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Inundation Potentials Analysis for Tsao-Ling Landslide Lake Formed by Chi-Chi Earthquake in Taiwan

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Abstract. Without any omen, massive landslides induced by the Chi-Chi earthquake blocked up gorges of Ching-Shui creek, and produced a new landslide lake. Although emergency spillways have been constructed to prevent dam failures, overtopping and possible breaching may still occur due to excessive inflows in raining seasons. As a result, the downstream valleys will have serious inundation and the safety of people and properties will be in immediate danger. The purpose of this work is to simulate and to analyze the inundation potentials downstream of Tsao-Ling landslide lake using a hydrologic/hydraulic approach and GIS (Geographic Information System) technology. Hydrologic analysis is employed to describe regional rainfall-runoff characteristics and to design rainfall/runoff scenarios. One-dimensional dam break flood routings are performed with different return periods of rainfall events and dam failure durations for downstream creeks. The depletion hydrographs of dam break routings are applied into two-dimensional overland flow simulations for downstream lowlands. The results of hydraulic computations are evaluated with GIS maps for inundation potentials analysis, which can be used to assist the planning of emergency response measures.

Key words: Dam break flood routing, hydrologic analysis, inundation potentials analysis, landslide lake, overland flow routing

Introduction

The Chi-Chi earthquake ($M_L = 7.3$), the most powerful earthquake of the century in Taiwan, struck the west-central island on 21 September 1999. For about 85 km along the Che-Lung-Pu fault (Figure 1), extensive surface ruptures with vertical thrust and left lateral strikes-slip offsets were observed with a maximum fault displacement of 9.8 m (Ma *et al.*, 1999). Tens of thousands of buildings collapsed and caused a total casualty of more than 10,000 including over 2,300 fatalities. Not only did urban areas suffer serious destruction, but also hydraulic facilities were severely damaged, including cracking and displacement of dams, distortion and tumbling of riverbanks and coastal levees, and devastation of irrigation systems. Five major

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landslides, including one at the junction of two creeks, were also triggered by the earthquake and produced six new lakes as earth and rock masses blocking rivers (Teng *et al.*, 2000). To prevent ensuing floods of landslide breakage, three sliding sites having small amounts of landslide materials were cleaned up by government agencies. Three lakes disappeared and river flows were back to normal. Since large amounts of landslide materials were difficult to handle for the other two sites, channelized spillways with bedrock armoring were constructed directly over landslide dams to control the water stages of impoundments from upstream flooding and to improve the stability of landslide dams from overtopping and breaching. They are Tsao-Ling Lake of the Tsao-Ling landslide in the Chou-Shui River Basin, and two lakes of the Chiu-Fen-Erh-Shan landslide in the Wu River Basin as shown in Figure 1. In this study, Tso-Ling landslide case was focused for investigation.

Although structural measures can be applied to improve the stability of landslide dams, no one can precisely predict how long these lakes will last if there is another destructive earthquake or unusually large precipitation. Significant loss of reservoir capacity due to upstream landslides or sediment depositions in the reservoir may also suddenly or gradually cause overtopping and dam failure. The longevity of landslide dams depends on many factors, such as rate of inflow into the impoundment, size and shape of the dam, and geotechnical characteristics of the dam, and 85% of 73 recorded landslide dams failed within one year of formation (Costa and Schuster, 1988). The landslide lake formed in Madison Canyon landslide, Montana, USA, which was triggered by a severe earthquake in 1959, was made permanent till now by construction of a protected spillway (Strahler and Strahler, 1989). No matter how long these lakes will last, the reality is that thousands of residents living in downstream valleys of landslide lakes will be in great danger if overtopping or breaching of dams does occur.

Structural measures of flood mitigation, such as constructions of spillways, pipes/tunnels, retention ponds, and levees, have been attempted to stabilize many landslide dams by engineers. However, on facing the necessary evil of flooding induced by dam failures when structural measures are defeated, non-structural measures, such as hazard warning systems, emergency response measures, and inundation potentials analysis, will be the ones to reduce the loss of lives and properties. The new concept of natural hazard mitigation that arose in recent years links structural measures with non-structural measures into an integrated strategic work. By combining hydrologic and hydraulic approaches with GIS (Geographic Information System) spatial analysis, this study investigates the inundation potentials downstream of Tsao-Ling landslide. The computed inundation potentials can provide essential and quantitative information (e.g., inundation depths and areas) to assist the planning of emergency response measures for local residents and government agencies.

