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Article

Landslide Catastrophes and Disaster Risk Reduction: A GIS Framework for Landslide Prevention and Management

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Abstract: As catastrophic phenomena, landslides often cause large-scale socio-economic destruction including loss of life, economic collapse, and human injury. In addition, landslides can impair the functioning of critical infrastructure and destroy cultural heritage and ecological systems. In order to build a more landslide resistant and resilient society, an original GIS-based decision support system is put forth in order to help emergency managers better prepare for and respond to landslide disasters. The GIS-based landslide monitoring and management system includes a Central Repository System (CRS), Disaster Data Processing Modules (DDPM), a Command and Control System (CCS) and a Portal Management System (PMS). This architecture provides valuable insights into landslide early warning, landslide risk and vulnerability analyses, and critical infrastructure damage assessments. Finally, internet-based communications are used to support landslide disaster modelling, monitoring and management.

Keywords: disaster management; landslide modelling; decision support system; web-GIS

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1. Introduction

As catastrophic events, the large-scale devastation caused by landslides is well-known: human injury and death, economic dislocation, environmental impacts, and the loss of cultural and natural heritage. In August 2010, floods and landslides across Asia have killed hundreds. In China, the worst seasonal flooding in a decade caused the debris-blocked Bailong River to overflow its banks creating a three-kilometer-long lake that sent mud, rocks and water crashing into communities in Northwest China, ripping houses from their foundations. Over three hundred Chinese have already been killed by the resulting massive landslides, with over one-thousand missing. More than four thousand first responders and medical staff have been sent to the area, as well as helicopters and other emergency vehicles. Other countries throughout Asia are also facing dire emergencies: At least and four million Pakistanis are currently facing food shortages amid their country's worst-ever flooding, while flash floods in Indian Kashmir have already killed 132 and high waters have washed away homes and damaged crops in North Korea.

Landslides also affect developed nations. In February 2010, massive mudslides on Portugal's Atlantic island of Madeira (located approximately 900 km southeast of Portugal) killed 38 people. More recently, over 1,500 people have been evacuated from Pemberton, BC, Canada due to an August 6, 2010 landslide that blocked Meager Creek. A large body of landslide research has investigated the modeling and management of landslide disasters with a focus on slope instability and landslide probabilities [1-9], field instrumentation [10,11], precipitation thresholds [12,13], the modeling and field investigations of specific landslides [14-16], and plans for mitigating landslide hazards [17-21]. Key features of landslide modeling software include slope stability analyses, landslide assessments and debris flows estimates. For example, the United States Geological Survey's (USGS) Stability Index Mapping (SINMAP) model, a GIS ArcView extension, computes and maps a slope stability index using digital elevation data. The SINMAP model has been used to identify landslide prone regions of West Central Idaho [22,23]. A number of tools are now available which allow landslide monitoring and management results to be displayed in a GIS. Two widely used three dimensional landslide digital elevation/terrain models (digital representation of ground surface topography) include the slope-stability model (SCOOPS) and the debris-flow inundation model (LAHARZ) [24-27]. Coupling these existing systems would help to predict the location and size of potential landslides and to model expected inundation areas from the resulting debris flows. Extensive research has been conducted on the causes, mechanisms, and distribution of landslides in order to provide a better understanding of landslide hazard and risk. This involves field-based landslide mapping landslides, the investigation of soil properties, computer modeling of rock slope stability and the impacts of groundwater on potentially unstable slopes [28-32]. For example, the Canadian Centre for Natural Hazard Research (CNHR) is involved in documenting of landslide frequency, intensity, and timing.

The proposed landslide disaster management system provides a solution to some of the most pressing and important problems associated with the development of landslide systems including incompatible platforms and database formats. Specifically, an original, efficient, cost-effective and integrated landslide management system is put forth. This integrated, real-time and interactive landslide system provides a reliable and scalable architecture that links various satellite, airborne and ground devices in order to facilitate disaster early warning, situational analysis, damage analysis and emergency management (including landslide identification, delineation and response). The system is comprised of three key components: a geo-database, application development modules, and an internet-based communication system. Multispectral and hyperspectral imaging systems are used to identify land surface parameters and to analyze slopes, drainage, land cover, road networks and other features. This original system will allow for improved command, control, and communication, thereby improving situational awareness, reducing landslide disaster risk and meeting unique client demands.

2. System Components and Functionalities

Figure 1 shows the schematic design and operational framework of the real-time landslide monitoring and management system while Figure 2 presents the software and hardware configuration of the landslide monitoring and management system. The system architecture includes a Central Repository System (CRS), Disaster Data Processing Modules (DDPM), a Command and Control System (CCS) and a Portal Management System (PMS), as discussed below:

(a) The Central Repository System (CRS) is composed of computer servers and database storage servers. ArcSDE v9.3 workgroup geodatabase and Oracle 10g database servers are used for storage and access management of spatial data.
(b) The Disaster Data Processing Modules (DDPM) assist with landslide monitoring and data modeling. Image analysis and processing is performed using Geomatica 10.1 while disaster models have been developed in ArcGIS 9.3.
(c) The Command and Control System (CCS) serves as a bridge between the portal system, the data processing modules and the central repository system. Predesigned forms were developed in JAVA Enterprise Edition (J2EE^{TM}) 1.4 to link with the ArcGIS Server.
(d) The Portal Management System (PMS) manages all incoming and outgoing data transactions through the CCS. The portal system is an internet based communication system which facilitates communications between all decision makers. It is a high-performance and secure messaging platform that provides extensive security features to ensure the integrity of communications through user authentication, session encryption, and content filtering. The portal system was developed using Java and ArcGIS server and supports GIS data transactions.

The system receives information through satellite images, airborne data and ground surveys or devices. Specifically, high resolution (less than 3 meter) stereo SAR and optical images can provide important geomorphic slope data that is used in the creation of landslide inventory maps to improve landslide mitigation. Our landslide architecture provides real-time landslide data (*i.e.*, rainfall data, flood levels, atmospheric conditions population data) to key decision makers in order to improve landslide modeling and overall situational analysis. Internet web technology is then used to link data directly to the central repository (which includes all tabular and spatial data required for landslide modeling as well as all thematic output products generated from disaster models).

