Development of landslide susceptibility map utilizing remote sensing and Geographic Information Systems (GIS)

Helmi Zulhaidi Mohd Shafri and Izni Mohd Zahidi
Department of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia, Serdang, Malaysia, and
Shamsul Abu Bakar
Department of Landscape Architecture, Faculty of Design and Architecture, Universiti Putra Malaysia, Serdang, Malaysia

Abstract

Purpose – The purpose of this research is to produce the landslide susceptibility map of Fraser's Hill and its surroundings in Pahang (Malaysia), utilizing remote sensing data and Geographic Information System (GIS) as a way to monitor sustainable highland development.

Design/methodology/approach – Ancillary data are collected, processed, and constructed into a spatial database in a GIS platform to produce the satellite image. The factors chosen that influence landslide occurrence are land cover, vegetation index (NDVI), precipitation, and geology. Landslide-hazardous areas are analyzed and mapped using the landslide-occurrence factors through the heuristic approach Analytic Hierarchy Process (AHP).

Findings – It is demonstrated that the integration of remote sensing data and GIS database is of assistance in managing land-use planning of sustainable development. The verification with the existing landslides record shows a noteworthy accuracy.

Research limitations/implications – The list of data/maps reflects a considerable understanding of the basic cartographic information that is needed to effectively deal with the landslide problem.

Practical implications – This approach indicates a potential long-term application of remote sensing and GIS in managing sustainable highland development by monitoring the hazard-susceptibility area.

Originality/value – The value of the work is in its integration and utilization of remote sensing and GIS to provide sustainable development which can be developed to aid landslide warning systems.

Keywords Sensors, Geographic Information Systems, Landslides, Hazards

Paper type Research paper

Introduction

Landsliding is one of the many natural processes that shape the surface of the earth. It is only when landslides threaten mankind that they represent a hazard. The force exerted by earth, rock and debris can crush structures, people, and animals. Moreover, landslides dislocate objects they come in contact with. Dislocation can include the uprooting of trees, severing of utility lines such as electric, telephone, gas, water and sewer (resulting in additional hazards), tossing of vehicles off of roadways, and destruction of roads, railways and bridges. The damages and casualties due to landslides are extensive in both the developed and the developing countries, including Malaysia.

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At the same time, the application of remote sensing and Geographic Information Systems (GIS) has been demonstrated in various fields including in natural hazards monitoring. The observations from the satellites are more frequent, the geographic location of images is becoming more accurate, sensors are increasing the number of their measuring bands and spatial resolutions, and the high-resolution hyperspectral sensors is embracing a new era. All of this will increase hundredfold information obtainable from space. Only our imagination will allow us to get to where remote sensing and GIS can take us. Although many studies have examined the application of remote sensing and GIS, little has employed these technologies for sustainable highland development (Culberston *et al.*, 1994; Haboudane *et al.*, 1999).

Gomez *et al.* (1999) studied the distribution of shallow landslide-prone areas in the tropical Andes (Venezuela) while Lee (2005) evaluated the landslides in Penang (Malaysia), both using remote sensing and GIS. Landslide locations were identified in the study areas from interpretation of aerial photographs and from field surveys. Topographical and geological data and satellite images were collected, processed, and constructed into a spatial database using GIS and image processing. The factors chosen that influence landslide occurrence were: topographic slope, topographic aspect, topographic curvature and distance from drainage, all from the topographic database; lithology and distance from lineament, taken from the geologic database; land use from TM satellite images; and the vegetation index value from SPOT satellite images. The results can be used as basic data to assist slope management and land-use planning.

In 2006, Lee and Pradhan conducted a further research on probabilistic landslide hazards and risk mapping of Penang and Selangor (Malaysia). Once again, landslide locations were identified from interpretations of aerial photographs and field surveys. The landslide inducing parameters considered in this study were topographic slope, aspect, curvature and distance from drainage, all derived from the topographic database; geology and distance from lineament, derived from the geologic database; land-use from Landsat satellite images; soil from the soil database; precipitation amount, derived from the rainfall database; and the vegetation index value from SPOT satellite images. Landslide susceptibility was analyzed using landslide-occurrence factors employing the probability-frequency ratio model. The qualitative landslide hazard analysis was carried out using the frequency ratio model through the map overlay analysis in GIS environment.