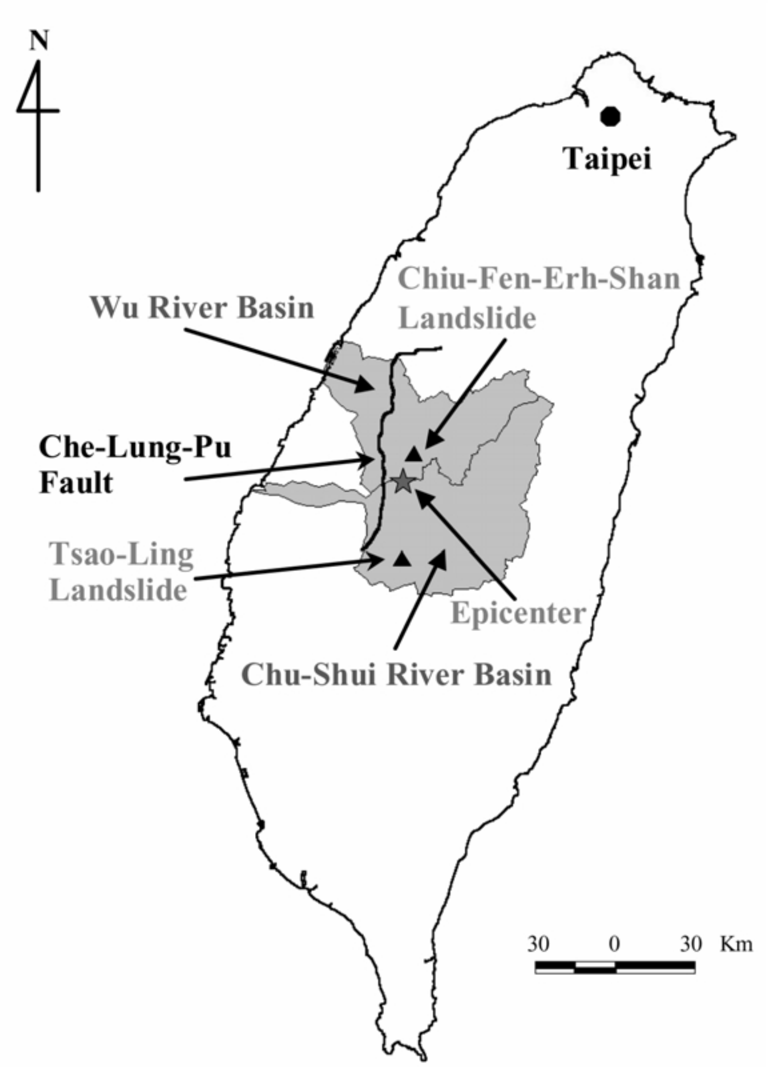

Figure 1. Epicenter of Chi-Chi earthquake and two basins having landslide lakes formed.

1. Sites Descriptions

The Tsao-Ling Lake is the largest landslide impoundment formed in the Chi-Chi earthquake as an entire mountainside slides into the Ching-Shui creek, a tributary of Chou-Shui River. The Ching-Shui creek basin has a total drainage area of 423.3 km^2, a main channel length of 47.5 km, an average channel slope of 1/58, and five major tributaries including Kuo creek, Chia-Tsou-Liao creek, Chu-Shan creek, A-Li-Shan creek, and Chen-Mao-Shu creek (Taiwan Provincial Water Conservancy Bureau, 1997) as shown in Figure 2. A series of formation and de-

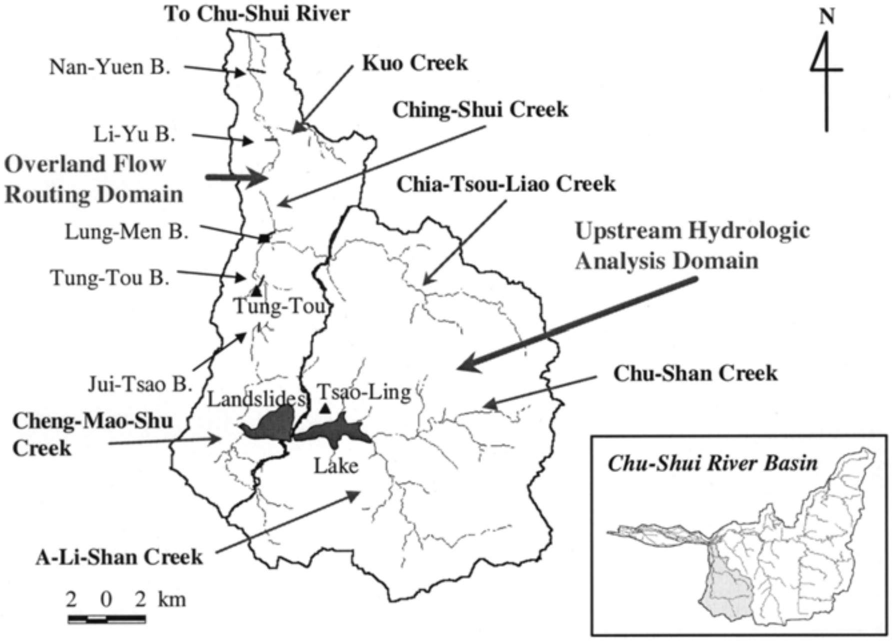

Figure 2. Simulation domain of Tsao-Ling landslide and its location in Chu-Shui River Basin.

struction of landslides in Tsao-Ling area have been documented for the past 140 years (Taiwan Provincial Water Conservancy Bureau, 1979). The first recorded Tsao-Ling landslide was triggered by a major earthquake in 1862, and the natural dam failed in 1898. Another major earthquake caused the second landslide at the same location in 1941, and a heavy rainfall led to the reactivation of a landslide with a bigger natural dam in 1942. The landslide dam failed by overtopping and caused serious disasters in downstream valleys killing 137 people due to several days of intensive rainfalls in 1951. The third landslide was activated by a heavy rainfall in 1979, and it was overtopped and failed 9 days later because of another severe rainstorm. Since emergency evacuation of downstream residents was undertaken before the complete dam failure, no fatality was reported. Only serious inundation over downstream lowlands and several bridges collapses were observed. From this brief review, the longevity of Tsao-Ling landslide dams varied from 9 days to more than 30 years. Earthquake and rainfall were mostly the reason of formation, and they also failed as a result of periods of heavy rainfalls.

