Nat Hazards (2013) 66:167–190
DOI 10.1007/s11069-012-0511-z

ORIGINAL PAPER

Identification and assessment of heavy rainfall–induced disaster potentials in Taipei City

Jui-Sheng Chou · Kuo-Hsin Yang · Min-Yuan Cheng · Wan-Ting Tu

Received: 31 October 2011 / Accepted: 10 September 2012 / Published online: 6 December 2012

Abstract With increasing threat to lives and properties, identifying and assessing disaster potentials has become necessary and prior for effective disaster preparation and rescue planning. This study first introduces practical methods currently used in Taipei City, Taiwan, to identify and assess heavy rainfall–induced potential risks on flood, debris flow, and landslide. The identified disaster potential information is further applied to a series of deterministic and probabilistic risk analyses using Shilin District of Taipei City as a case study. The deterministic risk analyses are conducted to evaluate the impact of various heavy rainfall intensities on the residents. The probabilistic risk analyses are performed to establish risk curves for the population affected by heavy rainfall–induced hazards. The risk curve represents the relationships between the affected population and the annual exceedance probability. This study found the annual exceedance probability is very sensitive to the assumed coefficients of variation of the affected population. It is recommended historical statistical data on the correlation between affected population and rainfall intensity should be recorded and compiled in order to assess the actual probability distribution function of the affected population. Risk analysis results are further applied to assess the community evacuation capacity in this district. Last, short-term and long-term mitigation strategies and recommendations are discussed.

Keywords Disaster potential · Flood · Debris flow · Landslide
Community evacuation capacity

1 Introduction

Heavy rainfall–induced natural hazards have caused significant damage and fatalities worldwide. Considerable effort has been expended to study hazard mechanisms and characteristics, assess their risks, and estimate loss of life and property for floods (Jonkman et al.

J.-S. Chou · K.-H. Yang (✉) · M.-Y. Cheng · W.-T. Tu
Department of Construction Engineering, National Taiwan University of Science and Technology (Taiwan Tech), 43, Sec. 4, Keelung Rd., Taipei 106, Taiwan
e-mail: khy@mail.ntust.edu.tw

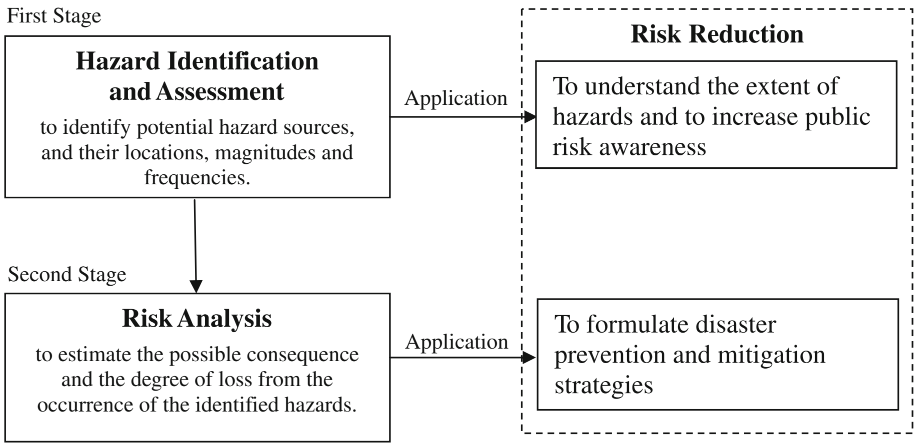


Fig. 1 Illustration of the process and application of identifying and assessing disaster potentials

2009, 2008a, b; Pande 2010), debris flows (Chen et al. 2008; Hu et al. 2009; Wang and Ling 2010), and landslides (Bonachea et al. 2009; Paudel et al. 2003; Salciarini et al. 2011). Among all of these works, identifying and assessing disaster potentials in a surrounding environment is very important and challenging, which offers decisive information for disaster preparation and rescue planning (Gilbert 2008; Minciardi et al. 2009; Lindell and Perry 2011). The initial stage includes identifying potential hazard sources and their locations, magnitudes, and frequencies. These works help the government and public understand the extent of hazards and enhance the public awareness of the necessity of disaster prevention and preparation in advance. During the next stage, risk analyses are conducted to estimate the possible consequence and the degree of loss from the occurrence of the identified hazards. The risk analysis results provide a valuable reference for government to formulate disaster prevention and mitigation strategies (e.g., establishing early warning systems and evacuation plans, executing disaster-related drills, and conducting community disaster prevention program). Figure 1 illustrates the process and application of identifying and assessing risk potentials.

Using flood hazard as an example, the authorities (e.g., local government or disaster response centers) can utilize the identified flood potential information to forecast which area would be affected by floods during typhoon and heavy rainfall season. By comparing flood potential data with rainfall forecasts, potential flood sites can be identified. Further, deterministic or probabilistic risk analyses can be conducted to estimate the impact of hazards on the affected structures, properties, and population. Deterministic risk analyses are performed to establish the relationships between hazard magnitude and affected factors. Probabilistic risk assessments, considering temporal and spatial uncertainty and variation in disaster systems, are to determine magnitude–frequency (or recurrence) relationship. In previous studies, many deterministic and probabilistic risk analysis methods have been proposed for the estimation of damaged structures, loss of properties, or affected population due to flooding (Jonkman et al. 2009, 2008a, b; Merz and Thieken 2009; Kim et al. 2012). The application of disaster potential information to debris-flow or landslide cases resembles that for floods (Crovelli 2000; Marion et al. 2003; Hu et al. 2009).

According to the above discussion, the first objective of this study is to present the practical methods currently used in Taipei City, Taiwan, to identify and assess potential risks on flood, debris flow, and landslide. The second objective is to conduct risk analyses to evaluate the affected population using both deterministic and probabilistic approaches.

More specifically, in the deterministic analyses, the impact of heavy rainfall with various rainfall intensities on the residents in Taipei City is evaluated. In the probabilistic analysis, risk curves for the population affected by heavy rainfall–induced hazards are established. The results are applied to assess the evacuation shelter capacity and provide useful information for planning disaster prevention and mitigation strategies.

2 Description of study region

The study area is focused on Taipei City, Taiwan. Situated at the northern tip of Taiwan, Taipei City is the capital and the largest metropolitan city of Taiwan. Taipei City consists of 12 administrative districts, covers 271.8 km^2, and has a total population of approximately 2,623,000 people (population density of approximately 9,760 people/km^2). Figure 2 shows the location and geographic environment of Taipei City. The Danshui River and Keelung River pass through the western side and cross central area of Taipei City, respectively. Taipei City is located at the middle and slightly eastern part of Taipei Basin; around 55 % area of Taipei city is covered by slopeland distributing mostly on the northern and eastern side of Taipei City. In terms of its geological conditions, the northern area primarily consists of igneous rock layers by Cising Mountain, the highest (extinct) volcano in Mt. Yangming National Park. The rest of the area of Taipei City mostly consists of sedimentary rock and alluvium formed by weathered sandstone and shale which is susceptible to rainwater infiltration and variation of groundwater levels, often causing mud slides and debris flows along the dip slope.

As Taiwan is situated in the Western Pacific typhoon region in which seasonal winds intersect, Taipei is at relatively high risk of natural disasters caused by heavy rainfall. Table 1 summarizes the statistical records of monthly average precipitation in Taipei and average number of typhoon lands in Taiwan from 2005 to 2011. Taipei City has annual average precipitation of 2,663 mm/year in flatland and 4,474 mm/year in slopeland, mostly concentrated during the typhoon and heavy rainfall season (from May to October). Heavy rainfall has caused inundation and severe damage in Taipei in the past. For example, the Typhoon Nari in 2001 brought torrential rainfall (a record-breaking rainfall intensity of 650 mm/24 h) to Taipei, causing the loss of life, water, and power, and inundation in metro system and thousands of building basements. Part of the reason for this inundation is that urban planning has not generated a comprehensive flood control, drainage, and pumping system or the existing system is inadequate. Another reason is that low-lying land is cheaper than land with little potential for flooding, often resulting in high population densities in low-lying areas.

