APPENDICES

APPENDIX A

Photographs illustrating seventeen locations of the rock and soil samples collected for geotechnical study (sample locations referred to Figure 5-1)

Appendix A-1 Location A-1

Appendix A-2 Location B-1

Appendix A-3 Location B-2

Appendix A-4 Location B-3

Appendix A-5 Location B-4

Appendix A-6 Location B-5

Appendix A-7 Location B-6

Appendix A-8 Location B-7

Appendix A-9 Location B-8

Appendix A-10 Location B-9

Appendix A-11 Location B-10

Appendix A-12 Location B-11

Appendix A-13 Location B-12

Appendix A-14 Location C-1

Appendix A-15 Location C-2

Appendix A-16 Location C-3

Appendix A-17 Location C-4

Appendix A-18 Location C-4

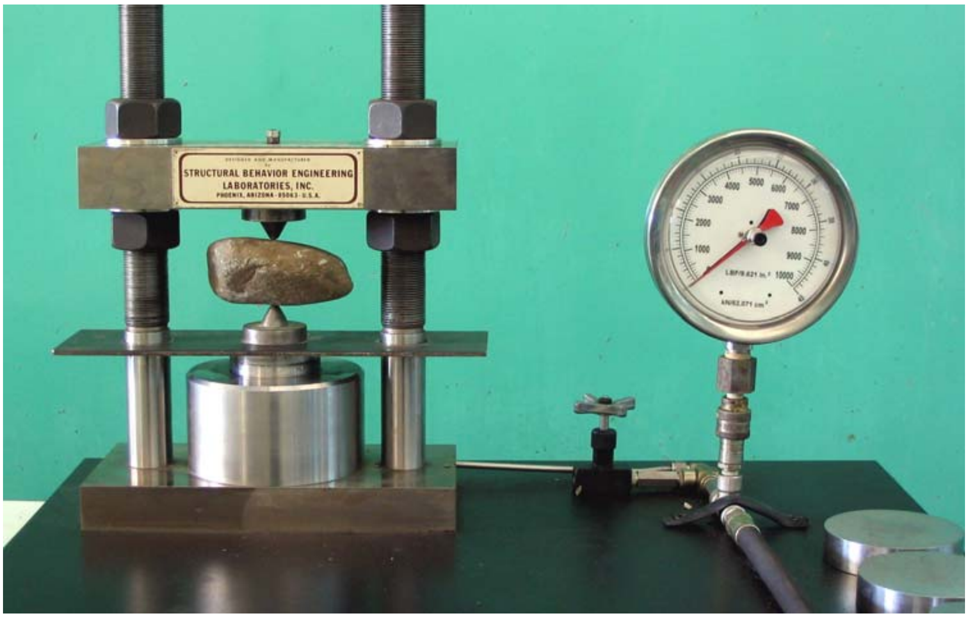
APPENDIX B

Photographs illustrating the locations of collected rock samples for geotechnical laboratorial studies and technique of point load testing in the Rock Mechanics Laboratory, Geological Engineering, Suranaree University of Technology

Appendix B-1 Field location along a stream (location B-2 as shown in Figure 5-1) from where rock specimens were collected for point load testing

Appendix B-2 The representative three rock-sample types of Phra Wihan sandstone/siltstone (lithologic unit Pw), Phu Kradung sandstone (lithologic unit Pk), and Lom Sak volcanic complex (lithologic unit Ls) respectively, that used in the point load testing

Appendix B-3 The point load apparatus (SBEL PLT-75) that has the highest force up to 75,000 pounds



Appendix B-4 Demonstration of a rock specimen forced by head-press until it is broken

Appendix B-5 Characteristics of ten rock specimens of Phra Wihan sandstone/siltstone (lithologic unit Pw) before point load testing

Appendix B-6 Characteristics of ten rock specimens of Phra Wihan sandstone/siltstone (lithologic unit Pw) after point load testing

Appendix B-7 Characteristics of twelve rock specimens of Phu Kradung sandstone/siltstone (lithologic unit Pk) before point load testing

Appendix B-8 Characteristics of twelve rock specimens of Phu Kradung sandstone/siltstone (lithologic unit Pk) after point load testing

Appendix B-9 Characteristics of ten rock specimens of Lom Sak volcanic complex (lithologic unit Ls) before point load testing

Appendix B-10 Characteristics of ten rock specimens of Lom Sak volcanic complex (lithologic unit Ls) after point load testing

Appendix B-11 Results of point load index strength test of rock specimens of Phra Wihan sandstone (Pw)