The Chi-Chi earthquake triggered the fourth landslide at the same location with more than 120 million m^3 of rock and earth masses blocking the gorge of Ching-Shui creek for 5,000 m. A debris dam with a height of 50 m at upstream and 150 m at downstream was formed in seconds, and the Tsao-Ling Lake having an estimated storage capacity in excess of 46 million m^3 was produced (Water Conservancy Agency, 1999). Inflows from upstream drainage basin (162 km^2 at the landslide site) rapidly raised the water stage of the lake and quickly expanded toward upstream flooding, which posed a broad threat to downstream valleys if the landslide dam fails. Although the impounded water overflowed through artificial spillways after three months of landslide formation, it would be very difficult to drain the lake water due to the landslide length and the large inflows from upstream basin (Duster *et al.*, 1999).

2. Methodology

Unlike any manmade gravity or concrete dam with engineering barrier and filter material, a landslide dam is formed by unconsolidated heterogeneous earth/rock masses in a naturally unstable state. For about 55 failures of landslide dams reviewed by Costa and Schuster (1988), more than 50 failed by overtopping, followed by breaching from erosion by the overtopping water. Periods of unusually high inflows, often induced by severe rainstorms, into the impoundment are the most common, causing the overtopping of landslide dams. Therefore, the inundation simulations for downstream of landslide lakes are performed in association with designed rainstorms in this study. The step-by-step procedures are described in the subsequent sub-sections, as well as how they are linked to each other.

2.1. HYDROLOGIC ANALYSIS

To understand the rainfall-runoff characteristics of study areas, past rainfall and runoff records were gathered from the Water Conservancy Agency and the Central Weather Bureau, Taiwan for frequency analysis. The maximum rainfall depths of different return periods and durations were evaluated by using the log-Pearson Type III distribution. Regional rainfall intensity-duration-frequency characteristic was described with the Horner equation. Each rainstorm event considered in this study was assumed to be homogeneous in space for a 24-h duration. The total precipitation was unevenly distributed in time by using the Alternating Block Method (Chow *et al.*, 1988). Although the rainfall distribution was assumed to be spatially uniform, the runoff hydrograph was evaluated by the method of Semi-distributed Parallel-type Linear Reservoir developed by Hsieh and Wang (1999) to represent the regional runoff characteristics. The computed rainfall and runoff hydrographs were applied as input conditions for dam break flood routing and 2-D overland flow routing.

2.2. DAM BREAK FLOOD ROUTING

The DAMBRK model of NWS (National Weather Service, USA) developed by Fread (1988) was applied in this study to perform dam break flood routing, which included the computation of outflow hydrograph through the breach of landslide dam and the routing of outflow hydrograph through downstream creek. The time-dependent outflow hydrograph was computed by using the broad-crested weir formula and the law of conservation of mass with several user specified parameters, such as breach description, reservoir inflow, reservoir storage characteristics, spillway outflows, and downstream tailwater elevations (Fread and Harbaugh, 1973).

The Saint-Venant equations were applied for the routing of outflow hydrograph through the downstream valley,

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \tag{1}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + gA\left(S_f + S_e + \frac{\partial h}{\partial x}\right) = 0, \tag{2}$$

where t = time, x = longitudinal distance along the channel, Q = discharge of channel, A = cross-sectional area, q = lateral inflow/outflow per unit distance along the channel, h = flow depth, g = gravitational acceleration, S_f = frictional slope, S_e = expansion-contraction slope. The weighted four-point implicit scheme of Preissmann (1961) was applied to discretize Equations (1) and (2), and the Newton–Raphson method was employed to solve the resulting system of nonlinear equations. The computed runoff hydrographs of the upstream drainage basin and the associated tributaries from hydrologic analysis were used as the inflow conditions of impoundments on computing the breach outflow hydrograph and the lateral inflow conditions of downstream creeks on routing the flood wave propagations, respectively.