Remote sensing

Success in image interpretation does not depend on the remotely sensed data solely. Ancillary facts are needed to verify and complement the processes of extracting information and analyzing data. Methods for efficient data gathering have been and are being developed for their use in GIS, and providing accuracy and reliability consistent with the application level of the information. The process usually involves the interpretation of intensive and well-designed field observations, and the support of all available existing data sources. That is, not only do GIS permit the automated mapping or display of the locations of features, but also these systems provide a capability for recording and analyzing descriptive characteristics about the features. Remote sensing products are an important data source, and are also used for monitoring and updating procedures.

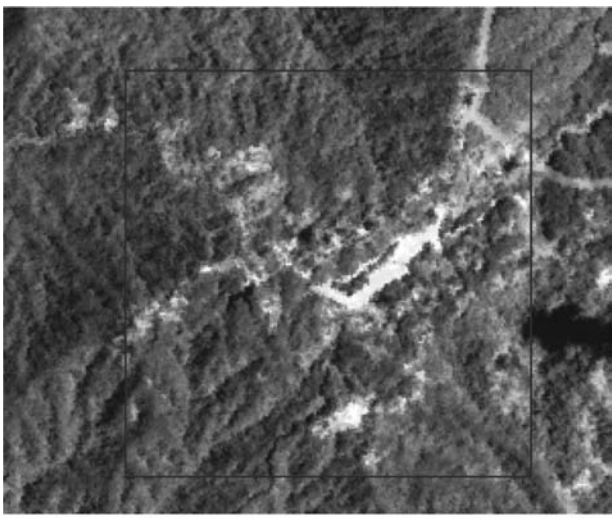
Conceived and designed by the French Center National d'Etudes Spatials (CNES), SPOT has developed into a large-scale international program with ground receiving stations and data distribution outlets located in more than 20 countries. On May 3, 2002, the SPOT program entered a new era with the successful launch of SPOT-5. The satellite carries two high resolution geometric (HRG) instruments, a single high resolution stereoscopic (HRS) instrument, and a Vegetation instrument similar to that on SPOT-4. The HRG systems are designed to provide high spatial resolution, with either 2.5 or 5 m-resolution panchromatic imagery, 10 m resolution in the green, red, and near-IR multispectral bands, and 20 m resolution in the mid-IR resolution. The satellite data for this study was a SPOT 5 satellite image of 10 m resolution, acquired from Malaysia Centre of Remote Sensing, dated March 2006 (see Figure 1).

Geographic Information Systems

Much of the power of a GIS comes from the database management system that is designed to store and manipulate the attribute data. A geographic database is a collection of spatially referenced data that acts as a model of reality. Geographic data has three major components: geographic position, attributes or properties, and time or dynamics. Databases are large collections of data in a computer, organized so that they can be expanded, updated, and retrieved rapidly for various uses. A GIS database is composed of sets of spatial (geographic) and descriptive (non-geographic) data managed by the computer software.

The digital maps produced by image processing were structured in a database according to four data themes (land cover, NDVI, precipitation, and geology). The baseline spatial data are stored in standardized formats for data nomenclature, data properties, and metadata in a one-system environment.

The final outcome was derived by applying heuristic approach through Analytic Hierarchy Process (AHP). Based on a priori knowledge, local experience as well as



Source: MACRES (2006)

Figure 1.
SPOT 5 satellite image

experts' judgment were included. Commonly, such information including geology, hydrology, and often vegetation coverage along with land use was considered, too. These factors were determined by either field observation and satellite image interpretation. The importance of different environmental factors were weighted based on experts' knowledge and experience, thus providing an initial assessment of landslide susceptibility

Study area

The area of study is Fraser's Hill, situated in the Raub district in the state of Pahang, about 103 km north of Kuala Lumpur. Fraser's Hill is one of the famous tourism spots in Malaysia. It lies approximately within the longitude 101 42′ 11″ latitude 3 44′ 13″ and longitude 101 46′ 39″ latitude 3 40′ 15″. The location map is given in Figure 2.