Number of Specimens : 10									
Rock Type : Pra Wihan Sandstone (Pw)									
Specimen No.	W	D	P	D_e^2 = 4WD/π	D_e	I_S = P/D_e^2	F = $(D_e/50)^{0.45}$	$I_{S(50)}$	σ_c = 24 $I_{s(50)}$
	(mm)	(mm)	(kN)	(mm^2)	(mm)	(MPa)		(MPa)	(MPa)
Pw - 1	49.1	117.3	18.0	7337	85.7	2.45	1.27	3.13	75.0
Pw - 2	40.9	94.0	12.5	4898	70.0	2.55	1.16	2.97	71.3
Pw - 3	54.0	127.1	11.5	8743	93.5	1.32	1.33	1.74	41.8
Pw - 4	82.0	50.2	12.0	5244	72.4	2.29	1.18	2.70	64.9
Pw - 5	72.8	42.0	8.7	3895	62.4	2.23	1.10	2.47	59.2
Pw - 6	78.5	47.4	9.4	4740	68.8	1.98	1.15	2.29	55.0
Pw - 7	54.8	36.8	7.8	2569	50.7	3.04	1.01	3.05	73.3
Pw - 8	71.6	30.6	6.5	2791	52.8	2.33	1.03	2.39	57.3
Pw - 9	61.1	27.3	7.0	2125	46.1	3.29	0.96	3.18	76.2
Pw - 10	37.5	32.4	4.7	1548	39.3	3.04	0.90	2.73	65.4
							MAX	3.18	76.2
							MIN	1.74	41.8
							MEAN	2.66	63.9
							S.D.	0.45	10.8

Appendix B-12 Results of point load index strength test of rock specimens of Phu Kradung sandstone (Pk)

Number of Specimens : 12

Rock Type : Phu Kradung Sandstone (Pk)

Specimen No.	W	D	P	$D_e^2 = 4WD/\pi$	D_e	$I_s = P/D_e^2$	$F = (D_e/50)^{0.45}$	$I_{S(50)}$	$\sigma_c = 24\ I_{s(50)}$
	(mm)	(mm)	(kN)	(mm^2)	(mm)	(MPa)		(MPa)	(MPa)
Pk - 1	112.0	51.3	7.8	7319	85.6	1.07	1.27	1.36	32.6
Pk - 2	106.4	48.9	5.5	6628	81.4	0.83	1.25	1.03	24.8
Pk - 3	112.5	59.8	8.1	8570	92.6	0.95	1.32	1.25	29.9
Pk - 4	108.2	52.0	9.9	7167	84.7	1.38	1.27	1.75	42.0
Pk - 5	89.8	45.4	11.2	5194	72.1	2.16	1.18	2.54	61.0
Pk - 6	112.8	63.5	14.0	9125	95.5	1.53	1.34	2.05	49.3
Pk - 7	103.9	43.1	11.6	5705	75.5	2.03	1.20	2.45	58.8
Pk - 8	62.0	55.3	12.0	4368	66.1	2.75	1.13	3.11	74.8
Pk - 9	89.7	41.8	12.0	4776	69.1	2.51	1.16	2.91	69.8
Pk - 10	102.5	50.0	9.0	6529	80.8	1.38	1.24	1.71	41.1
Pk - 11	97.8	51.3	8.5	6391	79.9	1.33	1.24	1.64	39.4
Pk - 12	65.0	48.5	9.8	4016	63.4	2.44	1.11	2.71	65.2
							MAX	3.11	74.8
							MIN	1.03	24.8
							MEAN	2.04	49.0
							S.D.	0.69	16.6

Appendix B-13 Results of point load index strength test of rock specimens of Lom Sak Volcanic Complex (Ls)

Number of Specimens : 10

Rock Type : Lom Sak Volcanic Complex (Ls)