Taiwan is also situated on the border between two major tectonic plates—the Eurasian Plate and Philippine Sea Plate. Movement of these plates causes rock fragmentation and complex fractures in Taiwan's geological environment. Thus, typhoons and heavy rains frequently result in slope failure, landslides, and debris flows. Debris flows and landslides can result in casualties and death as well as damaging homes, buildings, and infrastructure. These disasters are often caused by poor drainage systems and deteriorated retaining structures in the communities and villages in the slopeland.

To date, Taipei City has five areas deemed prone to inundation, 50 rivers or streams are classified as having potential for debris flows (GEO 2010), and 24 communities on slopelands are classified as having landslide potential (GEO 2009). The next section discusses the methods currently used to identify these disaster potentials in Taipei City. Local governments have responded to these threats by helping residents in at-risk communities relocate and resettle. However, residents often fiercely resist relocation. This makes implementing mandatory resettlement extremely difficult. Thus, the main challenge facing

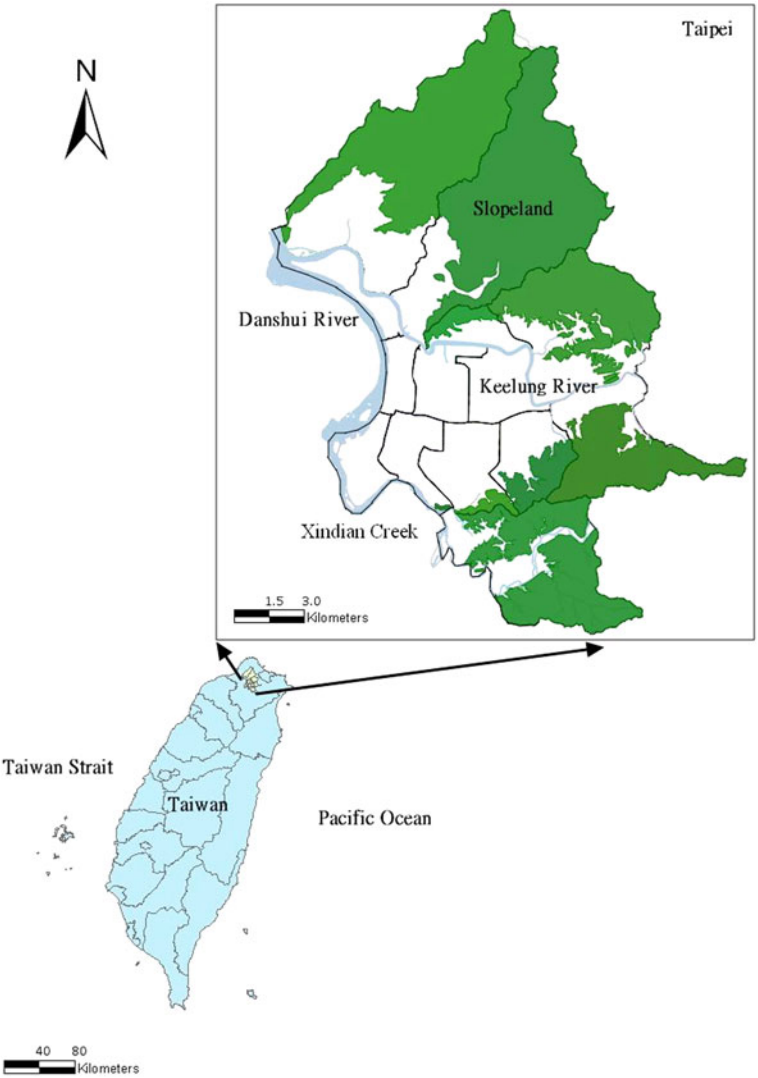


Fig. 2 Map of location and geographic environment of Taipei City. The *solid lines* inside the map of Taipei City indicate the boundaries of 12 administrative districts

engineers for emergency operations is to evaluate the potential impact of these disasters on the residents and plan shelters for affected residents in Taipei.

3 Identification and assessment of disaster potentials

3.1 Flood potential

The current methods for determining flood potential in Taipei involve numerical simulation and on-site inspection. Numerical simulation of flood potential provides an efficiency

Table 1 Statistical records of monthly average precipitation in Taipei and average number of typhoon lands in Taiwan from 2005 to 2011

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average rainfall in Taipei (mm)	77.5	133.8	171.2	139.1	242.0	388.9	195.2	361.1	337.9	177.2	127.6	78.3
Average number of typhoon landing in Taiwan (times)	0	0	0	0	1	1	1.67	1.5	1.25	1	0	0

Table 2 Information collected during on-site inspections for flood potential

Type	Data items
Hydrology	River discharge, river water level, amount of river sediment, groundwater level, and condition of drainage systems and water conservation facilities
Geography	Geographical conditions surrounding rivers and catchment areas
Human activity	Population, economy, development

and economical way to determine the overall flood potential, while the on-site inspection provides additional and detailed information for specific areas. Because the numerical approach is not likely to simulate all real conditions, such as the most recent land use, topographical changes, human activities, and resident conditions (Siegrist and Gutscher 2008), the simulation results may not entirely coincide with actual disaster conditions. Therefore, on-site inspection is conducted to compensate for inadequacies in numerical simulation. On-site inspection involves surveying recent factual information on disaster potential. Information gathered during on-site inspections can be classified as hydrological and geographical information and that for human activities (Table 2). By combining numerical simulation results and information gathered from on-site inspections, flood potential maps can be generated to identify the flood potential in areas of interests. Figure 3 shows an example of flood potential map of Taipei City for rainfall intensity of 600 mm/24 h by numerical simulation (Lin 2010) and five areas prone to water inundation identified from on-site inspection by the Hydraulic Engineering Office of Taipei City Government in 2010. The general procedures of numerical simulation are discussed as follows.

In numerical simulation for flood potential, hydrological analyses and flood modeling are utilized to establish relationships between rainfall (including rainfall patterns and frequencies) and flood depth in areas of interest (Lin 2010). Figure 4 shows the flowchart of hydrological analyses and flood modeling. Hydrological analyses can obtain temporal and spatial rainfall distributions which are input values for flood modeling. Flood modeling is utilized to predict the behavior of rainfall after striking the land. To simulate sparsely populated mountainous regions, the rainfall-runoff model is applied, and the river management model is mainly used to simulate flow conditions and river water levels. To

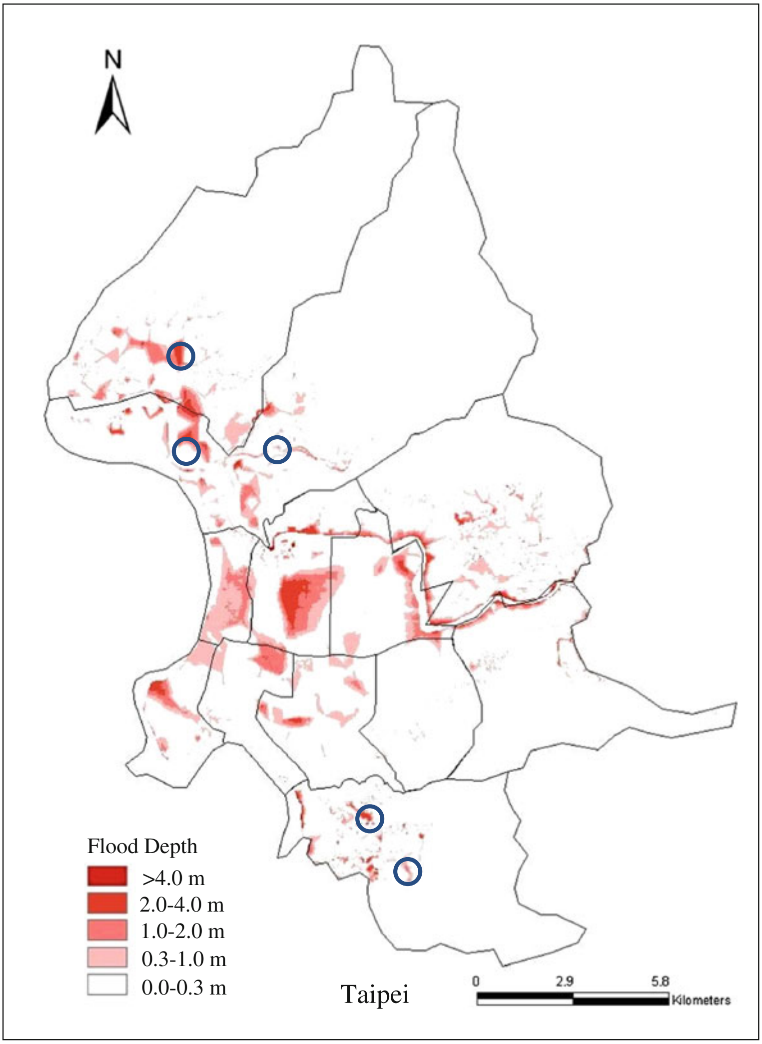


Fig. 3 Flood potential map under 600 mm/24 h rainfall intensity in Taipei City (modified from Lin 2010) and five areas (*blue circle*) prone to water inundation identified from on-site inspection

simulate densely populated plain regions, the two-dimensional inundation model is utilized. When calculating flood depth, the rainfall-runoff model first calculates rainfall runoff in mountainous regions. Under the corresponding spatial relationship, this runoff is input into the river management model (runoff flows into rivers) or the two-dimensional inundation model (runoff flows into plains). Flood modeling also considers whether river overflow will enter residential areas, or whether the water in residential areas will be channeled back to a river through gravity or by artificial means (i.e., pumping stations). Finally, floodwater information, such as depth and velocity, can be obtained when a simulation has attained equilibrium.