Located at an altitude of 1,524 m above sea level on the Titiwangsa mountain range of Peninsular Malaysia, the highlands have a distinctly different climate to the rest of Malaysia. According to Jabatan Meteorologi Malaysia, the temperatures average a very pleasant 24°C in the daytime and a comparatively cool 17°C at night – excellent for growing tea and for visitors, a pleasant contrast to the more humid lowland areas. Clear blue skies in the morning, showery afternoons, and chilly nights.

Landslides record

In 1994, one of the 24 luxurious condominium blocks of the Silverpark Holiday Resort at Fraser's Hill under construction was threatened by landslide due to soil erosion (Jabatan Meteorologi Malaysia, 1994). A major landslide following the occurrence of a heavy downpour happened in Fraser's Pine Resort, a cluster of 96 three-room apartments built on steep hill slopes. Some land movements at the back of the blocks

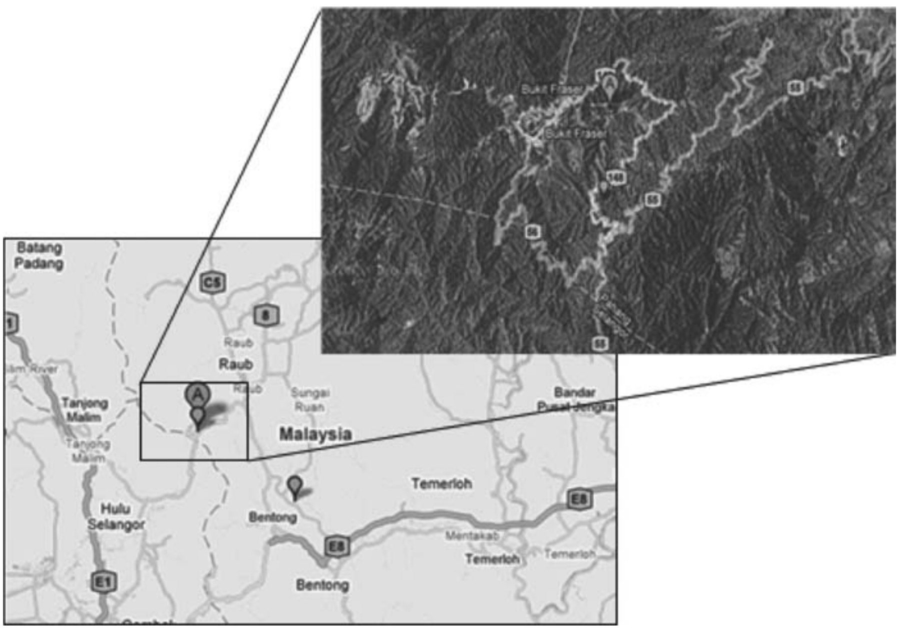


Figure 2.
Study area

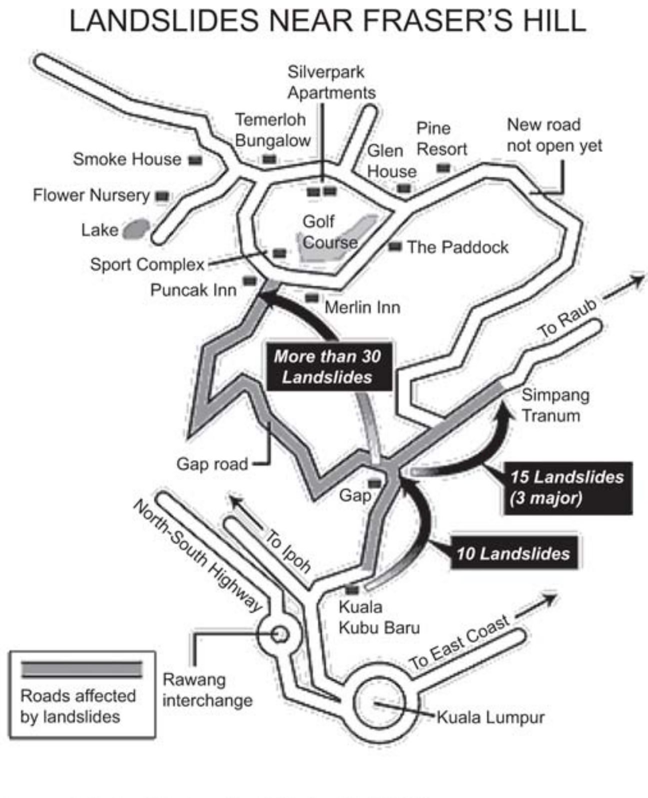
were also reported, and some pillars there were said to be no longer straight. In the period from November 1997 to January 1999, there have been two slides at the slope, and a few minor slips at the surface (see Figure 3).

Land cover

Land varies greatly, in topography, climate, geology, soil, and vegetation cover. Information about soil and site properties is the raw material for indirect land evaluation. These are often land characteristics which can be directly observed or assessed. Fraser's Hill mainly consists of build-up area, barren land, and dense forest.

Precipitation

From 2000-2007, the maximum rainfall was 126.5 mm (Jabatan Meteorologi Malaysia). The infinite number of possible rainfall and runoff events presents an improbable task of ever obtaining all of the unique data potentially available in the hopes of predicting hydrologic events precisely and accurately. The data required for a floodplain study will vary to some degree depending on the methods used, the level of detail required, and the desired results. The limits of the stream to be studied must be determined. However, there has been no record of flood in Fraser's Hill.



Source: Jabatan Meteorologi Malaysia (2000)

Figure 3.
Locations of landslides

Geology