Figure 1. Schematic Design and Operational Framework of the Landslide Monitoring and Management System.

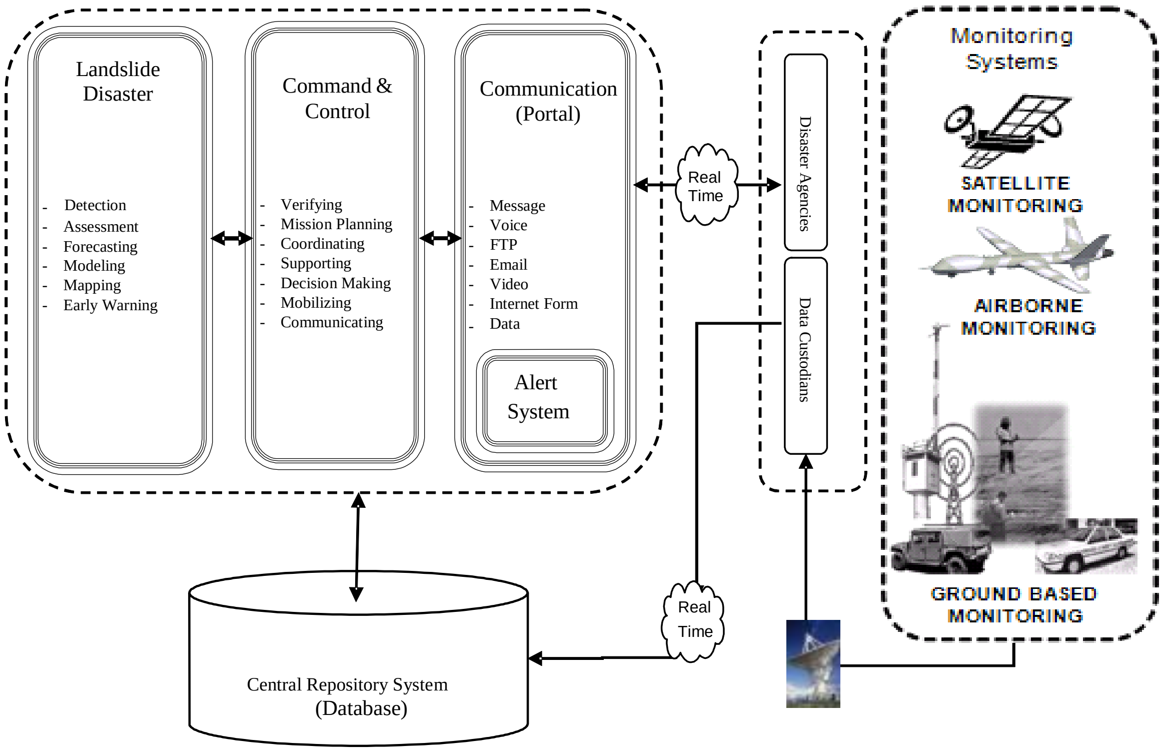
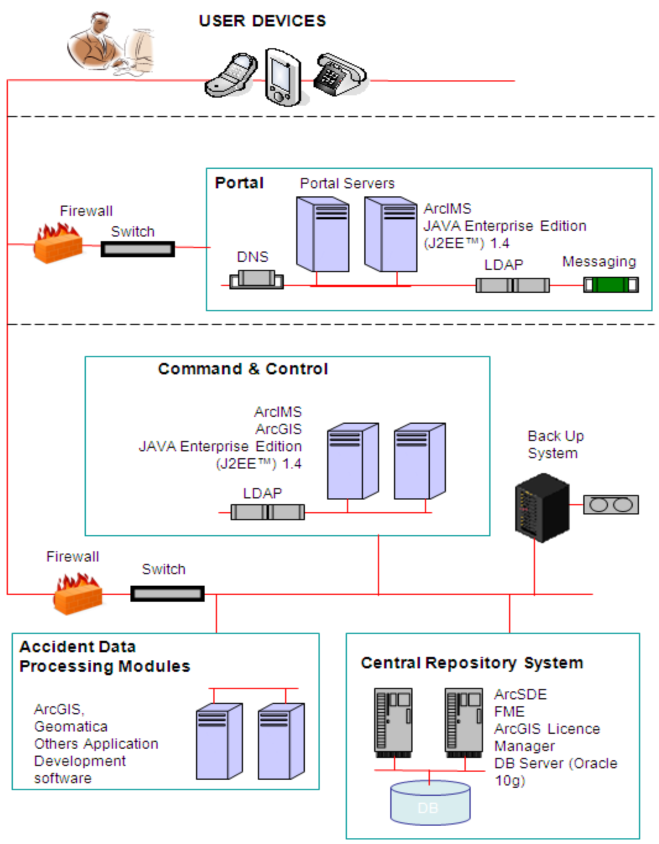