Specimen No.	W	D	P	$D_e^2 = 4WD/\pi$	D_e	$I_s = P/D_e^2$	$F = (D_e/50)^{0.45}$	$I_{S(50)}$	$\sigma_c = 24 I_{s(50)}$
	(mm)	(mm)	(kN)	(mm^2)	(mm)	(MPa)		(MPa)	(MPa)
Ls - 1	96.5	51.9	26.0	6380	79.9	4.08	1.23	5.03	120.8
Ls - 2	125.5	52.2	38.8	8345	91.4	4.65	1.31	6.10	146.3
Ls - 3	117.8	54.3	25.5	8148	90.3	3.13	1.30	4.08	98.0
Ls - 4	105.3	37.7	28.7	5057	71.1	5.68	1.17	6.65	159.6
Ls - 5	141.1	45.9	37.6	8250	90.8	4.56	1.31	5.96	143.1
Ls - 6	115.1	56.6	17.5	8299	91.1	2.11	1.31	2.76	66.3
Ls - 7	103.8	52.9	18.0	6995	83.6	2.57	1.26	3.24	77.8
Ls - 8	140.2	35.3	22.2	6305	79.4	3.52	1.23	4.34	104.1
Ls - 9	117.1	30.2	19.2	4505	67.1	4.26	1.14	4.87	116.8
Ls - 10	93.3	25.2	14.4	2995	54.7	4.81	1.04	5.01	120.2
							MAX	6.65	159.6
							MIN	2.76	66.3
							MEAN	4.80	115.3
							S.D.	1.24	29.8

Appendix B-14 Analytical results of point load testing by the method of ISRM of Brown (1981) and ASTM D5731-95.

Rock Unit	Description	No. of Samples	$I_{S(50)}$ (MPa)	Approx. UCS (MPa)	Grade	
Pw	Gray sandstone /siltstone	10	2.66	63.9	R4	Strong rock
Pk	Red siltstone	12	2.04	45.0	R3	Medium strong rock
Ls	Volcanic complex	10	4.80	115.2	R5	Very strong rock

Note: $I_{s(50)}$ – Point load strength index

UCS – Uniaxial compressive strength, (σ_C) = 24 $I_{s(50)}$

APPENDIX C

Photographs illustrating laboratorial instruments and technique in soil-geotechnical testing in the Rock Mechanics Laboratory, Geological Engineering, Suranaree University of Technology

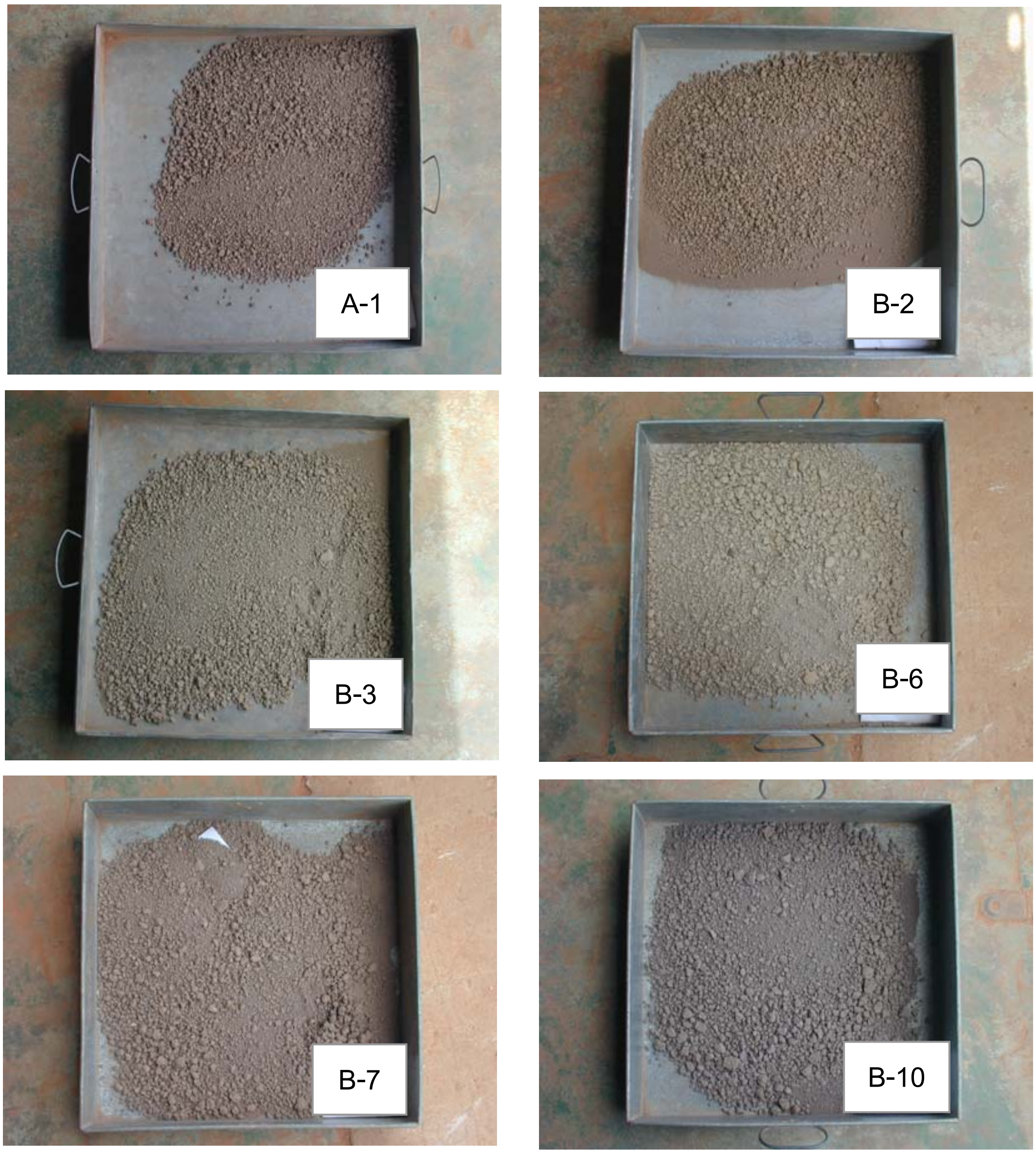
Appendix C-1 Sieve Analysis used for grain size distribution