2.3. OVERLAND FLOW ROUTING

The FLO-2D model (O'Brien *et al.*, 1993, 1998) was adopted in this study to perform downstream overland flow routing with inputs from both hydrologic analysis and dam break flood routing. The governing equations are depth-averaged continuity and dynamic wave equations,

$$\frac{\partial h}{\partial t} + \frac{\partial h V_x}{\partial x} + \frac{\partial h V_y}{\partial y} = I_e \tag{3}$$

$$S_{fx} = S_{ox} - \frac{\partial h}{\partial x} - \frac{V_x}{g}\frac{\partial V_x}{\partial x} - \frac{V_y}{g}\frac{\partial V_x}{\partial y} - \frac{1}{g}\frac{\partial V_x}{\partial t} \tag{4}$$

$$S_{fy} = S_{oy} - \frac{\partial h}{\partial y} - \frac{V_y}{g}\frac{\partial V_y}{\partial y} - \frac{V_x}{g}\frac{\partial V_y}{\partial x} - \frac{1}{g}\frac{\partial V_y}{\partial t}, \tag{5}$$

where I_e = rainfall excess or infiltration rate; V_x and V_y = the depth-averaged velocity components along the x- and y-coordinates, respectively; S_{ox} and S_{oy} = the bed slope components along the x- and y-coordinates, respectively; S_{fx} and S_{fy} = the friction slope components along the x- and y-coordinates, respectively.

The explicit finite difference method was employed to solve Equations (3) through (5) with the idea of nodal domain integration method (Hormadka and Yen, 1987). The depletion hydrographs of dam failure were used as inflow conditions. The rainfall hydrographs were assumed to be spatially uniform for the entire simulation domain. The runoff hydrographs of tributaries from drainage basins were implemented as lateral inflow conditions.

To perform overland flow routing often requires a huge amount of hydrologic and geographic data preparations. It is often painful and time-consuming for filed case simulations. The GIS technology developed in recent years has provided great improvements on data processing. With graphical user interfaces, users can easily manipulate and apply geographic data for versatile applications. Once the locations of landslides have been identified digitally, the simulation domains can be determined by combining and analyzing digital maps, including watershed maps, counties maps, land-use maps, and DTM (Digital Terrain Model) grids into a new database suitable for the simulation domain interested. According to the resolution (or grid size) needed on performing simulations, the coordinate and surface elevation of each grid was extracted from DTM grids. The roughness coefficients were determined by using the agrarian development indices of a digital land-use map as references. Furthermore, simulation results were analyzed with maps layers (e.g., streets, buildings, rivers) for inundation potentials analysis. In this study, a GIS spatial analyst named ArcView (Environmental Systems Research Institute, 1996) was employed to perform such data manipulations for overland flow routing.

3. Simulation Results

Based on the location of landslide and natural watershed divides, the entire Ching-Shui creek basin were divided into two regions, one for upstream hydrologic analysis and another for overland flow routing as shown in Figure 2.

3.1. HYDROLOGIC ANALYSIS RESULTS

High intensity rainfall was found for Ching-Shui creek basin from frequency analysis on past rainfall records. For a 20-y 24-h rainfall, Tsao-Ling and Tung-Tou stations (shown with "▲' in Figure 2) will have 879 mm and 646 mm of precipitation, respectively. When a 200-y 24-h rainfall is considered, the estimated maximum precipitation may become 1,539 mm and 1,168 mm at those two corresponding locations. The computed peak discharges at different locations of Ching-Shui creek basin are listed in Table I. The peak discharge at Tung-Tou bridge may reach 7,422 m^3/sec due to a 200-y 24-h rainfall, while the major downstream tributary, Chia-Tsou-Liao creek, has 1,594 m^3/sec, which is a relatively important lateral inflow for the hydraulic routing of Ching-Shui creek.

Table I. Peak discharges at different locations under various return periods of rainfalls for Tsao-Ling landslide (Unit: m^3/sec)

Rainfall return period	Tsao-Ling landslide lake	Tung-Tou bridge	Chia-Tsou-Liao creek	Cheng-Mao-Shu creek
20 years	4126	5972	1258	342
100 years	4870	7015	1497	452
200 years	5140	7422	1594	512

Table II. Maximum water stages and propagation time (shown in brackets) of flood wave from peak flood wave at site for different locations of the Tsao-Liong landslide case (Unit: m and hour)

Rainfall return period	Dam failure duration	Lung-Men bridge	Li-Yu bridge	Nan-Yuen bridge	Confluence of Chu-Shui River
20 years	6 hours	195.0 (3.0)	152.1 (3.3)	121.0 (3.6)	112.9 (3.6)
100 years	6 hours	195.6 (3.0)	152.9 (3.2)	121.4 (3.4)	113.6 (3.6)
200 years	2 hours	197.4 (1.7)	155.2 (1.9)	121.8 (2.0)	116.7 (2.1)

3.2. DAM BREAK FLOOD ROUTING RESULTS

Three cases were studied by using the DAMBRK model for Tsao-Ling landslide lake. Under a 20-y and 100-y return periods of rainfalls, dam failure duration was assumed to be 6-h. For the 200-y case, a shorter failure interval of 2-h was selected to represent the possible worst scenario. The initiation of dam failure for each case simulated in this study was assumed to coincide with the arrival of upstream peak recharges. The simulated maximum water stages and propagation time of flood wave from peak flood wave at site for selected locations are listed in Table II. The peak flood wave will reach the confluence of Chu-Shui River in less than 4 hours for cases with 6-h failure, and it takes only about 2 hours for the 2-h failure case.