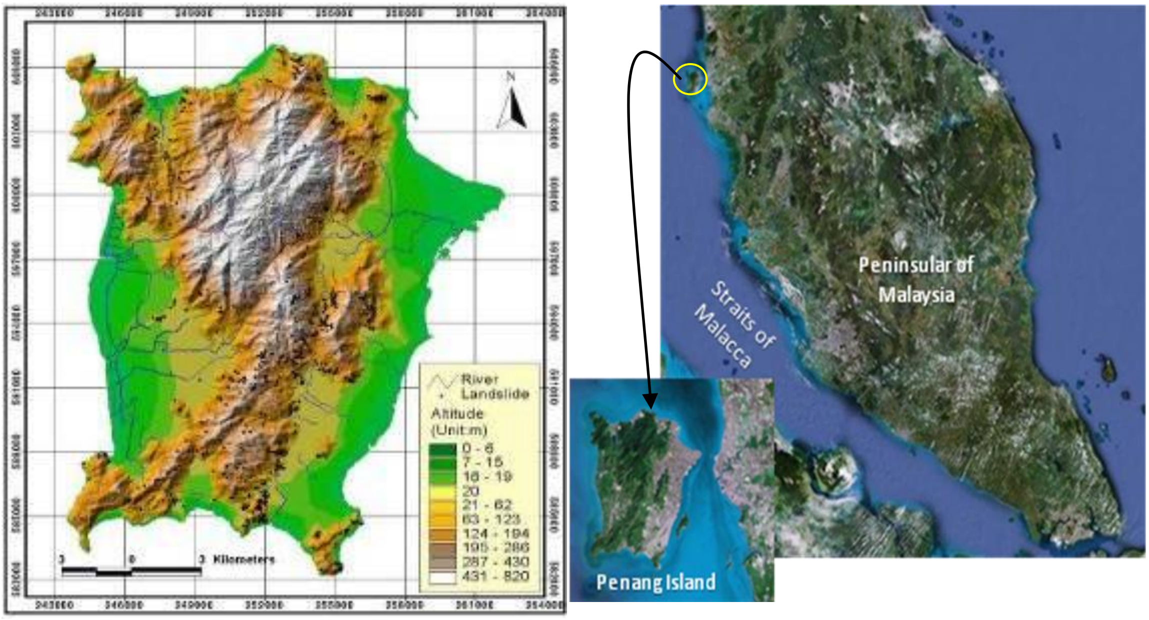
Figure 2. Landslide Monitoring and Management System Configuration.



3. Case Study Area

The original landslide system was tested as a pilot project for Penang Island in the Straits of Malacca, situated in the northwest of peninsular Malaysia (Figure 3). Here, the warm and sunny tropical rainforest climate is governed by two monsoon seasons (between March and May and from November to December) which bring plentiful rainfall—between the two monsoon seasons there are brief transitional periods [33]. The average maximum monthly temperature ranges from 30.4 °C (from September to November) to 32.2 °C (in February and March). The highest average monthly rainfall in Panang occurs in October (383 mm) [34]. The climate of the island of Penang is determined to a large extent by the surrounding sea and the wind climatic systems.

Figure 3. Location of the study area and topography.



3.1. Input Data

GIS layers such as administrative boundaries, transportation networks, population distributions, and river networks have been extracted from topographic maps at the scale of 1:25,000 in dxf format. In order to improve emergency response, evacuation centers throughout Penang Island were identified. Seventeen input GIS layers were used, including the location of previous landslide hazards, slope angle (in degrees), aspect directions, curvature values, and the distance from drainage areas. A detailed description relating to the type, format, and attributes of each layer is described in Table 1. Contour maps were extracted from topographic data and the Triangular Irregular Network (TIN) was generated from contours. Subsequently, the Digital Elevation Model (DEM) was constructed from the TIN. Table 1 and Figure 4 present spatial data and specifications stored in the Central Repository System (CRS).

Table 1. General Database Stored in the Central Repository System (CRS).

GIS Layer	Type	Format	Field Attribute	Description
Landslide location	Point	Vector	ID	Location of previous landslide hazards were mapped from the aerial photographs at the scale of 1:10,000–1:50, 000
Slope	Grid	Raster	Value	Slope Angle in degrees extracted from topographic data; Scale 1:25,000
Aspect	Grid	Raster	Value	Aspect direction extracted from topographic data; Scale 1:25,000
Curvature	Grid	Raster	Value	Curvature value extracted from topographic data; Scale 1:25,000
Distance from drainage	Grid	Raster	Value	Distance from drainage ; Scale 1:25,000
Lithology	Polygon	Vector	Types	Litho types extracted from lithologyogy maps; Scale 1:63,300
Lineament	Line	Vector	Length	Distance from lineaments extracted from topographic data; Scale 1:25,000
Soil Type	Polygon	Vector	Type	Soil texture types extracted from soil map; Scale 1:100,000
Land Use	Polygon	Vector	Type	Land use Types extracted from topographic and SPOT-5 data; Scale 10m × 10m
NDVI	Grid	Raster	Value	Vegetation Index NDVI value from SPOT-5 data; Scale 10m × 10m
Precipitation	Grid	Raster	Value	Precipitation (Historical Rainfall) amount; Scale 10m × 10m
Transportation	Line	Vector	Type	Road networks, highways and railways extracted from topographic data; Scale 1:25,000
Administrative Boundaries	Line	Vector	Length	Administrative areas extracted from topographic data; Scale 1:25,000
Contour (DEM)	Grid	Raster	Value	Terrain elevation using 10-meter interval contours and survey base points extracted topographic maps; scale 1:25,000
Settlement	Polygon	Vector	Type	Residential, public and administration buildings extracted from topographic data; Scale 1:25,000
Population	Grid	Vector	Value	Population Densities Scale 1:25,000 data collected from statistic department.
Emergency Resources	Polygon	Vector	Type	Emergency and mitigation resource locations including: Fire Fighter Stations, Police Stations, Hospitals, Schools, Religious Centers, Town Halls/Cultural, Airports, Army Base, Stadium, Open Fields

Figure 4. Spatial Data and Maps for the Landslide Disaster Modeling Stored in the Database.