Rainfall data, required for hydrological analysis, are obtained from annual records from Taiwan Central Weather Bureau (TCWB) or Water Resource Agency. Flood

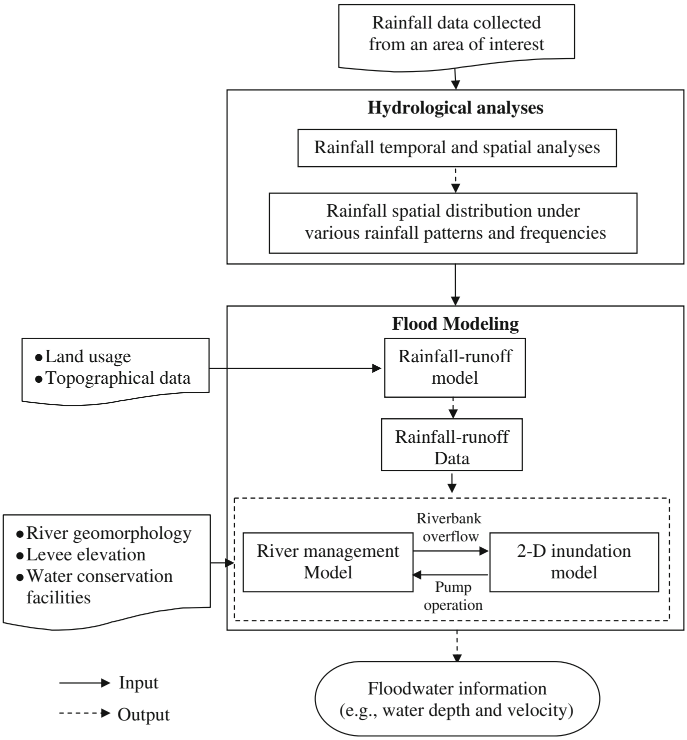


Fig. 4 Flowchart of hydrological analyses and flood modeling (modified from Lin 2010)

modeling requires data on land usage, topography, river channels, levee elevations, and water conservation facilities. Data for land usage refer to land classified according to usage, for example, categorizing land used for agriculture, transport, water conservation projects, construction, industry, recreation, aqua-farming, mining, and military purposes. Different land uses have a different surface roughness and infiltration rate and cause different amounts of surface runoff. Information on land uses is obtained from national land use surveys conducted by the Ministry of the Interior, Taiwan. Topographical data are used to calculate the area and slope of catchment areas. This information is then used with surface runoff data to estimate river discharge upstream of catchment areas. Topographical data are obtained from the digital elevation model DEM data provided by the Ministry of the Interior. Data on river channels (such as river cross section and length) are used as input for river geomorphology in the river management model. Data on levee elevation and water conservation facilities are used to calculate or assess whether riverbanks will overflow.

Generally, if relatively more detailed and recent data (implying increased accuracy) are obtained, the size of the computing grid in simulations can be decreased. If models have considered appropriate factors, flood simulation results should closely reflect reality. To enhance the accuracy of simulation results, Lin (2010) suggested that topographical data in flood simulations require a scale of 1/1000–1/5000 in urban areas and 1/5000–1/25000 in rural areas. For the size of computing grids, a 20 m $\times$ 20 m grid for urban areas and a 40 m $\times$ 40 m grid for rural areas are used.

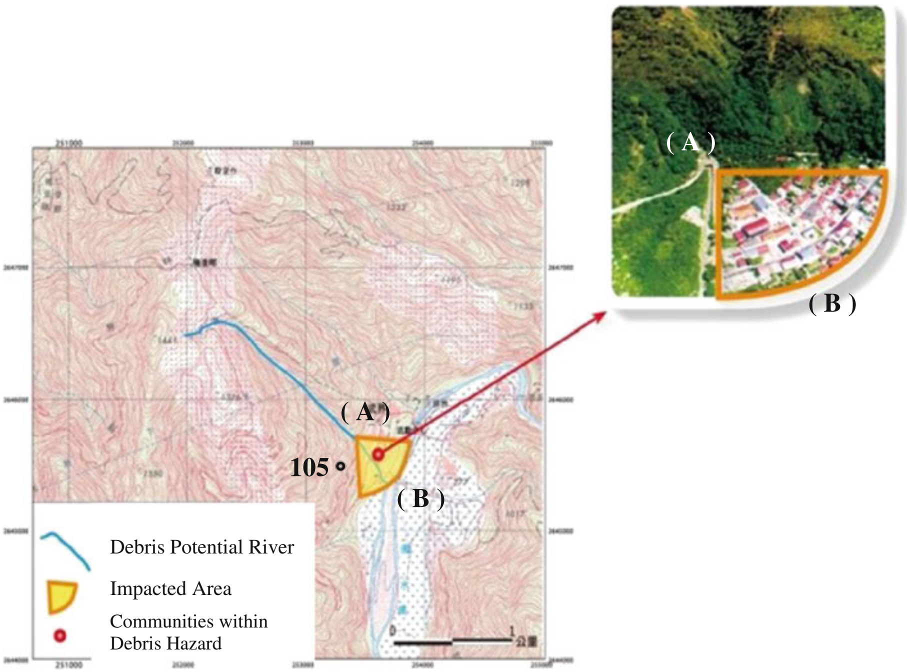


Fig. 5 Schematic illustration of determining the impacted area for a debris flow

3.2 Debris-flow potential

Rivers and streams with debris-flow potential in Taipei City are defined as either (1) rivers in which debris flows occurred previously and have potential for re-occurrence or (2) rivers that lack a history of disasters but present the possibility of debris flows (as determined by on-site inspections). For instance, rivers with a riverbed slope of exceeding 10° and an upstream catchment area of more than three hectares are deemed as having high debris-flow potential. Other factors, identified by Lai (2007), influence the debris-flow potential includes slope inclination, lithographical characteristics, land use, and the relationship between catchment areas and vegetation. To identify areas that would likely be affected by debris flows, one must first determine the danger zone vertex—Point A; this point can be a valley exit, alluvial fan apex, or a 10° slope (Fig. 5). Next, a fan-shaped region downstream from Point A is drawn according to the maximum spread angle of a debris flow 105°. Last, the 2° equal slope line B in the fan-shaped region is adopted as the debris-flow border. The region within the fan-shaped area and line B is the area that can be affected by a debris flow.