The hilly topography of Fraser's Hill appears to be related to its bedrock lithology. Fraser's Hill and its surrounding areas are underlain generally by granite rocks. It rises steeply to 1,323 m in the north-central part, 1,259 m in the north-west, 1,050 m in the south-west, and 1,183 m in the south-central part, creating several deep valleys between them. The Fraser's Hill area consists of porphyritic biotite granite, generally coarse in grain, rich in biotite, and carrying numerous feldspar phenocrysts. Cutting this granite are intrusions of fine-grained rocks comprising granite-porphyry, mirogranite, and occasionally quartz porphyry.

Methodology

Proper planning and reliable data are needed in order to produce dependable results. For this project, image processing and database development are emphasized as these are the critical parts before the data analysis can be done. This approach compares a data layer representing known landslides with a series of data layers (land cover, Normalized Difference Vegetation Index (NDVI), geology, precipitation) thought to influence landslide occurrence. The association of particular classes of the data layers with existing landslides is then used to establish "weights" or "indexes" of landslide hazard by applying Analytical Hierarchy Process. The weights are then applied to the entire study area to produce a landslide hazard zonation.

In image processing, the Supervised Classification was done by applying Minimum Distance method and supported by the land use map. The identity and location of the land cover types are known beforehand through a combination of field-work, interpretation of satellite image, and map analysis. The Minimum Distance method uses the mean vectors of each end member and calculates the Euclidean distance from each unknown pixel to the mean vector for each class. All pixels are classified to the nearest class unless a standard deviation or distance threshold is specified, in which case some pixels may be unclassified if they do not meet the selected criteria.

The Normalized Difference Vegetation Index (NDVI) is one of the oldest, most well known, and most frequently used Vegetation Indices (VI). The combination of its normalized difference formulation and use of the highest absorption and reflectance regions of chlorophyll make it robust over a wide range of conditions. Satellite observations of reflected red and near infrared radiation from the land surface indicate the absorption of radiation by vegetation, and the two reflectance measurements are combined to create NDVI. The value of this index ranges from -1 to 1. The common range for green vegetation is 0.2 to 0.8.