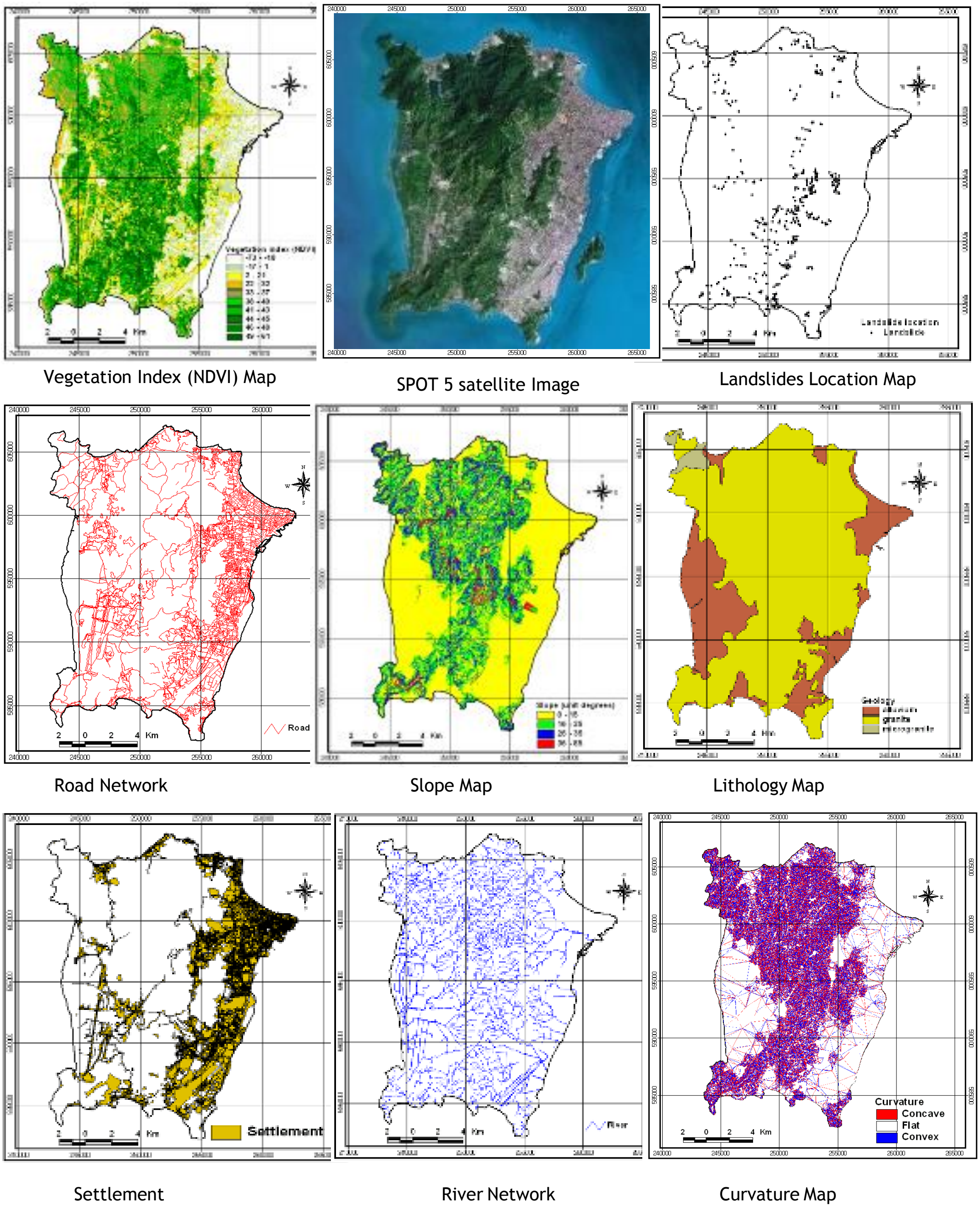
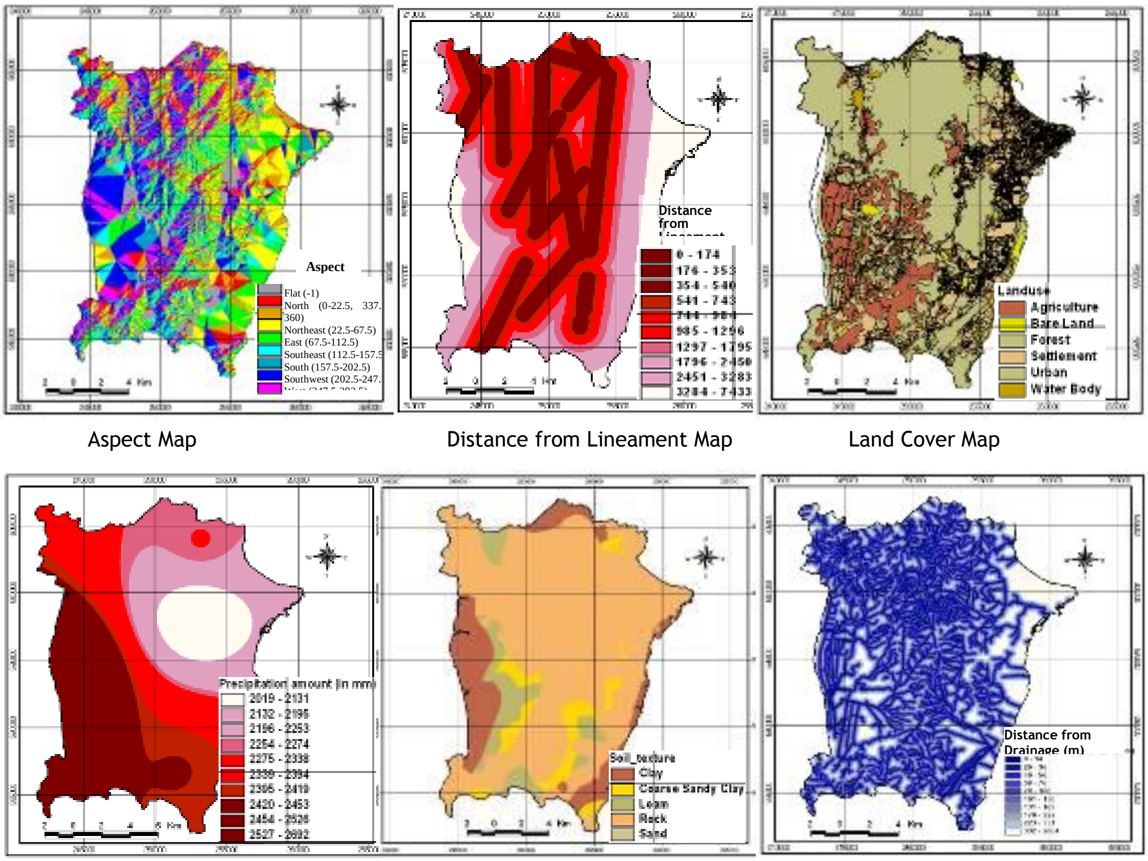


Figure 4. *Cont.*



Aspect Map | Distance from Lineament Map | Land Cover Map

Precipitation Map | Soil Texture Map | Distance from Drainage Map

3.2 Landslide Disaster Model and Products

Landslide disaster models provide specific maps including landslide location maps, risk maps, affected area maps, and emergency response maps. Table 2 provides a detailed description of the models, thematic layers used, functionalities, output products and model specifications. First, with respect to the landslide hazard map, thematic layers include the distribution of landslides, DEMs, roads, rivers, lithology, soil maps, rainfall and land cover. The landslide hazard map is used to predict future landslide areas and to show the classification and distribution of hazards. Second, we consider regions affected by landslides. This component provides information on the areal extent and location of landslide events and uses the following thematic layers as input: administrative boundaries, transportation networks, and population distributions. Third, the landslide risk map provides early warning information pertaining to disaster preparedness and mitigation. The landslide risk map uses several thematic layers including slope length, flow accumulation, catchment basins, distance from hazardous zones and land cover. Fourth the emergency response analysis shows the disaster location in addition to the distribution of support centers and the availability of specific resources.

