 0.7, as described above. Red pixels are widely scattered and not grouped in geographically sensible way because Lantau island contains a large amount of curved and steep mountainous terrain.

The main function of TRIGRS is to estimate FS by analyzing the dispersed runoff performance using the slope extracted from the DEM. In TRIGRS, water content and saturation differ depending on the characteristics of soil and rainfall intensity, respectively. It is necessary to input the characteristics of initial groundwater depth or soil depth as much as possible. However, it was difficult to obtain groundwater and soil parameter data. Thus, these input parameters were estimated as a constant value based on references of the hydrologic and geologic background; however, TRIGRS is modified and applied to the probability-based Monte Carlo simulation by assuming that the parameters are random, rather than a deterministic approach. Also, TRIGRS does not fit well at a slope of 60° or more, and is sensitive to the input DEM data. This explains the very complex and dispersed nature of highly susceptible landslide pixels in Figure 7.

This indicates that the results of this study show susceptible landslide areas based on individual pixels, and not by outlines. This study did not really identify the former landslide areas with any degree of certainty or clarity. Moreover, to assess the validity of the results, a comparison with 1999 landslide locations is shown in Figure 8. The application developed in this study showed a good agreement with the four previous landslide locations marked as highly susceptible (red color), which proves the validity of the study, despite the scattered nature of the red pixels. Most previous studies used the coincidence of pixels between simulated and historical landslides to verify the performance of their models [40,41]. However, to overcome the limitations of previously simulated models, various indices have been suggested, such as the success rate and the modified success rate [42], the D index [30], the receiver operating characteristic [43,44], the success and error indices [45], the scar concentration and landslide potential [14], the probability of detection, the false alarm ratio, and the critical success index [46]. The results of this study can be utilized in landslide hazard assessment and urban planning studies [47–49] as the cost-effective and efficient data and software application approach.

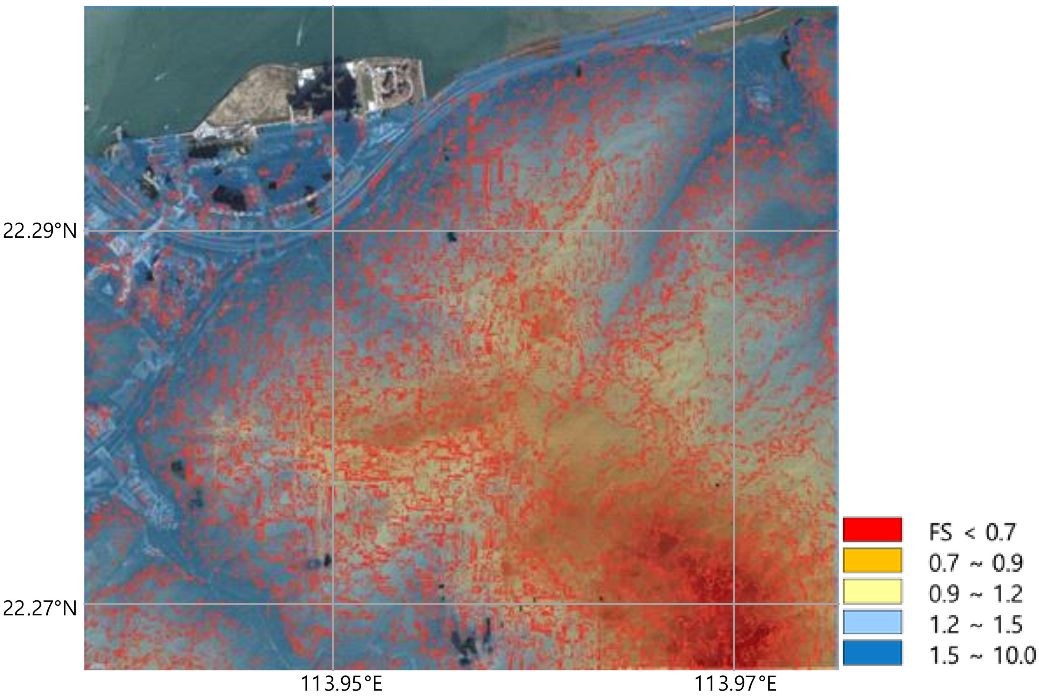

Figure 7. Simulation results using TRIGRS model. Red bands indicate higher susceptibility to landslides based on DEM analysis (elevation, slope angle, aspect, and curvature).