In the portion of the data analysis are the analytic operators that work with the database contents to derive new information. The objective of data analysis is to extract or query this useful information to satisfy the requirements or objectives of decision makers at all levels of detail. Data analysis includes analysis of adjacency (what adjoins a specified feature), proximity (what is within a selected distance from a specified feature), and connectivity (what is connected to a specified feature), as well as Boolean analyses of data on different layers.

For example, in selecting an optimum land development site, GIS may be asked to specify what areas within the study area have vegetation density of less than 10 percent are zoned for Z1 or Z5, but do not include land cover type A, B, or C. The GIS would perform a Boolean analysis of data on four different layers – boundary, NDVI, zoning, and land cover classification. An important use of the analysis is the possibility of predicting what will happen in another location or at another point in time. This ability provides the possibility to select the best possible alternative (see Table I).

Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is a mathematically rigorous, proven process for prioritization and decision-making. AHP is done in Expert Choice by structuring complexity as a hierarchy, and by deriving ratio scale measures through pairwise relative comparisons, which results in a reduction of measurement error as well as producing a measure of consistency of the comparison judgment. By reducing complex decisions to a series of pair-wise comparisons, then synthesizing the results, decision-makers arrive at the best decision with a clear rationale for that decision. The Graphical mode is used and the pairwise comparisons are made for the cells on the lowest diagonal of the matrix. Pairwise comparing elements on the diagonal provides the minimum number of comparisons necessary to calculate priorities, which gives a more accurate result. Hypothesis development leads to the specification of algorithms that relate inputs to outputs. Model algorithms can be based on expert opinions, quantitative analysis, or a combination of both (see Table II).

Weighted overlay

Weighted Overlay is a technique for applying a common measurement scale of values to diverse and dissimilar inputs to create an integrated analysis. Geographic problems often require the analysis of many different factors. In this study, four factors were taken into consideration: land cover, NDVI, precipitation, and geology. These information

Classification	Sub-classification	GIS data type
Geological hazard	Landslide	Point coverage
Satellite image	Land cover	Polygon coverage
	NDVI	Polygon coverage
	Precipitation	Point and polygon coverage
	Geology	Polygon coverage

Table I. Data layer of study area

Factor	Sub-factor	Coefficient of AHP
Land cover (0.333)	Buildings	1.000
	Barren land	0.500
	Dense forest	0.250
NDVI (0.167)	Very low	1.000
	Low	0.627
	Moderate	0.382
	High	0.232
	Very high	0.148
Precipitation (0.333)	3,288 mm	1.000
Geological (0.167)	Granite	1.000

Table II. Coefficients

existed in different raster layers. These overlays used a common measurement scale and were weighted according to its importance by applying the AHP values.

Results and discussion

The results illustrated five main classes of landslide susceptibility: very low, low, moderate, high, and very high. The very low hazard indicates a low probability of occurrence even with existence of strong triggering factors, such as heavy rainfall or land use change. Moderate hazard can be described as a situation where some mass movements can occur under the influence of intense triggering factors. The very high hazard may lead to a considerable amount of mass movements even with the presence of weak triggering factors. From this information, land use planning can be managed more efficiently to minimize negative environmental reactions. These capabilities suggest a greater power in managing nature for future development (see Figure 4).