Remote sensing data along with other tabular and spatial data were used to develop a landslide model for hazard mapping products. A wide variety of terrain information has been included, such as slope, aspect, curvature, distance from drainage, lithology, soil, land cover, Normalized Difference Vegetation Index (NDVI) and precipitation data. The frequency ratio model is used to verify and validate landslide hazard analyses and results as discussed by Lee and Pradhan, 2006 [35]. To calculate the frequency ratio, a table was constructed for each landslide factor. A correlation analysis was carried out and the spatial relationship between landslide locations and each landslide factor was extracted.

Table 2. Landslide disaster analysis in GIS Environment, input/output products and specifications.

	Model/System	Thematic Layers/Input	Functionalities
1.	Landslide Hazard Map	- Landslide Distribution - DEM - Road – Road Buffering - River – River Ordering - Lithology Structure - Soil Map - Landcover/Landcover - Rainfall	• Predict future landslide areas (Integration of susceptibility in association with rainfall). Map shows hazard classes and distribution.
2.	Areas affected by Landslides	- Administrative Boundaries - Transportation - Settlement - Landcover/Landcover	• Provides information on the areal extent and location of a landslide event
3.	Landslide Risk Map	- Landslide Hazard Map - Slope length - Flow accumulation - Catchment basin - Distance from high hazardous zone - Surface area - Landcover map (Settlement, agricultural land, urban and road class only)	• Provides early warning information for disaster preparedness and mitigation. The map shows risk classes based on values and distribution of classes
4.	Improved Emergency Management	- Landslide Risk Map - Emergency Response Assets	• Provide information for emergency responders. Maps show the disaster location and extent in addition to the distribution of support centers and the availability of specific resources.

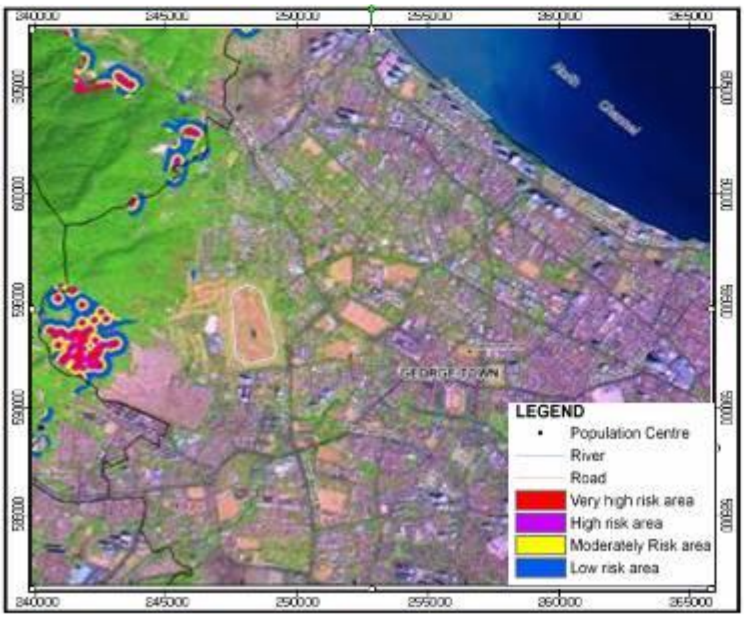
The Frequency ratio (FR) is the ratio of the area where landslides occurred to the total study area (for a given landslide attribute). The frequency ratio is the percentage of the probabilities of a landslide occurrence to a non-occurrence for a given attribute. The following steps were carried out to calculate FR. First, a fine grid of 10m x 10m units was generated over the study area. For each grid, the Landslide Hazard Index (LHI) is defined as the summation of FR values for each attribute as shown in Equation 1, where n is the number of factors for each grid:

$$LHI = \Sigma Fr\ (1,\ldots n) \tag{1}$$

The average FR value is equal to one. Higher FR values represent stronger correlations landslide occurrence and a specific landslide factor [36,37]. The landslide susceptibility was calculated by the classification of LHI values into appropriate classes for each 10m × 10m grid scale. Four different classes were defined: no susceptibility, the moderately susceptible class, the highly susceptible class and the extremely susceptible class.

The landslide hazard map categorizes a region into various stability zones. Key information is included in the landslide hazard map, such as data about slope, curvature, drainage, lithology, land cover, soil, the vegetation index (NDVI) and rainfall. A hazard index classification for the landslide hazard map is calculated by dividing the land surface into regions that are not susceptible to landslides, moderately vulnerable to landslides, highly vulnerable to landslides and extremely vulnerable to landslides [36]. Using property values, four landslide risk zones were identified as shown in Figure 5. The risks associated with catastrophic landslide events include human deaths, injuries the loss of cultural heritage. It was shown that the highest risk areas were associated with regions in which forestry and agriculture were the primary economic activities.

Figure 5. Landslide Risk Map.



The areas affected (or damaged) by landslides (affected area map) were determined after each landslide event. The Affected area map was prepared using the SPOT-5 satellite imagery and provides aerial information about damaged property. Landslide damages can be particularly costly to local governments that need to repair damaged public roads and drainage facilities. In addition, the affected area map can help to determine the liability of local governments for landslide damages. Finally, the emergency management maps provide information for emergency preparedness, planning mitigation and response. The emergency management maps are generated by overlying the landslide risk map with emergency assets and resources such as evacuation centers, hospitals, and transportation networks. Emergency management maps can help to improve the coordination of actions among all players involved in landslide response: first responders, government decision-makers and citizens.