Rivers or streams with debris-flow potential are further differentiated by risk ratings to facilitate rapid determination of risk levels. The environmental/geographical (Table 3) and target security factors (Table 4) are first assessed. The environmental/geographical factors (Table 3) are environmental and geographical conditions that affect debris-flow occurrence, including collapse scale, topographical factors, material damage conditions, lithographical factors (geological factors), and vegetation factors. The resulting scores (maximum, 100) indicate the likelihood of debris flows occurring in a river or stream. As the score increases, debris-flow potential increases. These scores can be used to classify

Table 3 Rating scores for environmental/geographical factors which affect debris-flow occurrence

Factors	Description	Score
Scale of slope failure (25)	Large-scale slope failure	25
	Small-scale slope failure	15
	No obvious slope failure	5
Slope factors (25)	Upstream slope angle exceeding 50°	25
	Upstream slope angle of 30–50°	15
	Upstream slope angle smaller than 30°	5
Crushed material (20)	Average particle diameter larger than 12″	20
	Average particle diameter of 12″–3″	13
	Average particle diameter less than 3″	2
	No obvious accumulation of crushed materials	2
Lithographical factors (15)	Geologic category 1 (sedimentary and igneous rocks)	15
	Geological category 2 (sub-metamorphic rocks and laterites)	15
	Geological category 3 (regional metamorphic rocks and plain terrain)	5
Vegetation factors (15)	Deposits of bare rock and fallen rock	15
	Sparse and scattered vegetation	15
	Moderately sparse and scattered vegetation	6
	Dense vegetation	3
Maximum total score		100

these areas as having high (score of $\geq$62), moderate (score of 46–62), or low potential (score of $\leq$46) for disaster. The target security factors (Table 4) are used to assess man-made objects, such as buildings and transportation systems, which may be jeopardized by debris flows. Public transportation systems generally have the greatest number of users; therefore, rating scores for public transportation systems are typically highest. Buildings with five or more apartments are also assigned the highest score, followed by buildings with 1–4 apartments. Table 4 lists the rating methods (maximum score, 100). From the resulting scores, the secured target can be classified as having high (scores of $\geq$60), moderate (scores of 40–60), or low (score of $\leq$40) hazard levels.

The overall risk ratings for rivers and streams with debris-flow potential can be obtained by incorporating these scores into a risk assessment matrix (Table 5). For instance, a large number of protected objects in an area with high potential for debris flows result in a high risk rating. Such areas are prime targets for reengineering or public education in disaster prevention and response. Conversely, areas with high debris-flow potential but few protected objects have a lower risk rating. These ratings are used later as a reference for disaster prevention strategies and establishing response priorities.

Based on the methods discussed previously, 50 rivers or streams in Taipei City are classified as having potentials for debris flows; two are categorized as "high risk," seven as "moderate risk," 12 as "low risk," and 29 as "under observation." The critical rainfall intensity, set by the Taipei City Government, for each river and stream is in the range of 500–600 mm/24 h. According to procedures for typhoon response in the Taipei City Disaster Operations Booklet (TCFD 2010), when the Taiwan Central Weather Bureau predicts that rainfall will exceed the critical rainfall intensity for rivers with debris-flow potential, Taipei City disaster response centers must strongly advise residents to evacuate areas with debris-flow potential. When actual rainfall reaches a threshold, disaster response centers conduct mandatory evacuation.

Table 4 Rating score for target security factors which are jeopardized by debris flow

Factors	Category	Score
Buildings (50)	Public facilities related to disaster prevention (e.g., schools, medical facilities, and evacuation shelters)	50
	Five or more residences	45
	One to four residences	20
	No household residences	0
Transportation system (20)	Bridges	20
	Roads	10
	None	0
Effectiveness of on-site reengineering (30)	Facilities that have not been renovated or require improvement	30
	Reengineering can be conducted	15
	In good condition or does not require renovation or reengineering	0
Maximum total score		100

Table 5 Risk assessment matrix of debris-flow potential

Risk level	Level of debris-flow potential		
	Low	Moderate	High
Importance of protected objects			
Low	Low (under continual observation)	Low	Moderate
Moderate	Low	Moderate	High
High	Moderate	High	High

3.3 Landslide potential

During earlier urban development in Taipei, many retired soldiers from the mainland and laborers who had relocated to the city for work built private residences on the mountainsides bordering Taipei. Over time, additional houses were built, eventually forming small communities or villages. However, these communities situated on slopelands lack comprehensive earth-retaining mechanisms and drainage facilities, thus creating potential for landslides. A slope inspection policy is extremely important to managing and controlling mountainside development and reducing landslide potential. During the typhoon and heavy rainfall season, the Geotechnical Engineering Office of Taipei City Government contracts teams of civil engineers and geologists to conduct on-site inspections to assess landslide potential in the communities on slopelands. These teams photograph and number each residence, building, retaining structure and drainage system in these communities. Afterward, experts then fill out risk assessment tables (Table 6) for each residence and building in these communities to assess their landslide potentials.

In Table 6, risk assessment table has six categories, including slope topographical characteristics, geology, erosion and vegetation, hydrology and drainage, earth-retaining structures, and architectural and structural factors (Yang 2006). These six categories are further divided into 33 items, with risk levels of no risk, low risk, moderate risk, and high risk. Figure 6 shows photographs associated with items in Table 6 indicating landslide potentials. Specifically, if any of the 18 items marked with the symbol "*" in Table 6 is

Table 6 Risk assessment table of landslide potential in communities on slopelands

No.	Item	Severity				No.	Item	Severity			
		None	Low	Moderate	High			None	Low	Moderate	High
(1) Slope topography factors						(4) Hydrological and drainage factors					
1	Landslides have occurred previously*					1	Swelling of groundwater*				
2	The slope toe is raised*					2	Waterlines obstructed*				
3	Improper earth fill					3	Insufficient vertical/horizontal drainage facilities				
4	Improper excavation*					4	Inadequate sediment capacity in drainage facilities				
5	Steep slope (earth slope)*					5	Drains show cracking or sagging in foundations				
6	Obvious decompression with cracks or depressions at the slope peak					(5) Factors of retaining structures					
7	Tilting of trees or electricity poles on the slope					1	Retaining walls show obvious convex deformation or fissures*				
8	Fissures or small landslides on the slope					2	The surface of retaining walls has an abnormal appearance of water				
9	Nearby roads have cracks or partial cave-ins*					3	The toe of retaining walls or slopes has soil collapse or piled earth and stones				
(2) Geological factors						4	Drain openings in the wall or horizontal drain pipes are obstructed or not functioning well				
1	Dip slope*					5	Ground anchor is cracking, peeling, or rusting*				
2	Colluvium					(6) Architectural and structural factors					
3	Fault zone					1	Buildings have insufficient distance from retaining structures				
4	Falling rock*					2	Buildings located on broken ridges*				
5	Potential mud flow*					3	Safety concerns about building foundations*				
(3) Factors of erosion and vegetation						4	Cracked walls				
1	Headward erosion*					5	Building is situated on a waterway*				
2	Pit erosion										
3	General soil erosion										
4	Poor vegetation on the upper slope										
Danger level		☐ Level A (high danger rating)			☐ Level B (moderate danger rating)			☐ Level C (low danger rating)			

* Among the 18 assessment items if the "high" severity field is checked for any item, this item corresponds to level A (high danger rating)

deemed high risk, the residence or building is classified as level A (high risk), meaning that evacuation is mandatory when accumulated rainfall exceeds the critical rainfall intensity of 400 mm/24 h set by the Taipei City Government. Figure 7 shows photographs of mandatory evacuation drills in a community in Taipei City. If any of the 33 items is at "moderate risk," which corresponds to level B (moderate risk), evacuation is strongly advised. All other circumstances correspond to level C (low or no risk), and evacuation is only recommended. A total of 24 communities on slopeland in Taipei City have been identified as having landslide potential; 525 residences and buildings are categorized as "level A," 736 as "level B," and 139 as "level C."

4 Evaluation of affected population

In this section, the identified disaster potential data from Shilin District of Taipei City are used as an example to evaluate the affected population by deterministic and probabilistic approaches. More specifically, in the deterministic analyses, the impact of heavy rainfall with various intensities on the residents in Shilin District is evaluated. In the probabilistic analysis, risk curves for the population affected by heavy rainfall–induced hazards are established. The risk curve represents the relationships between the affected population and the annual exceedance probability. The results are used to assess the evacuation shelter capacity in next section.

Shilin District is the largest of Taipei's 12 administrative districts, which covers 63.9 km^2, has a total population of 283,171 people, and contains 51 communities in this district. Two of the five "urban areas prone to water accumulation" in Taipei City identified in 2010 are located in Shilin District. Additionally, seven rivers and streams in this district have debris-flow potential; the critical rainfall intensity for these areas is 500 mm/24 h. Among seven rivers with debris-flow potential, four have "low" risk ratings, while the other three are rated as under "continual observation." Seven residences (33 people) in the area within reach of debris flows are classified as protected objects. Two communities in Shilin District have been classified having landslide potential; the critical rainfall intensity for these areas is 400 mm/24 h. In one community, 26 residences are classified as risk level A, six as level B, and 0 as level C. In another community, 36 residences are classified as risk level A, six as level B, and 0 as level C. In total, 74 residences (199 people) are in these two communities.