Appendix C-2 Retained soils from each sieve class

Appendix C-3 Grain size distribution of soils from sedimentation by Hydrometer Test

Appendix C-4 Copper bowl apparatus for liquid limit of soil samples

Appendix C-5 Dried and crushed soil samples (number A-1, B-2, B-3, B-6, B-7 and B-10) used for soil-geotechnical testing



Appendix C-6 Oven-dried soil samples (number A-1, B-2, B-3, B-6, B-7 and B-10) used for Plastic Limit (w_P) and Liquid Limit (w_L) testing

APPENDIX D

Letter from Dr. Philip E. LaMoreaux, Edition-in-Chief of Environmental Geology, and the manuscript title “2001 debris flow and debris flood in Nam Ko area, Phetchabun province, central Thailand” for publication in *Environmental Geology of USA.*

Environmental Geology

March 22, 2006

Dr. Nopadon Muanoicharoen/Sombat Yumuang
Department of Geology, Faculty of Science
Chulalongkorn University, Phyathai Road
Bangkok 10330, THAILAND

Dear Nopadon and Sombat:

I have reviewed the manuscript, "2001 debris flow and debris flood in Nam Ko area, Phetchabun province, central Thailand".

The manuscript is very interesting and good; however, it needs a few revisions before publication in *Environmental Geology*. Enclosed for your review is a copy of your edited manuscript and a few reviewer comments. You must incorporate the suggested revisions and **resubmit to this office two hardcopies of the revised manuscript** for publication in *Environmental Geology*.

You must also submit your manuscript, tables, and figures on diskette(s) or CD-ROM, according to the enclosed instructions. Please fill out the bottom of the form and return it with the diskette.

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If you have any questions, please feel free to contact me.

Sincerely,

Phil

Philip E. LaMoreaux
Editor-in-Chief

Enclosures: Edited manuscript, copyright form, colored publication form letter, diskette submission instructions, formatting instruction sheet

2001 debris flow and debris flood in Nam Ko area, Phetchabun province, central Thailand

S. YUMUANG

Abstract The factors of the debris flow and debris flood (debris flow-flood) occurrence on 11 August 2001 on the active Nam Ko alluvial fan in Phetchabun province, central Thailand were studied. Evidences of past activity registered in the alluvial fan, and the debris flow-flood event were reconstructed. The disastrous debris flow-flood event was not the work of the unusual high amount of rainfalls alone, as previously theorized, but is a work of combined factors from the terrain characteristics with specific land covers to the time-delay for accumulation of debris and sediments. This combination of factors could lead to a debris flow-flood after a high amount of precipitation. The process could also be worse if a landslide formed a natural dam, then the dam was destroyed under the weight of impounded water. After such a disastrous event, it would take time for more plant debris and sediments in the sub-catchment area to accumulate before the next debris flow-flood.

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Keywords *Debris flow and debris flood - GIS and remote sensing - Nam Ko - Phetchabun – Thailand*

Introduction

On 11 August 2001 (8/11) at 3:30 a.m., a disastrous debris flow and associated debris flood (debris flow-flood) severely damaged Nam Ko Yai village on the alluvial fan just below the canyon mouth of the Nam Ko Yai stream (Fig. 1), a major tributary of Pa Sak river in Lom Sak district, Phetchabun province, central Thailand. The flood water, full of debris and fallen trees, destroyed several houses on the stream banks and claimed 136 lives with over 5 million US dollars in property damage. This is one of many severe tragedies caused by the debris flow-flood in Thailand in the past few decades.