3.3. OVERLAND FLOW ROUTING RESULTS

The simulation domain of overland flow routing for the Tsao-Ling case, shown in Figure 2, was discretized with uniform grids having the sizes of 120 m × 120 m. There were 10,215 grids accounting for 147.1 km^2 of downstream lowlands of Tsao-Ling landslide lakes. Under different return periods of 24-h rainfalls and dam failure durations, Figures 3, 4, and 5 show the simulated results of 20-y event with 6-h failure, 100-y event with 6-h failure, and 200-y event with 2-h failure, respectively, for Tsao-Ling Lake. Since the ground surface and channel slopes after Tung-Tou bridge become smoother than upstream of Ching-Shui creek, broader in-

Table III. Maximum inundation depths at different locations for Tsao-Ling landslide (Unit: m)

Rainfall return period	Dam failure duration	Lung-Men bridge	Li-Yu bridge	Nan-Yuen bridge	Confluence of Chu-Shui River
20 years	6 hours	7.4	7.1	3.7	3.4
100 years	6 hours	8.8	7.3	4.3	3.7
200 years	2 hours	9.5	8.7	4.5	4.0

undation extent and deeper inundation depth were found. The computed maximum inundation depths at downstream of Tsao-Ling landslide are listed in Table III.

One thing should be mentioned here, the existence of mixed subcritical and supercritical flow regimes or the so-called transcritical flows (Meselhe *et al.*, 1997) were found through reaches of Tsao-Ling case by analyzing dam break routing results. Since it is difficult for overland flow models to handle 2-D mixed subcritical and supercritical flows, results of FLO-2D were checked with channel routing results of DAMBRK model to meet feasible engineering applications. Overland flow routing results obtained in this study were mainly employed to describe off-channel inundations, rather than to evaluate local hydraulic characteristics.

4. GIS-Assisted Inundation Potentials Analysis

Common structural measures applied for mitigating natural hazards like landslide dam failures include constructions of channelized spillway, water barrier, filter zones, drain zones, and outlet protections to improve stability of dams, as well as levees, sediment intercepting dams to diminish downstream flooding. On the other hand, non-structural measures may involve monitoring and warning system of landslide dam and water stages, dam breach routing, inundation potentials analysis, and emergency response plans. The GIS-assisted inundation potentials analysis performed in this study is expected to serve the purpose of helping people and government agencies on planning emergency response measures.

The GIS-assisted inundation potentials of landslide downstream can be obtained by mapping simulation results of overland flow routing with various digital data, including streets, rivers, buildings, and counties, etc., from GIS database to present meaningful inundation messages to general publics. Different levels of possible inundation areas can be delimited in association with various rainfall and dam failure scenarios. Furthermore, the amount of time available for evacuation, which can be estimated from the propagation time of flood wave from peak flood wave at site, is critical to how many lives can be saved in such natural disasters. With GIS-assisted inundation potentials analysis, people living downstream will know when to evacuate and where to go once landslide dams really fail.