4.1 Deterministic risk analyses

Deterministic risk analyses are performed to establish the relationships between hazard magnitude and affected factors. Figure 8 illustrates the fundamental concept of this analysis. Typically, the affected factor (e.g., damage) increases with the increasing hazard magnitude. In this study, the affected factor on the y-axis represents the affected population, while hazard magnitude on the x-axis is rainfall intensity. The affected population is determined according to different rainfall intensities (i.e., 200, 350, 450, and 600 mm/24 h). The primary reason why rainfall intensity is selected to identify an affected population is because rainfall prediction data are easily obtained from television broadcasts and the TCWB Web site. Additionally, as discussed, various Taipei City Government departments use rainfall intensities to generate different evacuation-related warnings according to different risk levels. The affected population is estimated separately according to the three hazards—flood, debris flow, and landslide—and then summed up to obtain the

Fig. 6 Photographs indicating landslide potentials: **a** buildings have insufficient distance from retaining structures; **b** cracked walls; **c** ground anchor is cracking and peeling; **d** nearby roads have cracks

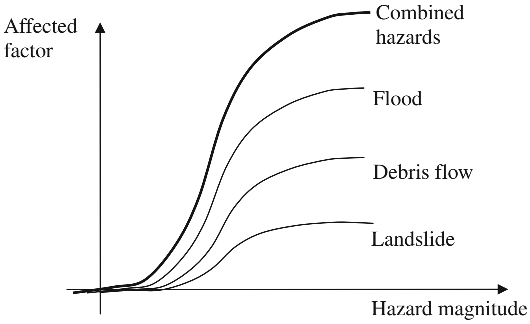
total affected population. Detailed calculation procedure for each hazard is described as follows.

The population that would be affected by floods is estimated by summing the products of the flood-prone area in each community in Shilin District and population density in that community. Flood-prone areas are obtained from flood potential maps by Lin (2010). Figure 9 shows the flood potential map for Shilin District under rainfall at 450 mm/24 h. The map uses 20 m $\times$ 20 m grids; thus, the flood-prone area of each grid is 400 m^2. The total flood-prone area is obtained by multiplying the number of grids with flood depths exceeding 50 cm by 400 m^2. Population density is obtained by dividing the population of each community by the total area of a community.

To estimate the population that could be affected by debris flows and landslides, as addressed previously, when the TCWB predicts rainfall will exceed 350 mm/24 h, the two communities having affected by landslide potential in Shilin District are immediately placed on alert and must prepare to evacuate. When predicted rainfall exceeds 400 mm/24 h, protected residents must evacuate. As a result, we assume protected residents in these two communities must prepare for evacuation when actual rainfall reaches 350 mm/24 h. In such circumstances, these residents are categorized as already affected by landslide potential. Further, when the TCWB predicts that rainfall in Shilin District will exceed 500 mm/24 h for rivers with debris-flow potential, residents living in the

Fig. 7 Photographs of mandatory evacuation drills in a community with landslide potential in Taipei City: **a** community volunteers broadcast the message of evacuation; **b** resident evacuation; **c** assist elder during evacuation; **d** transport residents to shelter

Fig. 8 Schematic illustration of deterministic risk analyses for various hazard sources



debris-flow areas must be advised to evacuate. When actual rainfall reaches the critical rainfall intensity of 500 mm/24 h, resident evacuation is mandatory. Therefore, we assume protected residents must prepare for evacuation when rainfall reaches 450 mm/24 h. In such circumstances, these residents are categorized as already affected by debris-flow potential.

4.2 Deterministic analysis results

Figure 10 presents calculation results of the affected population in Shilin District under various rainfall conditions. When accumulated rainfall reaches 200 mm/24 h, the area with

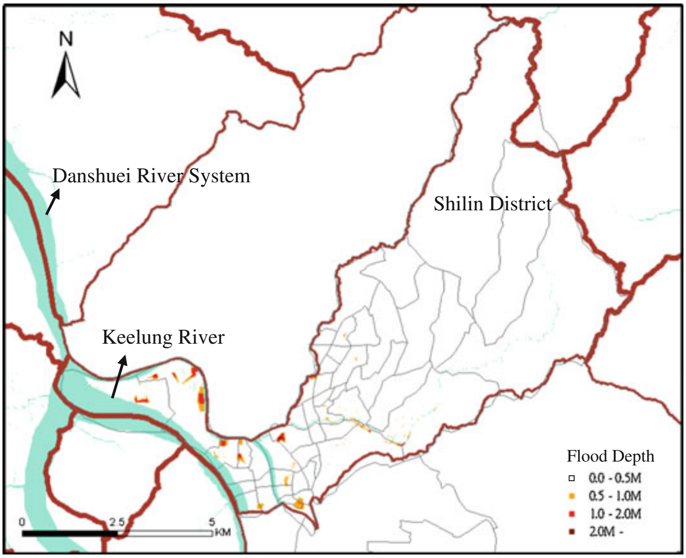


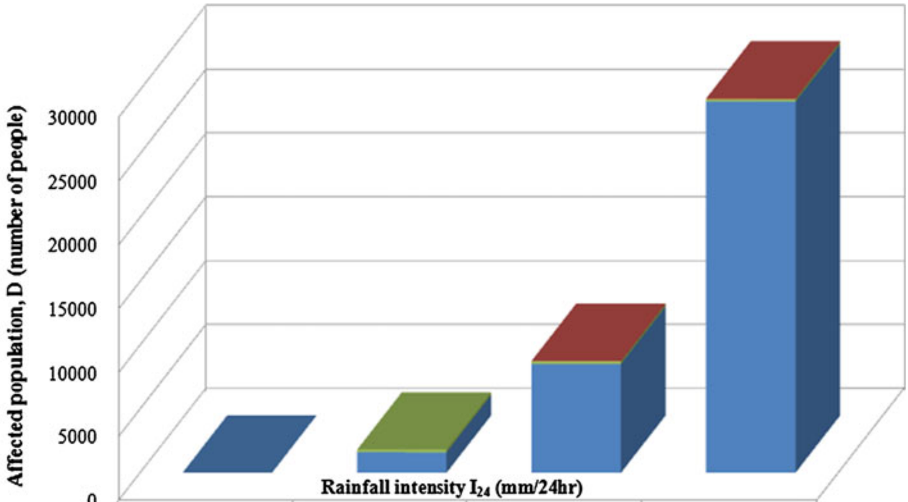
Fig. 9 Flood potential map under 450 mm/24 h rainfall intensity in Shilin District of Taipei City (modified from Lin 2010)

flood depths exceeding 50 cm is 800 m^2, and only two people are affected. The rainfall at this point has not yet reached the danger threshold for rivers with debris-flow potential or communities with landslide potential; thus, the protected residences in these areas are not affected. When accumulated rainfall reaches 350 mm/24 h, the flooded area in Shilin District is 125,200 m^2, and 1,612 people are affected. At this point, rainfall still has not yet reached the danger threshold for rivers with debris-flow potential. However, 199 residents in the 74 protected objects in communities with landslide potential must prepare to evacuate. Therefore, when the rainfall intensity reaches 350 mm/24 h, 1,811 people are affected.

Furthermore, when the rainfall intensity reaches 450 mm/24 h, the flood area is 528,499 m^2, and 8,537 people are affected. At this point, the rainfall intensity is nearing the danger threshold of 500 mm/24 h for rivers with debris-flow potential. Therefore, residents living inside the impacted areas must prepare for evacuation. For protected residents in communities with landslide potential, because rainfall has exceeded the mandatory evacuation threshold of 400 mm/24 h, all 199 residents should have been evacuated. The total population affected is then 8,770 people. Notably, when the rainfall intensity reaches 600 mm/24 h, the flood area is 1,606,000 m^2, and 29,097 people are affected. At this point, the rainfall intensity has reached levels for mandatory evacuation of residents of river areas with debris-flow potential and communities with landslide potential. Thus, the total population affected reaches 29,329 people.