Figure 1

A complete understanding of the processes and the factors that influenced this incident in Nam Ko Yai sub-catchment and the alluvial fan below in terms of action, source areas and run-out zones, as well as the identification of the potentials for hazards has never been accomplished. Expected frequency of such a debris flow-flood in this area is yet to be evaluated. However, a case study analysis of this event will provide essential basic information to mitigate future debris flow-floods under similar geographical conditions.

This study identifies the relationship of influencing factors of the debris flow-flood occurrence, defines the evidences of past activity registered in the alluvial fan, and determines the potential for future disastrous events in this area. The results will provide planners and decision-makers with adequate and understandable information for more effective planning with the appropriate strategies to reduce and mitigate debris-flow hazards and related phenomena in a long term risk analysis that could occur in areas of similar geographical conditions, and particularly, along the western flank of Phitsanulok-Phetchabun mountain range.

General concepts

Debris flows and related sediment flows are fast-moving flow-type landslides composed of slurry of rock, mud, organic matter, and water that move down drainage-basin channels onto alluvial fans. Debris flows are generally initiated by one of two processes, by land sliding or by sediment bulking of surface water flows from intense rainfall or rapid snowmelt on steep slopes or in channels. When flows reach an alluvial fan and lose channel confinement, they spread laterally. In addition to being debris-flow-deposition sites, alluvial fans are also often favored sites for settlement. Debris flows pose a hazard different from other types of landslides and floods due to their rapid movement and destructive power. In addition to threatening lives, debris flows can damage buildings and infrastructure by sediment burial, erosion, direct impact, and associated flooding.

Beverage and Culbertson (1964), Pierson and Costa (1987), and Costa (1988) describe the following flow types that build alluvial fans based on generalized sediment-water concentrations and resulting flow behavior: stream flow (less than 20% sediment by volume), hyperconcentrated flow (20 to 60% sediment by volume), and debris flow (greater than 60% sediment by volume). All three flow types can occur during a single event. The U.S. National Research Council (1996) also considers stream, hyperconcentrated, and debris-flow types in alluvial-fan flooding. The term debris flood has been used to describe hyperconcentrated flow (Wieczorek et al. 1983), waterfloods with large sediment load (Costa and Jarrett 1981), sediment flow (Miyajima 2001) and mud flood (National Research Council 1982).

Understanding the processes that govern a debris flow-flood initiation, debris- and water-transport action in the drainage basin, sediment bulking and deposition on the alluvial fan is vital to hazard evaluation. The guidelines for such geologic evaluation are necessary for safe and appropriate land use to prevent loss of life and property damage. The general technique used address debris flow-flood hazards is to evaluate past flows on the alluvial fan and the drainage basin, as well as channel sediment-supply conditions (Cannon 1997; National Research Council 1996; Giraud 2002).

Investigation methods

Three data inputs were used: thematic data preprocessed from geographic information system (GIS) and remote sensing techniques, field observation, and mechanical testing of soil and rock samples. Scar-scouring locations in Nam Ko Yai sub-catchment and deposition locations in the alluvial fan were detected and interpreted from multi-temporal satellite images, aerial photographs, rectified orthophotographs. Field visits were performed to determine the nature of some debris. The univariant probability analysis method of Dai et al. (2001) was used to present the spatial relationships between the detected scar-scouring locations and major debris flow-flood factors. To define the evidence of past debris flow-flood activity recorded in the alluvial fan, the geologic evaluation and age determination were used in a two-step procedure. This procedure (National Research Council 1996) consists of an initial delineation of the active depositional area and a subsequent detailed site-specific analysis of the hazard within the active depositional area.

The digitally based inventory of important input data themes in the study area was also preprocessed and compiled from secondary data, field investigation and interpretation of the multi-temporal rectified orthophotographs (1:25,000 and 1:50,000 scales), as well as satellite images of medium resolution (Landsat TM) and of high resolution (IKONOS). These important input data themes were provided a basis for detailed analysis of initial terrain and damage sites using GIS and remote sensing techniques of Varnes (1984) and Westen (1994). These input data themes (Table 1) were primarily used for defining the evidence of past debris flow-flood activities, analyzing the factors affecting flow-flood processes, and identifying the potential for flow-flood hazards.