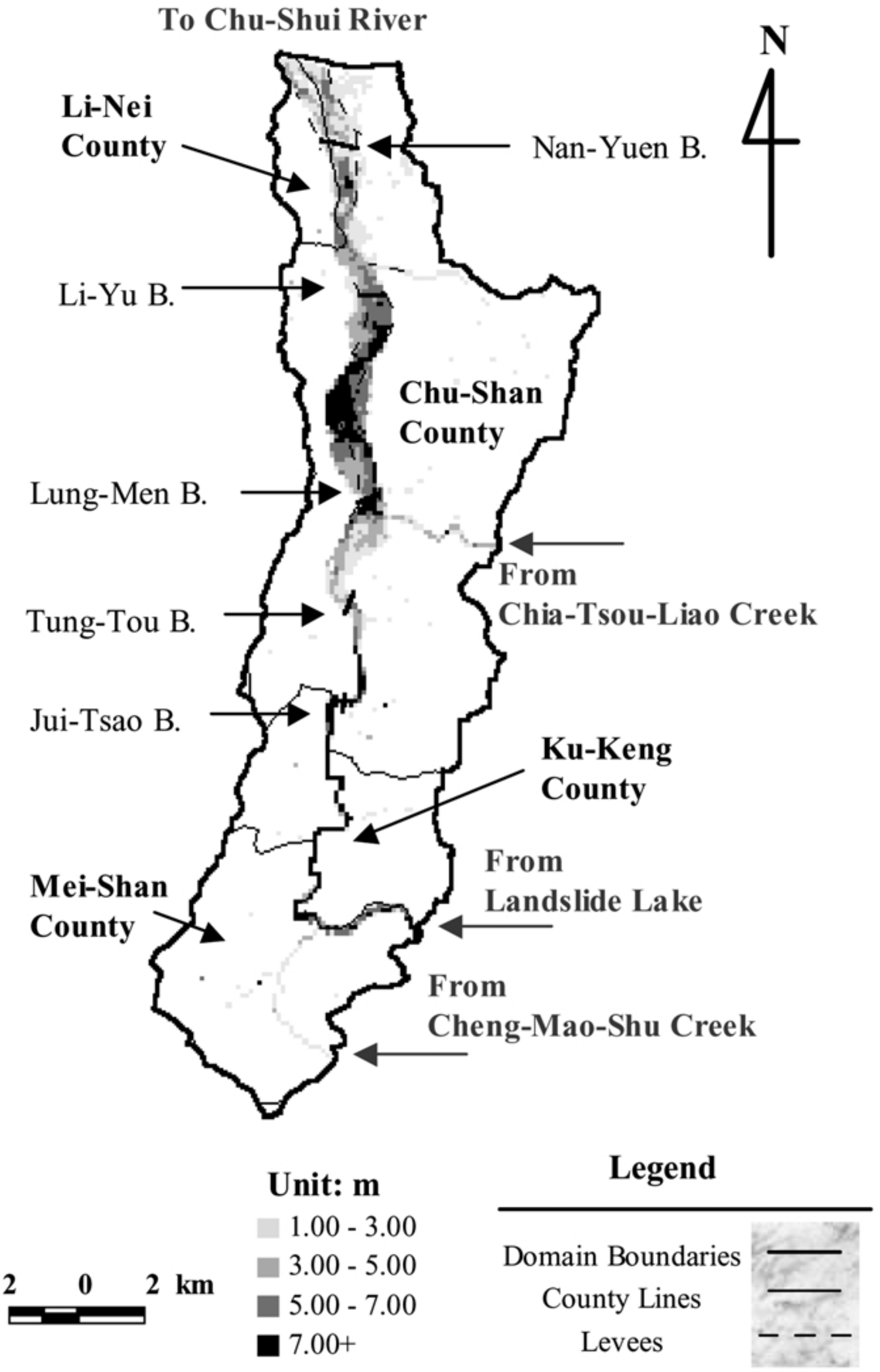

Figure 3. Downstream inundation depths of Tsao-Ling landslide lake under a 20-y 24-h rainfall with 6-h dam failure duration.