4.3 Probabilistic risk analyses

The probabilistic risk analysis applies the probability density function for affected population to construct relationships between affected population and the annual exceedance probability, which indicates the probability of exceeding a particular number of affected



	200mm/24hr	350mm/24hr	450mm/24hr	600mm/24hr
Debris Flow	0	0	33	33
Landslide	0	199	199	199
Flood	2	1612	8537	29097

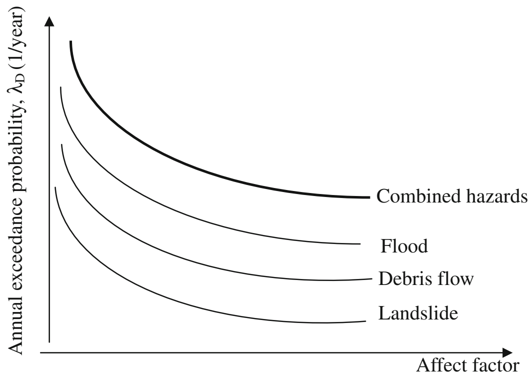
Fig. 10 Estimate of affected population under various rainfall intensities in Shilin District of Taipei City

population per year. This relationship is illustrated using a risk curve. Readers are referred to Reiter (1990) and Cornell (1968) for additional details on the theory and methods of probabilistic risk analysis. The calculation steps for the probabilistic risk analysis in this study are described as follows.

1. Select floods, debris flows, and landslides in communities as the primary hazard sources, and identify the disaster potentials of these hazards.
2. Establish a relationship between rainfall intensity and its annual probability of exceedance using hydrological data provided by the Taiwan Central Weather Bureau (TCWB) and Water Resource Agency.
3. Construct a probability density function for the population that may be affected by heavy rainfall.
4. Construct a relationship between the affected population and its annual exceedance probability. This last relationship is represented as a risk curve as illustrated in Fig. 11, in which λ_D (unit: 1/year) indicates the annual exceedance probability for the affected population.

In Calculation Step 2, Fig. 12 shows the recurrence relationships between 24-h rainfall intensity I_{24} (unit: mm/24 h) and its annual exceedance probability λ_I (unit: 1/year) in Taipei City. The curves for the rainfall recurrence relationships were compiled from the analyses (Lin 2010; Cheng 2001; MOEA 1988) using hydrological data at the Taipei weather station (CWB No. 466920) during different data collection periods. Likely due to the influence of global climate change, 24-h rainfall intensity has gradually increased over the years. For instance, based on research results from MOEA (1988), 24-h rainfall intensity I_{24} was approximately 400 mm/24 h under the annual exceedance probability of 0.01 (equal to a return period of 100 years). Research results from Lin

Fig. 11 Schematic illustration of probabilistic risk analyses for various hazard sources



(2010) showed that I_{24} had increased to 500 mm/24 h under the same annual exceedance probability. To coordinate the risk analysis with the flood potential maps used in this study and address the recent rainfall patterns that vary with global climate change, the recurrence relationship in Fig. 12 proposed by Lin (2010) was adopted. The regression equation is as follows:

$$\ln \lambda_I = 1.32 - 0.012 I_{24} \tag{1}$$

where λ_I is the annual exceedance probability of a given rainfall intensity (unit: 1/year) and I_{24} is 24-h rainfall intensity (unit: mm/24 h).

In Calculation Step 3, historical statistics are commonly used to establish the probability density function of a population affected by heavy rainfall; however, the relevant historical data are rare, and the only historical statistics available in Taiwan are the number of deaths and injuries from typhoons or heavy rainfall, which does not match the definition of “affected population” in this study. Therefore, we assume the probability density function of a population affected by heavy rainfall has a lognormal distribution. The reason of assuming lognormal distribution is to avoid negative values of affected population during calculation. The lognormal distribution was also adopted by Jonkman et al. (2008b) for the estimation of loss of life due to floods. The mean value of the probability distribution was the mean affected population μ_D (unit: people) obtained from the total affected population calculated from deterministic analyses. Figure 13 shows the predictive relationships between mean affected population and 24-h rainfall intensity. The regression equation is as follows:

$$\mu_D = 0.0004726 I_{24}^3 - 0.3357 I_{24}^2 + 96.152 I_{24} - 8581.3 \tag{2}$$

where μ_D is the mean affected population (unit: number of people) and I_{24} is 24-h rainfall intensity (unit: mm/24 h).

The coefficients of variation (COV) in this probability distribution were taken as 30 and 50 % to model normal and larger variability in affected population, respectively. Additionally, the influence of COV on the probability distribution and final probabilistic risk analysis results was also investigated. Figure 14 shows the resulting conditional probability of a particular number of affected population for a given rainfall intensity with different assumed COV.

In Calculation Step 4, Equation (3) is applied to assess the relationships between the affected population and its annual exceedance probability:

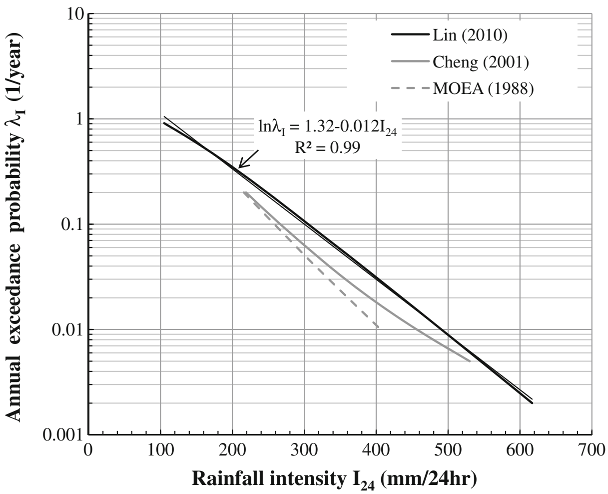


Fig. 12 Recurrence relationships between rainfall intensity and its annual exceedance probability in Taipei City

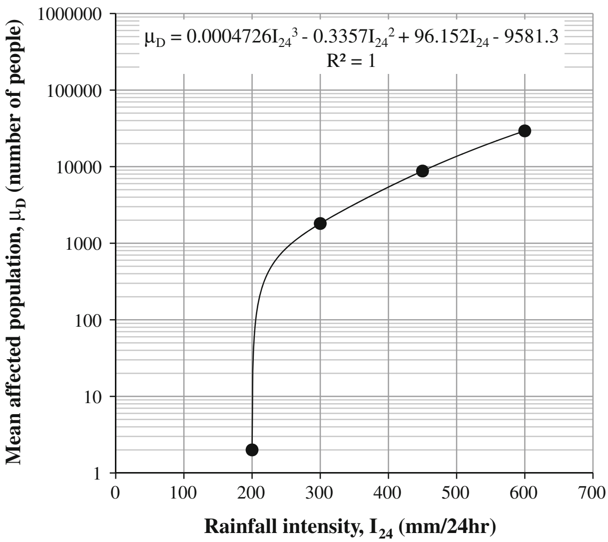


Fig. 13 Predictive relationships between mean affected population and rainfall intensity in Shilin District of Taipei City

$$\lambda_D = v \int P[D > D^* | m] \cdot f_M(m) \mathrm{d}m \tag{3}$$

where λ_D is the annual exceedance probability of a given affected population (unit: 1/year); $P[D > D^*|m]$ is the conditional probability that affected population D exceeds specific population D^* (unit: number of people) under a given hazard magnitude m (i.e., 24-h rainfall intensity I_{24} used in this study). Values of $P[D > D^*|m]$ can be obtained using Fig. 14 generated from Calculation Step 3. $f_M(m)$ is the probability that a hazard magnitude m would occur, which can be obtained from the recurrence relationship (Fig. 12) in Calculation Step 2. ν is a coefficient that can be evaluated using the method proposed by McGuire (1995):