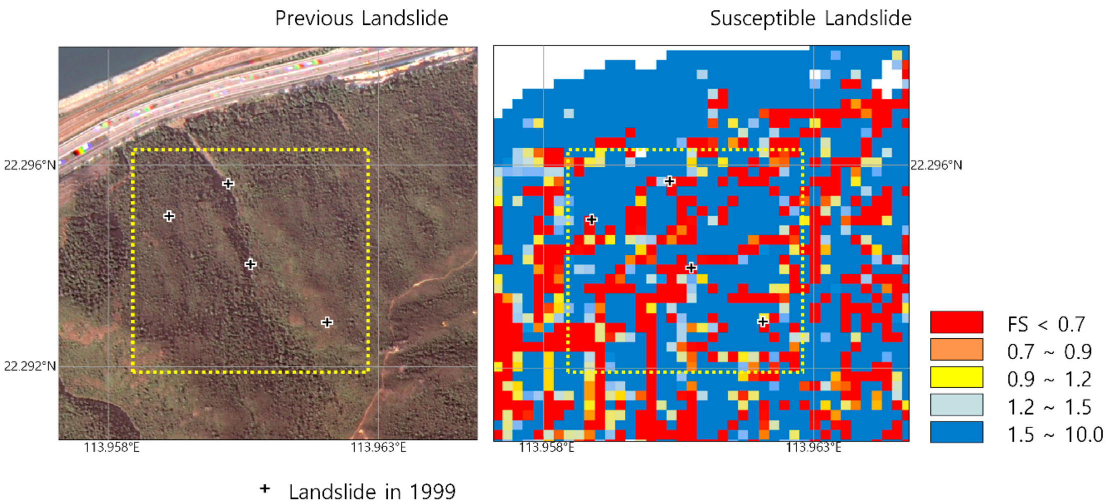

Figure 8. Comparison between (**a**) 1999 landslide locations and (**b**) landslide potential predicted by the proposed model. Note: The plus (+) signs indicate the landslide locations in 1999.

4. Conclusions

Although a number of landslide susceptibility models exist, they are rarely accessible, affordable, and easily manageable for non-specialists. In particular, commercially restricted geographic information and applications make such processes more inaccessible. Therefore, the purpose of this study was to develop sustainable and feasible landslide susceptibility models using open-source applications and geographic data. This approach consisted of three main components: the development of software based on TRIGRS and QGIS, the implementation of freely available data resources, and the application of the model to a case study site on Lantau Island, Hong Kong. The results showed that this application can identify the spatial distribution of landscape risk while illustrating a substantial correspondence between the modeled outputs and previous landslides.

Various scenarios for landslide risk assessment can be considered by using a significant number of environmental variables drawn from open-source data. Baseline DEMS can be generated for any location using satellite imagery, followed by analysis using TRIGRS and QGIS software in order to visualize and map geographic data (such as soil parameters) and reproduce field measurements (such as soil moisture). This improves the model's performance in terms of safety factor computation.

Landslide risks can be calculated simply through GIS spatial modeling, when the major causes or locations of landslides are already known. However, where this is not clear, the credibility of landslide predictions relies heavily on other environmental variables and modeling applications. For that reason, TRIGRS-based applications are the prevailing method for landslide risk mapping, in particular when combined with various advanced applications such as spatial modules in GIS. Therefore, in conjunction with GIS capabilities, landslide hazard risks can be predicted accurately by spatial and temporal environmental variables such as soil conditions, temporal rainfall intensities, pore pressure, and rainfall infiltration. The final step of this study was to validate the developed open-source application by testing its mapping results of landslide susceptibility against previously known landslide locations within the case study area. In this test, four historic landslide locations were identified as high landslide risk zones.

In summary, the open-source model developed in this study can be implemented as a first-hand approach to evaluating landslide hazard risk. This is an accessible and efficient approach relying on widely-available open-source software and resources, based mainly on DEMs and other easily acquired environmental variables. Further research should focus on improving the validity of this landslide risk prediction process by considering more environmental variables such as debris flow mechanics, soil mechanics, friction angles, and cohesive soil parameters.

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