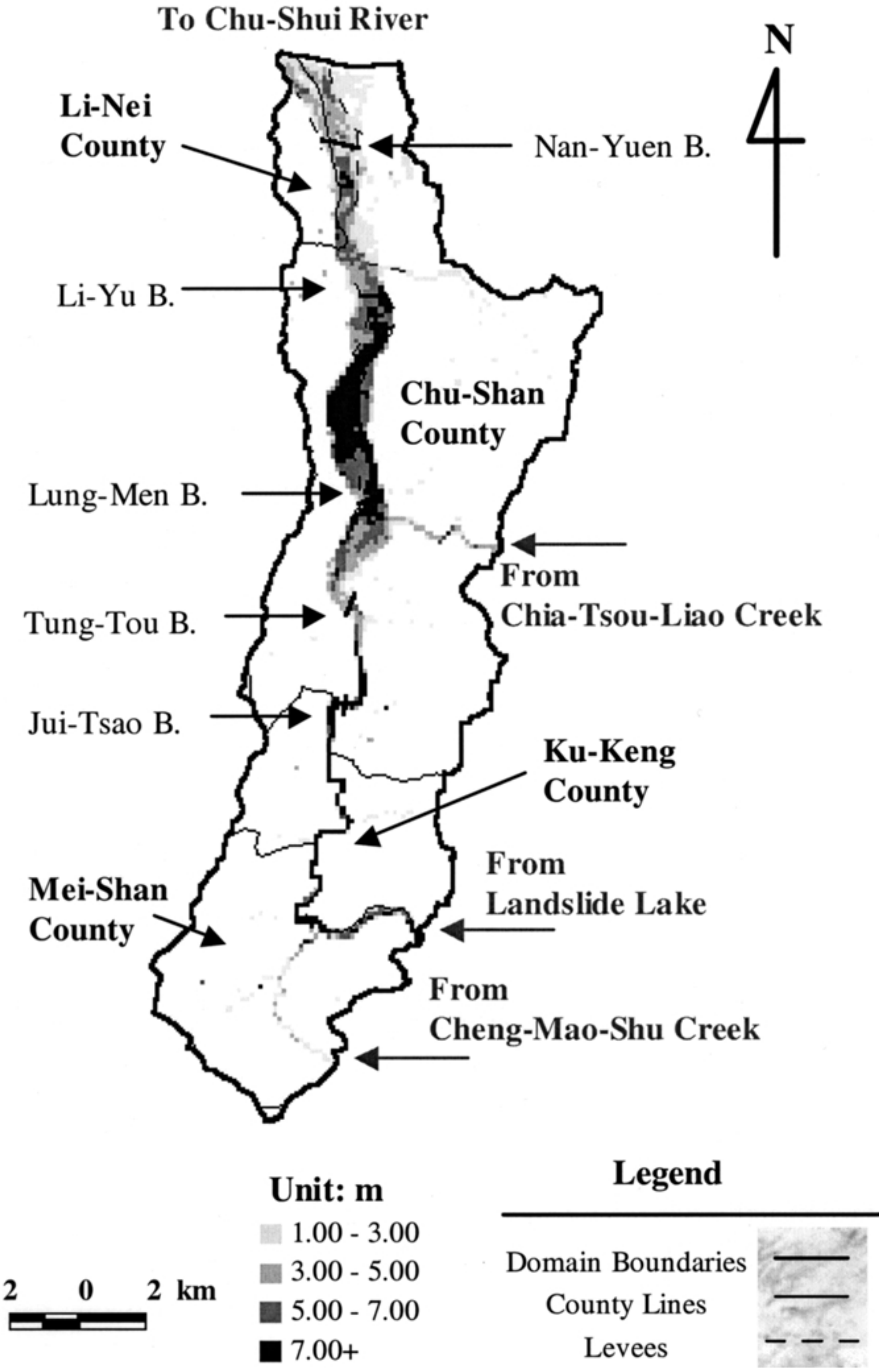

Figure 4. Downstream inundation depths of Tsao-Ling landslide lake under a 100-y 24-h rainfall with 6-h dam failure duration.

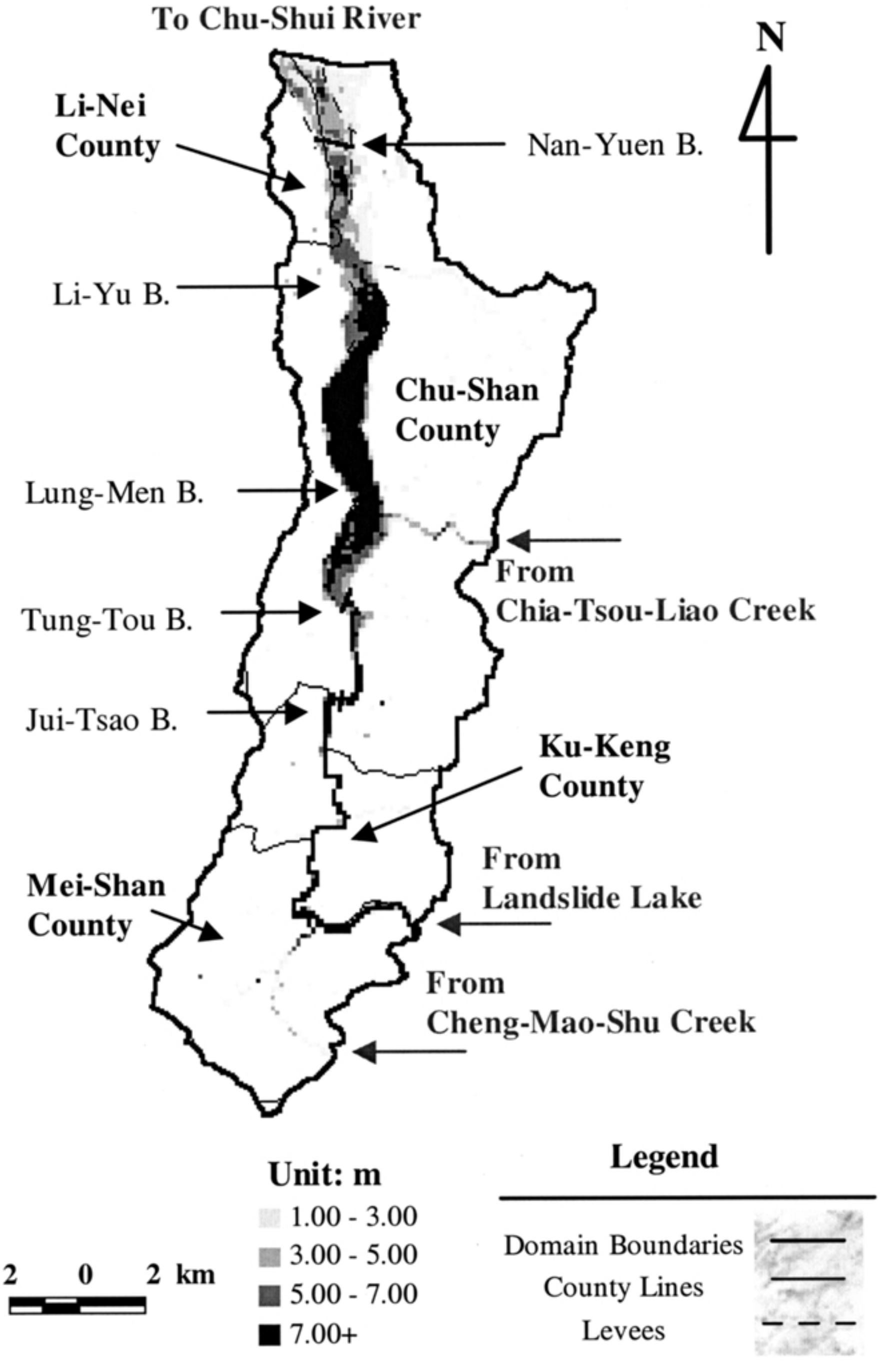

Figure 5. Downstream inundation depths of Tsao-Ling landslide lake under a 200-y 24-h rainfall with 2-hr dam failure duration.