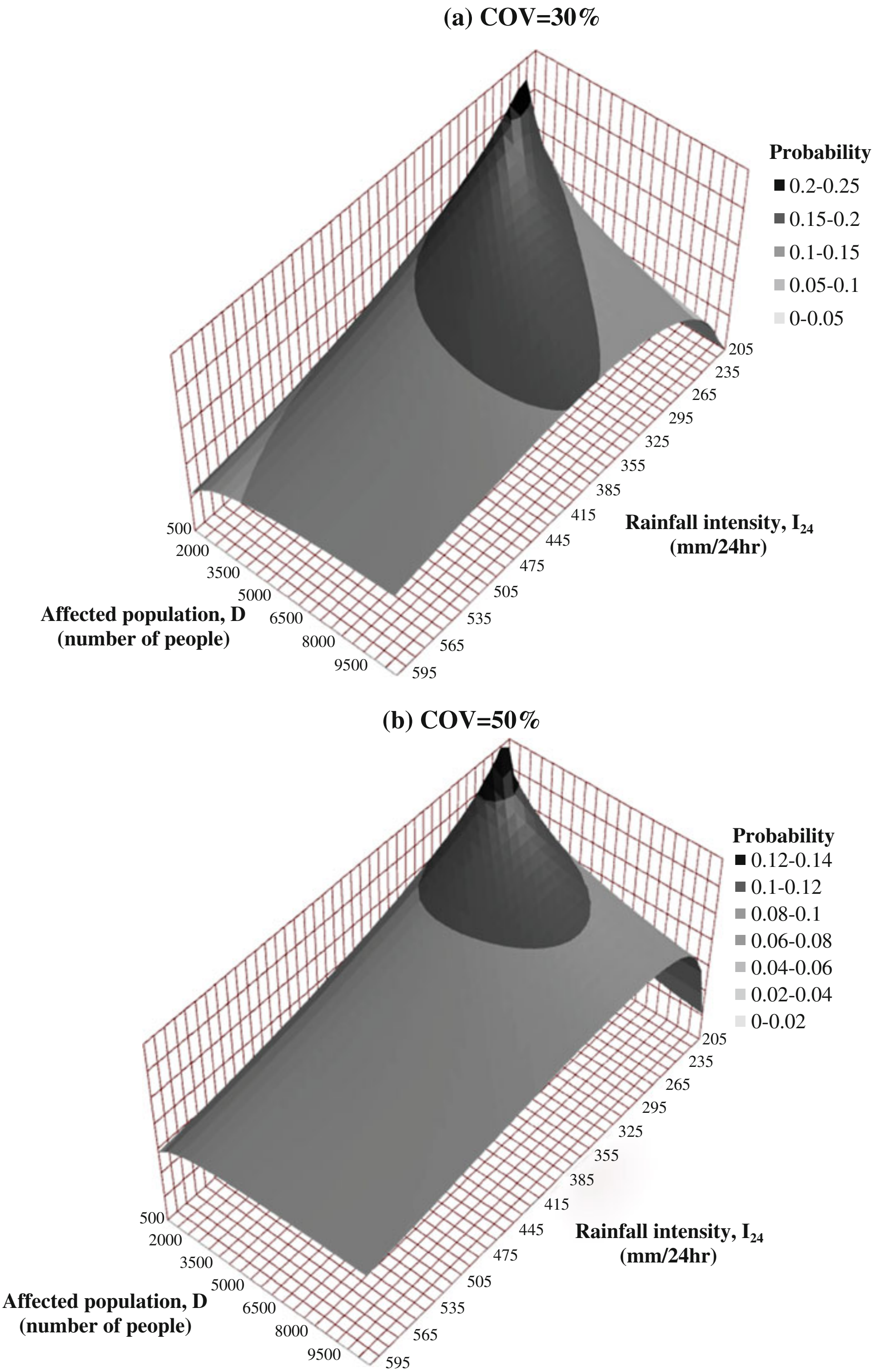


Fig. 14 Conditional probability of a particular number of affected population for a given rainfall intensity

Fig. 15 Risk curves of affected population for heavy rainfall–induced hazards

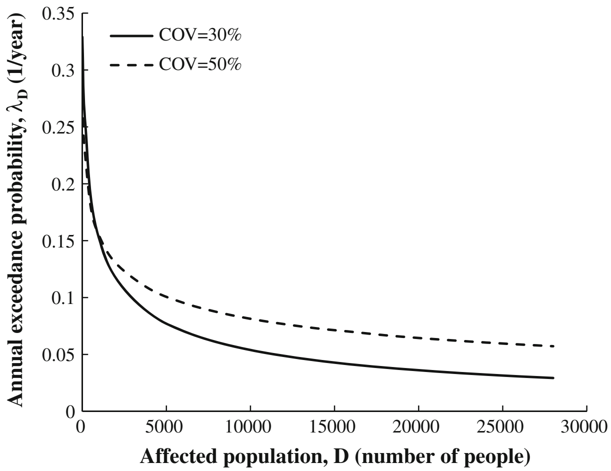


Table 7 Community evacuation capacity in Shilin District of Taipei City

Administrative district	Shilin presidential residence park*		District activity centers			Schools		District sports center	
	Area (m^2)	Estimated capacity (people)	Area (m^2)	Estimated capacity (people)	Number	Area (m^2)	Estimated capacity (people)	Area (m^2)	Estimated capacity (people)
Shilin district	92,800	23,200	7,313	1,823	26	29,100	4,999	N/A	2,281

* The Presidential Residence Park is excluded for the evacuation sites during heavy rainfall periods because there is no cover for rain in the park

$$v = \exp(\alpha - \beta m_0) \quad (4)$$

where α and β are a constant term and coefficient of Eq. (1), respectively (i.e., $\alpha = 1.32$; $\beta = 0.012$), and m_0 is the minimum hazard magnitude that can affect any population. Based on the result shown in Fig. 13, minimum hazard magnitude can be determined as $m_0 = 200$ mm/24 h.

4.4 Probabilistic analysis results

Based on the probability analyses, a risk curve for the population affected by heavy rainfall–induced hazards can be generated and shown in Fig. 15. The risk curve indicates the probability of exceeding a particular number of affected population per year. Figure 15 indicates the annual exceedance probability decreases as the affected population increases. Under the same affected population conditions, an increase in the COV of affected population implies an increase in the annual exceedance probability or a corresponding reduction in the return period. Using affected population $D = 10{,}000$ people as an example, under the assumed COV of 30 %, annual exceedance probability is of $\lambda_D = 0.054$ per year (approximately equal to a return period of 18.5 years). For the same affected population and under the assumed COV of 50 %, annual exceedance probability increases to $\lambda_D = 0.081$ per year (approximately equal to a return period of 12.3 years).

4.5 Assessment of community evacuation shelter capacity

Risk analysis results were applied to assess the evacuee accommodation capacity in Shilin District of Taipei City. This study surveyed existing evacuation shelters in Shilin District and their maximum capacity. The results are summarized in Table 7. Existing evacuation sites or shelters include activity centers, schools, and a sports center, all of which can accommodate a maximum of 9,103 evacuees. The Presidential Residence Park listed in Table 7 is mainly used when earthquake happens and should be excluded for the evacuation sites during heavy rainfall periods because there is no cover for rain in the park. Compared with the deterministic and probabilistic analysis results in Figs. 10 and 15, the capacity of Shilin District of Taipei City to accommodate evacuees is limited to heavy rainfall not exceeding 500 mm/24 h. Its annual exceedance probability is of $\lambda_D = 0.057$–0.083 per year (a return period of 12–18 years) according to the assumed COV of the affected population from 30 to 50 %.

Additionally, a sensitivity study result indicates when the COV of the affected population reduces to 10 %, the annual exceedance probability can decrease to $\lambda_D = 0.02$ per year, corresponding to a return period of 50 years. Compared to the results obtained by assuming the COV of 30 and 50 %, the return period of the affected population assuming COV = 10 % increases 32 and 38 years, respectively. This result indicates the high sensitivity of the calculated λ_D to the assumed COV of the affected population. Therefore, historical statistical data on the correlation between affected population and rainfall intensity are strongly recommended to be recorded and compiled. These data can be used to assess the actual probability density function of the affected population, resulting in enhancing the accuracy in assessing the annual exceedance probability of the affected population.

5 Discussions and recommendations

This study introduces practical methods currently used in Taipei City, Taiwan, to identify and assess heavy rainfall–induced potential risks on flood, debris flow, and landslide. The main advantages of these methods are simple to use and fast to assess the risk level. So, these methods can be easily carried out by the local government. These methods also give an advantage of direct comparison of the risk level, which allows the local government to allocate limited resources in proportion to the level of each risk. Furthermore, it is suggested that the outcomes of these methods can be compared with information from recent hazard events to refine and update these methods. Additionally, there are two limitations that should be addressed. First, the number of affected population estimated from risk analyses is applied to assess the evacuation shelter capacity in this study. However, this study probably overestimates the required evacuation shelter capacity, in particular for the hazard with low magnitude. That is because possibly not all of the affected population would need to evacuate to public shelters. For example, for temporary and low-magnitude flood event, people can choose to move vertically to higher floors in the same building until the inundation recedes. Second, because of the paucity of the statistic data of a population affected by heavy rainfall, the probability distribution function of the affected population was assumed in this study. However, this study found the probabilistic risk analysis results are very sensitive to the assumed COV of the affected population. Therefore, we recommend that historical statistical data on the correlation between affected population and rainfall intensity should be recorded and compiled in order to assess the actual probability distribution function of the affected population.