The Command and Control System (CCS) facilitates disaster management, emergency operation and landslide administration based on output products from the landslide disaster models. In Table 3 and Figure 6 the CCS components and functionalities are shown. The developed system is being used by emergency management professionals and first response organizations in all four phases of emergency management: mitigation, preparedness, response and recovery. Managers can access the system through the internet with a computer, Personal Digital Assistant (PDA) or mobile phone. Finally, report and record management involves reviewing, verifying, updating and managing all of the elements in Situational Report in order to improve situational awareness and better understand the impacts of the landslide disaster. Screen shots from the landslide management system are provided in Figure 7. This figure highlights the GIS interface, the CRS, the CCS and the Web Portal.

Table 3. Command & Control System Components and Functionalities.

Command & Control System Components	**Functionalities;** Provide Tasks or Information About:
Alert Messages	Disaster Event, Danger And Warning Notification (SMS, Email, Portal)
Disaster Reports	Landslide Situational Awareness, Damage, Victim, Evacuation Information
Human Resources	Contact Person, Officers on Duty, Role & Responsibilities, Task Assigned, Directive & Feedback, Designation, *etc.*
Inventory	Availabilities, Request, Approval, Receive, Utilization, Allocation, Return, *etc.*
Support Center	Disaster Capacity, Location, Distribution, Type (Evacuation, Operation And Relief)

Figure 6. Configuration of the CCS and the communication disaster protocols.

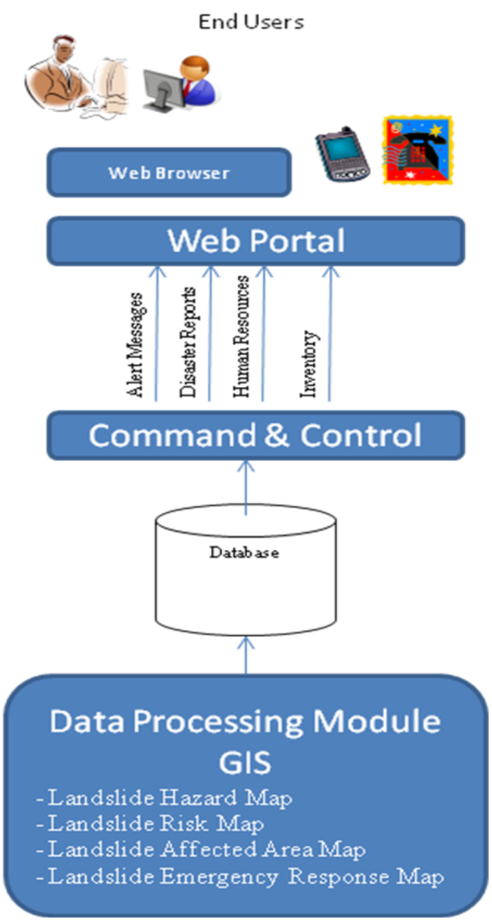
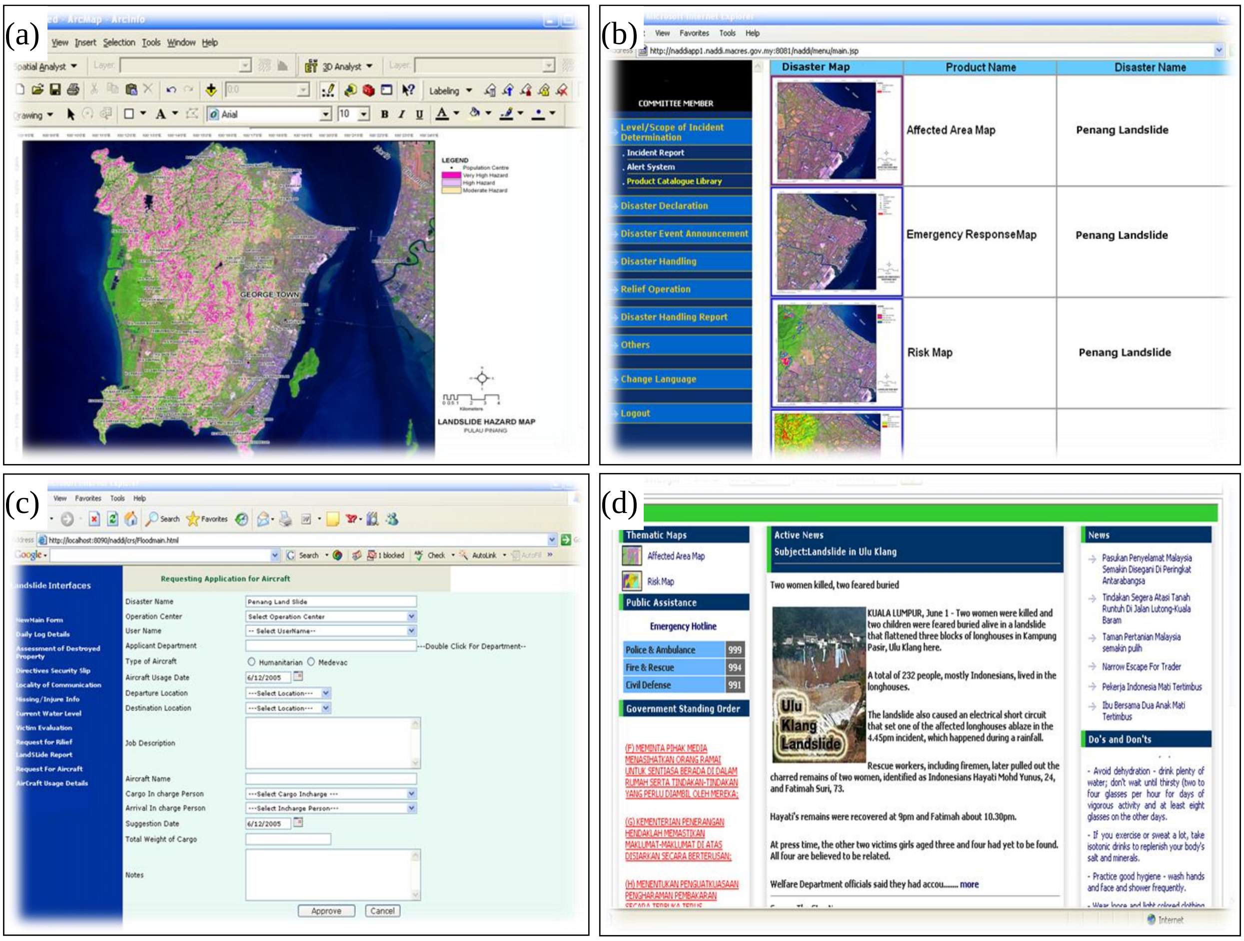