Table 1

Description of the study area

The study area (Fig. 2) is in the northwestern corner of the main upper Pa Sak catchment at the feet of Khao Ko and Phu Hin Rong Kla Mountains in the

Phitsanulok-Phetchabun range. Nam Ko Yai village is situated on the alluvial fan. The sub-catchment area is 14 km long and 5 km across. The upstream rims are bounded by the steep slopes to a maximum altitude of 1,746 m in the northwestern part, down to the gentler slopes, then flat rolling sub-catchment terrain and the alluvial fan is at an altitude of 160 m.

Figure 2

Various rock units ranging from the uppermost Paleozoic and Mesozoic sedimentary and volcanic rocks to younger unconsolidated sediments occur in the study area. Stratigraphically, the lowest rock unit generally exposed in the eastern part of the study area is Permian Lom Kao (Lk) Formation. It consists of folded limestone, massive shale and slaty shale. Unconformably above is the Triassic Lom Sak (Ls) Formation that is a volcanic complex, plus siltstone, shale and slate. Ls Formation covers most of the study area, especially adjacent to the central stream channel. Ls Formation is subsequently angular-unconformably overlied by the gently westerly-dipping Khorat Group that is mainly exposed on the steepest and highest western and northern rims, near the tops of a flat highland away from the study area. This Khorat Group consists of Phu Kradung (Pk) Formation (red siltstone, conglomeratic sandstone, tuffaceous sandstone and siltstone) and Phra Wihan (Pw) Formation (gray sandstone, tuffaceous siltstone, and red shale), both Jurassic in age, and Phu Phan (Pp) Formation (pebbly sandstone) of Cretaceous period. The younger unconsolidated sediments (Qa) of Quaternary age are mainly stream deposits, composed of river sands and gravels, silts, clays and gray soils along the drainage system. The Qa sediments also include those that form the alluvial fan from the canyon mouth to the southeastern limit of the area.

The Nam Ko Yai sub-catchment is covered by dense forests on the western and northern high steep-slopes. Within the undulating valley floor along Nam Ko Yai stream in the central part of the sub-catchment, deforestation preceded agricultural usage. Erosion includes: sheet and rill, mass movement, gullies and badlands, that are widespread across the sub-catchment area. In the eastern extreme of the sub-catchment and on the alluvial fan, there are irrigated orchards and densely populated settlements.

In this upper Pa Sak region, the average annual rainfall normally exceeds 1,000 mm. The climate is tropical, occasionally with tropical storms in the early and middle periods of rainy season (June-October). The tropical storm “Usa-ngi” that passed through during the first two weeks of August 2001 was blamed for the 8/11 tragedy.

Evidence and factors affecting debris flow-flood processes in Nam Ko Yai sub-catchment

Factors affecting the 8/11 event included: landforms, slope gradient, underlying materials, land cover and unusual amount of rainfall. Evidence of the 8/11 occurrence were scar-scouring and depositional locations from the flow/flood. A key assumption is that the potential (occurrence possibility) of the debris flow-flood processes is the same as the actual frequency of those processes.

Landsat 7 ETM+ imageries data and geomorphometric data (e.g. slope, terrain aspect, topographic shape, etc.) were derived from a Digital Elevation Model (DEM) and combined to determine and classify newly formed distinctive scar-scouring and depositional locations in the sub-catchment and alluvial fan areas. These characteristics were detected in the Landsat imageries, aerial photographs and rectified orthophotographs. Brief field traverses were carried out locally. The ground-truth information was used to verify and adjust the accuracy of Landsat imagery classification, as well as aerial photograph and rectified orthophotograph interpretation.

Two sets of multi-spectral Landsat imageries of different periods, one on 5 January 2001 (before 8/11) and the other on 21 November 2001 (after 8/11), were classified (Fig. 3). Preprocessing of the six spectral bands of these Landsat imageries involve an atmospheric correction based on the standard atmospheric-model approach. Orthorectification was accomplished using GIS vectors of road- and stream data, as well as a DEM interpolated from contour vectors (1:25,000 scale). Slope and terrain aspect were calculated from the DEM. A Normalized Different Vegetation Index (NDVI) was created from the red and infrared spectral bands. NDVI was used to establish a threshold of vegetated and unvegetated pixels in the images for change detection at the scar-scouring and depositional locations (Fig. 4).

Figure 3

Figure 4

The classification scheme used to detect the scar-scouring and depositional locations utilized a user-specified hierarchical structure to eliminate non-relevant image objects. The first level was a division between the vegetated and unvegetated objects based on their NDVI value. The choice of 150.00 NDVI value (ratio) was empirically based on an inspection of the objects from the ground-truth information**.** Those objects with NDVI value below 150.00 were considered as unvegetated objects, and those above 150.00 as vegetated ones.