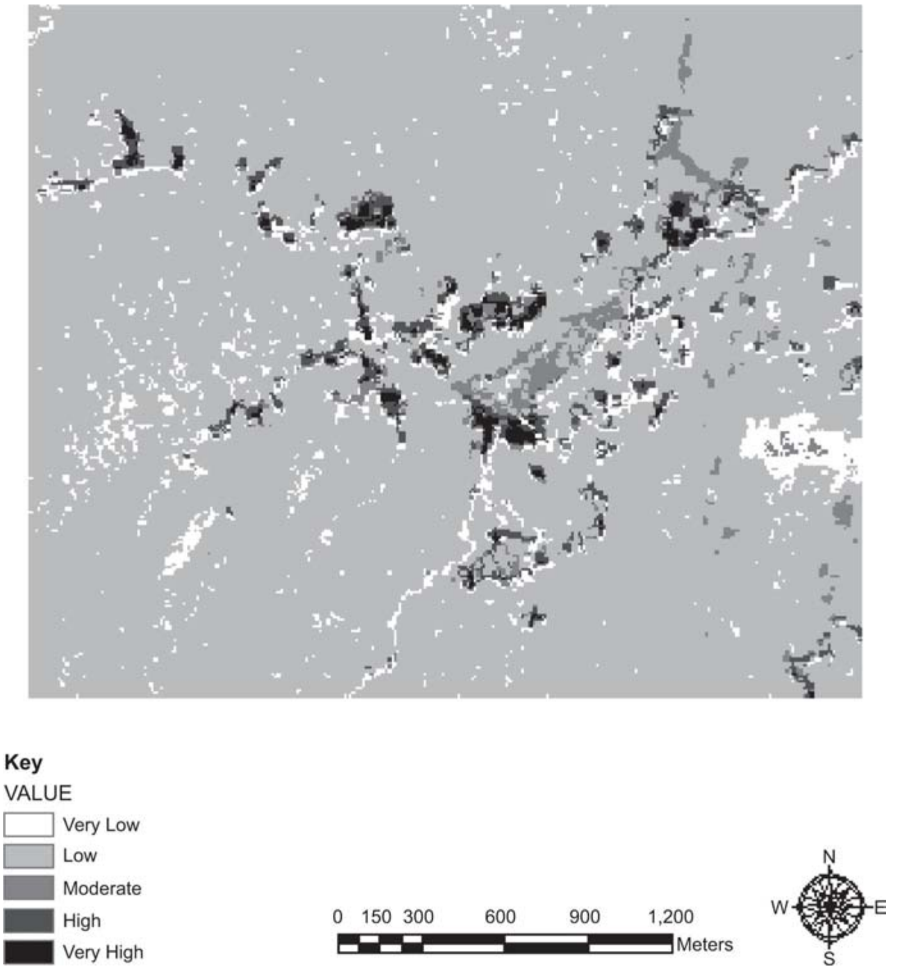


Figure 4.
Landslide Susceptibility Map (Fraser's Hill)

Verification

Based on the available past record of landslides in Fraser's Hill, all the misfortune events happened in zones of moderate susceptibility to very high susceptibility as shown below. This demonstrates how the occurrences are proved to be parallel with the generated landslide susceptibility map (see Figure 5).

As a tool for displaying information, it is possible for GIS to combine and customize map features or variables (e.g.: points and polygons that represent land cover, NDVI, precipitation value, and geological property) which influence landslide occurrence within a single display. Data exploration by image processing aids the understanding of relationships between the variables for the development of the landslide hazard zoning. These factors are converted into layers in ArcMap, and a database is developed. The main output is the landslide susceptibility map which is derived from analyzing the contributing factors. Hazard and risk zonation helps to divide various zones according to their degree of hazard or risk, which are quantified from hazard and risk analysis. The main aim of this hazard and risk assessment is to facilitate decision-making concerning new developments within urbanized sloping areas susceptible to landslide. Through the similar application of remote sensing and GIS, it is advised for the decision-makers (e.g.: local authorities) to identify where landslide might occur to minimize the impact of development.