Figure 7. Key system functionalities include: **(a)** landslide disaster analysis in GIS, **(b)** Landslide disaster products in the Central Repository System (CRS) **(c)** Command and Control and **(d)** Web portal.



4. Conclusions

In order to build a more landslide resistant and resilient society, an original GIS-based decision support system is developed in order to help emergency managers better prepare for and respond to landslide disasters. The GIS-based landslide monitoring and management system includes a Central Repository System (CRS), Disaster Data Processing Modules (DDPM), a Command and Control System (CCS) and a Portal Management System (PMS). This architecture provides valuable insights into landslide early warning, landslide risk and vulnerability analyses, and critical infrastructure damage assessments. Finally, internet-based communications are used to support landslide disaster modeling, monitoring and management. This GIS-based landslide disaster system has been applied to the Penang Island landslide case study. The system has proven effective in delivering critical information pertaining to landslide situational awareness including landslide early warning. The developed decision support system can also assist with real-time landslide detection and monitoring, as well as disaster mitigation and preparedness. The system has been extensively tested to rigorously determine risk in areas affected by active landslides.

It was shown that emergency messages could be expeditiously sent to all parties following a landslide event. The developed system allows emergency management decision makers to acquire landslide hazard management information in real time, such as location of critical resources and assets (*i.e.*, nearby operation centers, hospitals, schools area, settlements, and airports). In summary, the landslide system improves real-time communications and information sharing during a disaster and creates valuable landslide risk maps. These maps can assist with the implementation of technical landslide countermeasures as well as the development of non-structural mitigation measures (stabilization procedures), such disaster risk reduction education, zoning maps, and regulations pertaining to slope designs (e.g., slope grades). It is shown that our systems architecture and implementation can reduce the large-scale devastation caused by landslides including human injury and death, economic dislocation, environmental impacts, and the loss of cultural and natural heritage.

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References and Notes

1. Soeters, R.; Van Westen, C.J. Slope instability recognition, analysis, and zonation. In *Landslides, Investigation and Mitigation*; Turner, A.K., Schuster, R.L., Eds.; Transportation Research Board Special Report 247; National Research Council: Washington, DC, USA, 1996; pp. 129-177.
2. Harp, E.L.; Baum, R.L.; Wilson, R.C.; Laprade, W.T.; Conradi, K. Government-private partnership in mapping landslide hazards in Seattle, Washington. In *Proceedings of Association of Engineering Geologists 41st Annual Meeting*, Seattle, WA, USA, September 1998; p. 93.
3. Baum, R.L.; Harp, E.L.; Hultman, W.A. *Map Showing Recent and Historic Landslide Activity on Coastal Bluffs of Puget Sound between Shilshole Bay and Everett, Washington*; US Geological Survey Miscellaneous Field Studies Map MF 2346; USGS: Denver, CO, USA, 2000.
4. Schulz, W.H. *Landslides Mapped Using LIDAR Imagery, Seattle, Washington*; US Geological Survey Open-File Report 2004-1396 2004a; USGS: Seattle, WA, USA, 2004.
5. Schulz W.H. *Landslide Mapping in Seattle, Washington Using LIDAR Imagery*; US Geological Survey Open-File Report 2004-1396 2004b; USGS: Seattle, WA, USA, 2004.
6. Godt, J.W. Observed and Modeled Conditions for Shallow Land Sliding in the Seattle, Washington, Area. Ph.D. Dissertation, University of Colorado, Boulder, CO, USA, 2004.
7. Wu, T.H; Tang, W.H.; Einstein, H.H. Landslide hazard and risk assessment. In *Landslides, Investigation and Mitigation*; Turner, A.K., Schuster, R.L., Eds.; Transportation Research Board Special Report 247; National Research Council: Washington, DC, USA, 1996; pp. 106-118.
8. Coe, J.A.; Michael, J.A.; Crovelli, R.A.; Savage, W.Z. *Preliminary Map Showing Landslide Densities, Mean Recurrence Intervals, and Exceedance Probabilities as Determined from Historic Records, Seattle, Washington*; US Geological Survey Open-File Report 2000 00-303; USGS: Seattle, WA, USA, 2000.
9. Coe, J.A.; Michael, J.A.; Crovelli, R.A.; Savage, W.Z.; Laprade, W.T.; Nashem, W.D. Probabilistic assessment of precipitation-triggered landslides using historical records of landslide occurrence, Seattle, Washington. *Environ. Eng. Geosci.* **2004**, *10*, 103-122.