The scar-scouring and depositional locations were identified and validated. Classification accuracy was determined by comparing a sample of classified pixels with ground-truth information derived from the rectified orthophotographs and field observation (Fig. 5). The validity of the classified results was tested through the identified ground-truth information of the scar-scouring and depositional locations.

Figure 5

The univariant probability analysis was used to present the spatial relationship between the detected scar-scouring locations and each of the flow-flood related factors. Factors were the rock units (lithology), geomorphology (elevation, slope and topographic shape), soil thickness, land cover, and hydrological data (catchment characteristics and rainfall intensity). The spatial data revealed the correlation between the scar-scouring locations and those influent factors. For this, the spatial data were converted to a 10 x 10 m grid or cell (ARC/INFO GRID type) then further converted to ASCII data for a use with a general statistical program. In the study area, the total number of cells was 753,423 while the detected scar-scouring number of cells was 50,935. The correlation ratings were performed on the relationship between the detected scar-scouring locations and each factor's range, i.e., the ratio of the number of cells where scar-scouring was not detected to the number of cells where scar-scouring was detected. The relationship analysis is based on the ratio of the area of detected scar-scouring to the total area. A value of 1 defines an average value. The value greater than 1 means a high correlation, and less than 1 a low correlation. A high correlation indicates a high probability of the scar-scouring occurrence.

For slope configuration (Fig. 6), it was concluded that the steeper the slope, the greater the landslide probability was. For the slope inclination of 35-40° and more than 40°, the ratios were 1.57 and 1.70, respectively, indicating a slightly high probability for the scar-scouring occurrence in both cases.

Figure 6

For elevation above mean sea level (Fig. 7), the higher elevation, the greater the scar-scouring probability. For elevations between 1,000-1,100; 1,100-1,200; 1,200-1,300; and 1,300-1,400 m, the ratios were 3.16, 3.41, 3.99, and 2.54, respectively, indicating a very high probability for scar-scouring. Similar elevation ranges were observed in the steep-cliff areas.

Figure 7

The different topographic units, peak, ridge, saddle, flat, ravine, pit, convex hillside, concave hillside, slope hillside, inflection hillside, saddle hillside, seemed to be less significant. The frequencies of scar-scouring locations for any specific topographic shape were varied.

The frequencies of scar-scouring as related to the lithologic groups (Fig. 8) were determined for the different stratigraphic units. In the alluvial deposits (Qa1), Phra Wihan (Pw), Phu Kradung (Pk) and Lom Sak (Ls) Formations, the ratios were 3.188, 3.079, 2.302, and 2.713, respectively, indicating very high probabilities for scar-scoring occurrence in all units.

Figure 8

A relationship between the frequencies of scar-scouring and topsoil thickness was also attempted. Ranges of less than 50 cm, between 50 and 100 cm, and more than 100 cm were defined. Topsoil thickness was insignificant. Perhaps the scar-scouring occurrence was more directly related to the underlying basement rocks than to topsoil thickness.

Lom Sak (Ls) Formation is the most wide-spread rock unit in the study area and supplied the most debris of all sizes for deposition along the channel-bank of the stream system. The debris were further transported downstream toward the alluvial fan, and perhaps formed a significant temporary landslide dam along the way. Special interest was paid to engineering properties of the weathered products of this rock formation. Six weathered samples from this rock unit were collected along a tributary from the main Nam Ko Yai stream channel to the toe of the steep slope just below the exposures of Khorat Group. Geotechnical studies performed included grain size analysis, determination of Atterberg limits and indices, natural moisture content, and shear strength (Table 2). All specimens were non-uniform clay to clayey sand, with natural water content of 21-50 %, with the plastic limit and liquid limit between 17-31 and 24-55 %, respectively. The clayey soils also illustrate a low permeability value of about 10^{-2} to 10^{-7} m/sec. This indicates that the natural moisture could hardly be drained out of the soils, which staying close to the liquid limit. If the soils receive more water, their weight increases while the shear strength decreases, thus the soils would easily flow. These soils had varied shear strength values from about 10-100 kPa. Ls Formation soils, however, had shear strength values lower than other common soils thus were highly movable.

Table 2

The relationship between the scar-scouring and different types of land cover (Fig. 9) was also determined. The study revealed a high probability value on the banks close to the stream course and in forest areas further away, but lower in the cultivated flat areas. This is contrary to a general belief that cultivated lands played a major role in this event. The explanation could be that the debris flow-flood occurred close to the main stream where there was high energy for erosion and transportation of sediments, and in the forested areas where water could be accumulated and retained to introduce more effective transport when the catastrophic event occurred.