In a regional risk assessment, it is important to consider the impact of hazards not only on affected population but also on the resilience and viability of the community as a whole. It is also important to ensure critical facilities and utilities, such as emergency services, hospitals, evacuation shelters, and water supply, are not in the identified hazard-prone areas. Also, the blockage of main roadways and transportation systems which can cause potential isolation of communities should be taken into account or prevented. As development of city extends further on to the slopeland or to the potential flooding areas, disaster potentials may increase unless adequate mitigation strategies are taken. For short-term mitigation strategies, Taipei City Government currently conducts evacuation plans for areas in potential danger. The evacuation plans are supported by a public awareness and education program to advocate both the awareness of nature hazards and the evacuation plan. The evacuation plans also involve in executing disaster-related drills for each district in Taipei City before the typhoon and heavy rainfall season. For long-term mitigation strategies in Taipei City, detailed site-hazard-specific assessments are carried out by professional engineers or experts. Based on the site-hazard-specific assessment results, engineering works and solutions, such as installing adequate drainage and pumping systems, monitoring and improving retaining structures and levees, and relocating and resettling communities at risk, are implemented to avoid losses or reduce the risk to an acceptable level.

6 Conclusions

As the world is now facing threats of extreme and complex climate hazards, understanding and identifying disaster potential have become very important and challenging. This study first discussed the methods currently used in Taipei City to identify flood potential, rivers with debris-flow potential, and communities with landslide potential. The current methods for determining flood potential in Taipei involve numerical simulation and on-site inspection. Methods incorporating the environmental/geographical and target security factors into a risk assessment matrix are applied to rank the risk level of debris-flow and landslide potentials.

The identified disaster potentials were applied to a series of deterministic and probabilistic risk analyses using Shilin District of Taipei City as a case study. In the deterministic risk analysis, the population affected under various rainfall conditions was determined. In the probabilistic risk analysis, the relationship between the affected population and the annual exceedance probability was established. The risk curve for the population affected by heavy rainfall–induced hazards was constructed based on this relationship. Based on risk analysis results, this study found the capacity of Shilin District, Taipei City, to accommodate evacuees is limited to heavy rainfall not exceeding 500 mm/24 h. Its annual exceedance probability λ_D is 0.057–0.083 (COV, 30–50 %), corresponding to a return period of 12–18 years. This study also found the annual exceedance probability of the affected population is very sensitive to the assumed COV of the affected population. If the COV of the probability distribution of the affected population is reduced to 10 %, annual exceedance probability of evacuee accommodation capacity reduces to $\lambda_D = 0.02$, corresponding to a return period of 50 years This analytical finding demonstrates the importance of accurately assessing the probability density function of the affected population from historical statistical data on the correlation between affected population and rainfall intensity.

Last, it is also important to consider the impact of hazards on the resilience and viability of the community in a regional risk assessment. Critical facilities and utilities, such as emergency services, hospitals, evacuation shelters, and water supply, cannot locate in the identified hazard-prone areas. The blockage of main roadways and transportation systems which can cause potential isolation of communities should be prevented. Short-term and long-term mitigation strategies, as discussed previously, should be implemented to avoid losses or reduce the risk to an acceptable level.

Acknowledgments The finical support for this study was provided by the Taiwan Ministry of Interior under the grant for “Disaster Prevention and Protection Project of Taipei City.” The authors also would like to thank the Taipei City Fire Department, Geotechnical Engineering Office, and Hydraulic Engineering Office of Taipei City Government for providing valuable information and feedback for this study. Last, the authors sincerely appreciate the constructive comments by the anonymous reviewers.

References

Bonachea J, Remondo J, De Terán JRD, Gonzalez-Diez A, Cendrero A (2009) Landslide risk models for decision making. Risk Anal 29:1629–1643

Chen CY, Chen LK, Yu FC, Lin SC, Lin YC, Lee CL, Wang YT, Cheung KW (2008) Characteristics analysis for the flash flood-induced debris flows. Nat Hazards 47:245–261

Cheng KS (2001) Hydrological design manual. Water Resources Agency, Ministry of Economic Affairs

Cornell CA (1968) Engineering seismic risk analysis. Bull Seismol Soc Am 58:1583–1606

Crovelli RA (2000) Probability models for estimation of number and cost of landlsides. US Geological Survey open file report 00-249, p 23

GEO (2009) Aged villages investigation report in Taipei. Taipei City Geotechnical Engineering Office

GEO (2010) Debris-flow-prone streams and characteristics of rains triggering debris flows in Taipei. Taipei City Geotechnical Engineering Office

Gilbert RB (2008) Our role as engineers in mitigating natural hazards. In: Proceedings, geocongress 2008: geosustainability and geohazard mitigation, March 9, 2008–March 12, 2008, New Orleans, LA, United States

Hu K, Li Y, Wei F (2009) Annual risk assessment on high-frequency debris-flow fans. Nat Hazards 49:469–477

Jonkman SN, Kok M, Vrijling JK (2008a) Flood risk assessment in the Netherlands: a case study for dike ring south Holland. Risk Anal 28:1357–1374

Jonkman S, Vrijling J, Vrouwenvelder A (2008b) Methods for the estimation of loss of life due to floods: a literature review and a proposal for a new method. Nat Hazards 46:353–389

Jonkman SN, Maaskant B, Boyd E, Levitan ML (2009) Loss of life caused by the flooding of New Orleans after Hurricane Katrina: analysis of the relationship between flood characteristics and mortality. Risk Anal 29:676–698

Kim YO, Seo SB, Jang OJ (2012) Flood risk assessment using regional regression analysis. Nat Hazards. 4 Jun 2012 (Online)

Lai CC (2007) Characteristics of landslides caused by rainfalls and earthquakes in Taiwan. Master Thesis, Department of Hydraulic and Ocean, National Cheng Kung University

Lin GF (2010) Upgrading potential flooding map of Tamsui River, Taipei City, Taipei County, Taoyuan County and Keelung City. Water Resources Agency, Ministry of Economic Affairs

Lindell MK, Perry RW (2011) The protective action decision model: theoretical modifications and additional evidence. Risk Anal. 20 Jun 2011 (Online)

McGuire RK (1995) Probabilistic seismic hazard analysis and design earthquakes: closing the loop. Bull Seismol Soc Am 85:1275–1284

Merz B, Thieken A (2009) Flood risk curves and uncertainty bounds. Nat Hazards 51:437–458

Michael-Leiba M, Fred B, Greg S, Granger K (2003) Regional landslide risk to the Carins community. Nat Hazards 30:233–249

Minciardi R, Sacile R, Trasforini E (2009) Resource allocation in integrated preoperational and operational management of natural hazards. Risk Anal 29:62–75

MOEA (1988) Study and application of Taiwan hydrological data. Water Resources Agency, Ministry of Economic Affairs

Pande RK (2010) Flash flood disasters in Uttarakhand. Disaster Prev Manag 19:565–570

Paudel PP, Omura H, Kubota T, Morita K (2003) Landslide damage and disaster management system in Nepal. Disaster Preven Manag 12:413–419

Reiter L (1990) Earthquake hazard analysis-issues and insights. Columbia University Press, New York

Salciarini D, Tamagnini C, Conversini P, Rapinesi S (2011) Spatially distributed rainfall thresholds for the initiation of shallow landslides. Nat Hazards 61:1–17

Siegrist M, Gutscher H (2008) Natural hazards and motivation for mitigation behavior: people cannot predict the affect evoked by a severe flood. Risk Anal 28:771–778

TCFD (2010) Taipei disaster prevention manual. Taipei City Fire Department

Wang JJ, Ling H (2010) Relationships between typhoon types and debris flow disasters in Taiwan. Nat Hazards 54:373–394

Yang CJ (2006) Preliminary assessment of slope stability. Master Thesis, Department of Construction Engineering, National Taiwan University of Science and Technology