There are groups who agree that the application of remote sensing data and GIS in monitoring sustainable development such as this study will ease decision making and problem solving. What makes GIS an excellent tool for these two functions is its ability

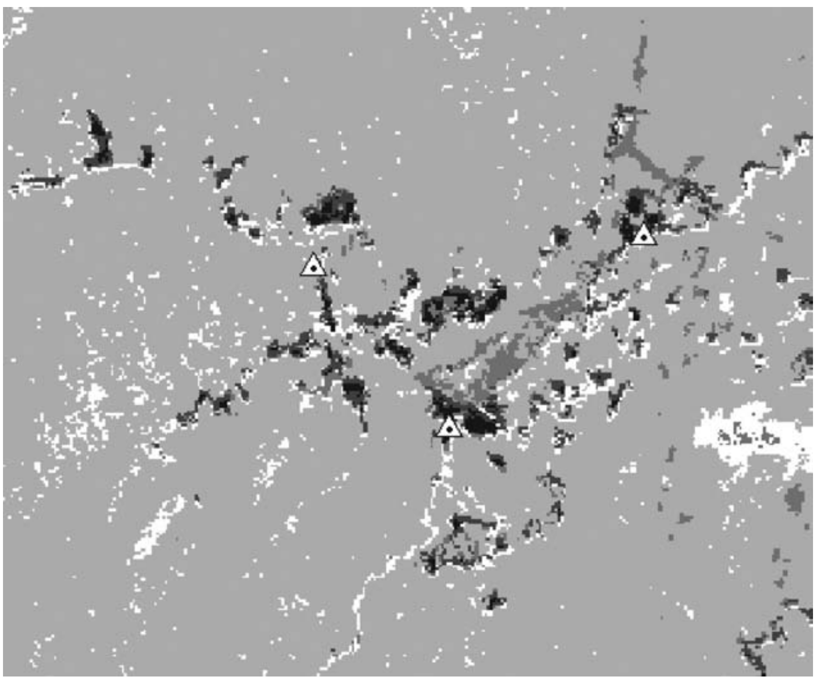


Figure 5.
Verification with existing landslides record

to create simplified visual displays and representations while at the same time maintaining accurate numerical data at the foundation of the system.

The local benefits of GIS are likely difficult to ascertain. In most local governments, GIS are still in the beginning phases of development and is typically a single-department operation, located usually in planning or engineering. Even within these areas, little comprehensive information about the effectiveness of GIS is available. While the contributions that GIS can make to land-use or other policy decisions may seem trivial in the short term, they could have significant cumulative effects in the long term. For example, the database can be updated any time to resolve how future development will fit into the existing characteristics of an area.

The most important part is to acquire in-depth comprehension on the matter, so accurate data can be assembled to establish the final result. Often a huge percentage of a project budget is dedicated to building data layers, so there is an urgent need for easier data access to facilitate this operation with minimum time and cost. As more basic layers become generally available, GIS efforts will shift from data capture towards data access and data analysis. When the right data and the right expertise are geared up, there are endless possibilities of how the integration of remote sensing data and GIS will contribute immensely to both the nation and sustainable development.

It is hoped that this study will initiate further discussion on the major issues concerning the environment today and in the future. Further research is suggested both from a theoretical and an empirical perspective. Auxiliary work is advised on refining the data used in the system. There is an anticipation that satellite image processing and spatial analysis will be as common as word processing systems and spreadsheets are now.

Conclusions

The central objective of this project was to produce a landslide susceptibility map by integrating remote sensing and GIS technologies. Hazard and risk zonation helps to divide various zones according to their degree of hazard or risk, which are quantified from hazard and risk analysis. The main aim of this hazard and risk assessment is to facilitate decision-making concerning new developments within urbanized sloping areas susceptible to landslide. Through the similar application of remote sensing and GIS, it is advised for the decision-makers (e.g.: local authorities) to identify where landslide might occur to minimize the impact of development.

This project used integrated model approach which requires decision makers to agree on how to value various desirable and undesirable features of the landscape. When these values are processed by the GIS, the result is a single, integrated map that displays the ranking of various options. In a large-scale, this type of operation will help to establish and operationalize a system of integrated spatial database on national resources and the environment to support sustainable development planning. Additionally, this strengthens the capacity of human resource development in remote sensing and related technologies.

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Corresponding author
Helmi Zulhaidi Mohd Shafri can be contacted at: helmi@eng.upm.edu.my