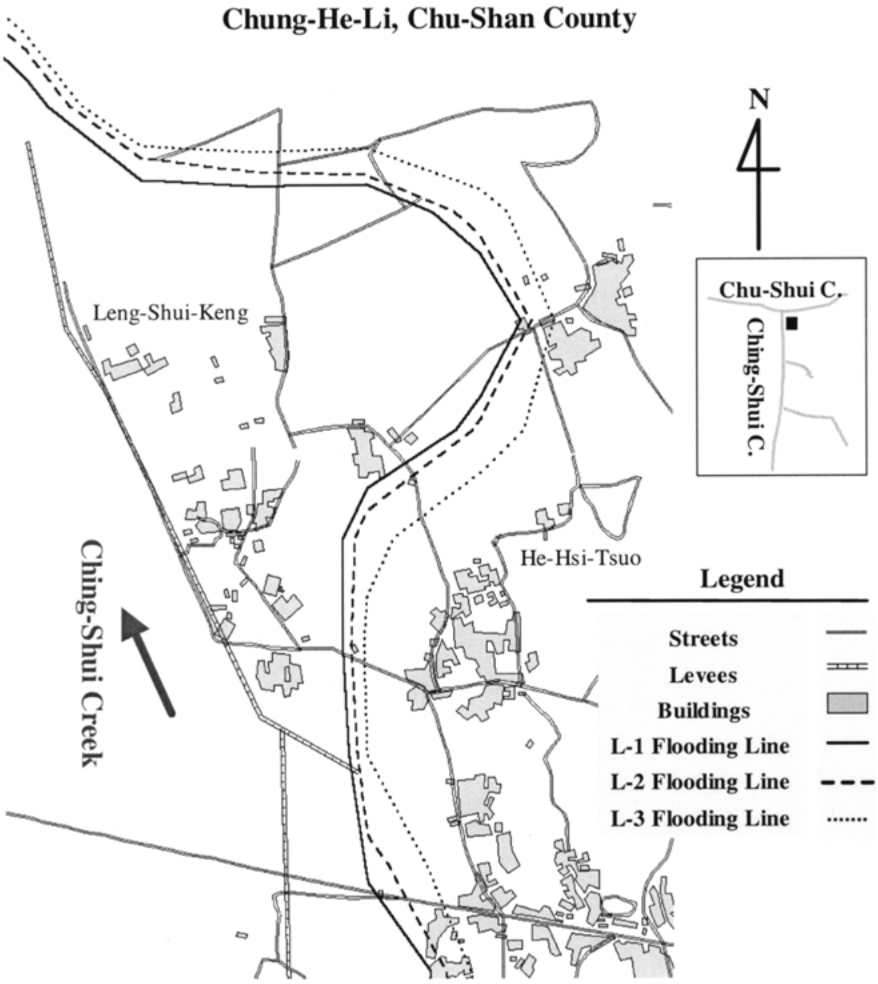

Figure 6. Different degrees of flooding lines evaluated from inundation potentials analysis for Chung-He-Li of Chu-Shan County, downstream of Tsao-Ling landslide.

By contouring regions having inundation depths greater than 0.5 m for three simulated cases, three levels of flooding lines at Chung-He-Li of Chu-Shan County, downstream of Ching-Shui creek, were drawn in Figure 6. The L-3 flooding line depicts the potential inundation regions if Tsao-Ling landslide dam fails in 2 hours under a 200-y 24-h rainstorm, while the L-2 and L-1 flooding lines are for 100-y 6-h break and 20-y 6-h break, respectively. Corresponding to each flooding line, the emergency responding time can be estimated from the propagation time of flood wave (Table II). For example, residents of Chung-He-Li may have 2.1 hour for evacuation once the Tsao-Ling landslide dam fails in 2 hours under a 200-y 24-h rainfall, and they should move toward the northeast or southeast highland areas regarding any combination of failure.

5. Conclusions

In this study, inundation potentials analysis for downstream of Tsao-Ling Landslide Lake were performed with cooperation of hydrologic analysis, 1-D dam break flood routing, and 2-D overland flow routing. Simulation results are analyzed with GIS digital maps to delimit different levels of inundation zones, which can be used to assist the planning of emergency response measures for downstream residents.

From simulation results, the inundation depths and extents were found to be greatly affected by many factors, such as rainfall-runoff intensity, dam failure duration, and whether there is any lateral inflow or not. The most serious flooding disaster among three scenarios studied was found to be the combination of the largest return period of rainfall event and the shortest dam failure duration. The propagation time of flood wave from peak flood wave at site was mainly dominated by the dam failure duration, which is an important index on determining emergency responding time for downstream residents. Therefore, the safety assessment of landslide dams requires continuously repeated monitoring and examining the stability of the dam, which is expected to provide accurate estimation of dam failure duration once there is any possibility of failure.

Since topographic information was extracted from DTM for 2-D overland flow routing, the accuracy of simulation results will rely on whether the DTM can keep up with current natural or man-made topographical changes. In other words, the DTM requires periodic renovation to authentically represent the most updated topography, especially when there is large surface displacement caused by a destructive earthquake such as the Chi-Chi earthquake.

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