10. Baum, R.L.; Chleborad, A.F.; Schuster, R.L. *Landslides Triggered by the December 1996 and January 1997 Storms in the Puget Sound Area, Washington*; US Geological Survey Open-File Report 98-239; USGS: Seattle, WA, USA, 1998.
11. Baum, R.L.; Godt, J.W.; Harp, E.L.; McKenna, J.P.; McMullen, S.R. Early warning of landslides for rail traffic between Seattle and Everett, Washington, USA. In *Proceedings of the International Conference on Landslide Risk Assessment*, Vancouver, BC, Canada, 2005.
12. Chleborad, A.F. *Preliminary Method for Anticipating the Occurrence of Precipitation-Induced Landslides in Seattle, Washington*; US Geological Survey Open-File Report 00-0469; USGS: Seattle, WA, USA, 2000.
13. Chleborad, A.F. *Preliminary Evaluation of a Precipitation Threshold for Anticipating the Occurrence of Landslides in the Seattle, Washington, Area*; US Geological Survey Open-File Report 03-463; USGS: Seattle, WA, USA, 2003.
14. Arndt, B.P. Determination of the Conditions Necessary for Slope Failure of a Deep-Seated Landslide at Woodway. M.Eng. Thesis, Colorado School of Mines, Golden, CO, USA, 1999; p. 216.
15. Savage, W.Z.; Baum, R.L.; Morrissey, M.M.; Arndt, B.P. *Finite-Element Analysis of the Woodway Landslide, Washington*; US Geological Survey Bulletin 2180; USGS: Denver, CO, USA, 2000.
16. Baum, R.L.; Godt, J.W.; Highland, L. *Landslides and Engineering Geology of the Seattle, Washington Area*; Geological Society of America: Boulder, CO, USA, 2008; p. 181.
17. Burns, S.F.; Burns, W.J.; James, D.H.; Hinkle, J.C. *Landslides in Portland, Oregon Metropolitan Area Resulting from the Storm of February 1996: Inventory Map, Database, and Evaluation*; METRO: Portland, OR, USA, 1998.
18. Cornforth, D.H. *Landslides in Practice Investigation, Analysis, and Remedial/Preventative Options in Soils*; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2005.
19. Hofmeister, R.J.; Miller, D.J.; Mills, K.A.; Hinkle, J.C.; Beier, A.E. *GIS Overview of Potential Rapidly Moving Landslide Hazards in Western Oregon*; Interpretative Map Series IMS-22; Department of Geology and Mineral Industries: Portland, OR, USA, 2002.
20. Skaugset A.; Robison, G.E.; Mills, K.A.; Paul, P.E.; Dent, L. *Storm Impacts and Landslides of 1996: Final Report*; Forest Practices Technical Report Number 4; Forest Practices Monitoring Program, Oregon Department of Forestry: Salem, OR, USA, 1999.
21. Wold, R.L.; Jochim, C.L. *Landslide Loss Reduction: A Guide for State and Local Government Planning*; Open-File Report 1995, 0-95-8; Department of Geology and Mineral Industries: Los Angeles, CA, USA, 1995.
22. Pack, R.T.; Tarboton, D.G.; Goodwin, C.N. *SINMAP—A Stability Index Approach to Terrain Stability Hazard Mapping—Users Manual*; Utah State University: Logan, UT, USA, 1997. Available online: http://www.fs.fed.us/informs/sinmap/sinmap_users_guide.pdf (accessed on 12 August 2010).
23. Pack, R.T.; Tarboton, D.G.; Goodwin, C.N. The SINMAP approach to terrain stability mapping. In *The 8th Congress of the International Association of Engineering Geology*, Vancouver, BC, Canada, 1998.

24. Dianne, L.B.; Mark, E.R. *Modeling 3-D Slope Stability of Coastal Bluffs Using 3-D Ground-Water Flow, Southwestern Seattle, Washington*; US Geological Survey Scientific Investigations Report 2007-5092; USGS: Seattle, WA, USA, 2007.
25. Dianne, L.B.; Mark, E.R. Assessing deep seated landslide susceptibility using 3-D groundwater and slope-stability analysis, southwestern Seattle, Washington. *Reviews Eng. Geol.* **2008**, *20*, 83-101.
26. Schilling, S.P. *LAHARZ: GIS Programs for Automated Mapping of Lahar-Inundation Hazard Zones*; US Geological Survey Open-File Report 98-638; USGS: Seattle, WA, USA, 1998.
27. Schilling, S.P.; Griswold, J.P.; Iverson, R.M. Using LAHARZ to Forecast Inundation from lahars, debris flows, and rock avalanches: Confidence limits on prediction. In *Proceedings of American Geophysical Union, Fall Meeting*, San Francisco, CA, USA, 2008.
28. Friele, P.; Jakob, M.; Clague, J.J. Hazard and risk from large landslides from Mount Meager Volcano, British Columbia, Canada. *Georisk* **2008**, *2*, 48-64.
29. Hewitt, K.; Clague, J.J.; Orwin, J.F. Legacies of catastrophic rock slope failures in mountain landscapes. *Earth-Sci. Review.* **2008**, *87*, 1-38.
30. McKillop, R.J.; Clague, J.J. Statistical, remote sensing-based approach for estimating the probability of catastrophic drainage from moraine-dammed lakes in southwestern British Columbia. *Glob. Planet. Change* **2007**, *56*, 153-171.
31. Clague, J.J. Tsunamis. In *A Synthesis of Geological Hazards in Canada*; Brooks, G.R., Ed.; Bulletin 548; Geological Survey of Canada: Ottawa, ON, Canada, 2001; pp. 27-42.
32. Clague, J.J.; Evans, S.G. Geologic framework of large historic landslides in Thompson River valley, British Columbia. *Environ. Eng. Geosci.* **2003**, *9*, 201-212.
33. Fauziah, A.; Ahmad, S.Y.; Mohd, A.F. Characterization and geotechnical properties of penang residual soils with emphasis on landslides. *Amer. J. Environ. Sci.* **2006**, *2*, 121-128.
34. *The Climate of Malaysia*; National Environmental Agency, Government of Singapore: Singapore, Year? Available online: http://app2.nea.gov.sg/asiacities_malaysia.aspx (accessed on 12 August 2010).
35. Lee, S.; Pradhan, B. Probabilistic landslide hazards and risk mapping on Penang Island, Malaysia, *Earth Syst. Sci.* **2006**, *115*, 661-672.
36. Mehrnoosh J.; Helmi, Z.M.S.; Mansor, S.B.; Mohammad, S.; Saeid, P. Landslide susceptibility evaluation and factor effect analysis using probabilistic-frequency ratio model. *Eur. J. Scientific Res.* **2009**, *33*, 654-668.
37. Pradhan, B.; Lee, S. Delineation of landslide hazard areas on Penang Island, Malaysia, by using frequency ratio, logistic regression, and artificial neural network models. *Environ. Earth Sci.* **2010**, *60*, 1037-1054.