Figure 9

The rainfall records during 1-10 August 2001, a period of 10 days before the 8/11 occurrence, were collected from seven surrounding rain-gauge stations (Fig. 10). The frequency of scar-scouring was determined by counting the scar-scouring locations in each isohyet range of rainfall accumulation. The results revealed a high probability value of scars-scouring locations in the western areas where the rainfall accumulation was over 150 mm during this period (Fig 11).

Figure 10

Figure 11

In addition, the rainfall data and the inflow hydrograph from rainfall data of 1-10 August 2001 (pre-8/11 period) in related to the configuration of sub-catchment and channel characteristics were analyzed. The result was used as one of the most critical factors to identify the potential for the debris flow-flood. The graph of rainfall measurements in August 2001 from seven surrounding locations (Fig. 10) is presented in Figure 12. The average 24-hour rainfall value of pre-8/11 period was 12.98 mm. The two highest values of about 60 and 100 mm recorded on 10

August 2001 at the Ban Lao Ya station (southwest of the study area) and Ban Hin Hao station (northeast of the study area), respectively. The pattern of rainfall during 1-11 August 2001 recorded in most stations was the same as that of continuous rainfall during 2 - 14 August 2002.

Figure 12

The debris flow-flood may have begun before 11 August 2001 when the storm was in progress. Soils may have reached critical saturation at an earlier point, especially in the mountainous areas in the western and northern parts of the sub-catchment where the strongest intensity of rainfall was noted.

Evidence of the channel configuration and proposed natural dam location in the central part of Nam Ko Yai sub-catchment

From field investigations and rectified orthophotograph interpretation at a point along the course of Nam Ko Yai stream in the middle of the study area, the stream here issues from a flat open land to a very narrow V-shape channel with a sudden change of elevation at Tad Fa waterfall (Fig. 13). It could be hypothesized that this specific location is suitable for an accumulation of sediments composed of plant debris, soils, and rock boulders to form a natural dam. A field check revealed fallen trees and vegetation traces. This probably indicated that the temporary natural dam was broken, sending the debris and water to flood further downstream, eroding the channel along the way, and finally dropping its load on the alluvial fan at the canyon mouth. The evidences of 8/11 event could be observed where Nam Ko Yai stream had a steep V-shape cross-section. The traces of the erosional feature in the outer curving-bank were common. Some huge logs or intertwined bamboo clumps were left in the channel. Newly deposited large boulders were found in the channel where the gradient of stream bed changes from steep to flat. Eroded soil banks were also common.

Figure 13

Topographically, the area of Nam Ko Yai sub-catchment immediately upstream from this proposed natural dam location is a basin shape of about 100,000 square meters. This flat terrain is of a very gentle slope, less than 5°, surrounded by sloping walls with abrupt change in elevation. The stream here was of a wide U-shape and was straight for about 2,500 m. The area is suitable for forming a reservoir if a dam was built at the location. Downstream from the waterfall, the stream changes to a narrow V-shape with strong sinuosity for about 8,000 m to the canyon mouth area. This narrow V-shape and strong sinuosity channel is accompanied by increasing energy of torrent stream flow. This destructive form of mass movement was certainly not caused by the 8/11 alone, but indicates repeated strong debris flow-flood in the past.

From the field evidences and the oblique aerial photographs taken immediately after the 8/11 occurrence, the plant debris and soils transported from the sinusoidal stream banks (Fig. 14) were spread out onto the alluvial fan at the toe of the mountain front. This fan was concluded to have been formed by several similar debris flow-flood activities in the past.

Figure 14

Evidence of past debris flow-flood activity in the alluvial fan

The stratigraphic characteristics of the alluvial fan deposits are essential for evaluating past flows. A two-step geological evaluation was performed, consisting of an initial delineation of the active depositional area and a subsequent detailed, site-specific analysis of hazards within the active depositional area as suggested by the National Research Council (1996).

In step 1, which was to define an activeness, multi-temporal aerial photographs, rectified orthophotographs and Landsat 7 ETM+ imageries were interpreted and integrated with topographic characteristics for preliminary identification of location and morphology. Detailed investigation of past representative sedimentary sequences and resistivity investigation were also conducted to determine the criteria for alluvial fan activeness.

The available multi-temporal low-altitude images of aerial photographs (1:15,000 scale) taken on 24 December 1974, rectified orthophotograph (1:50,000 scale) taken on 6 January 1996, and rectified orthophotograph (1:25,000 scale) taken on 9 January 2002 (Fig. 15) were used to characterize the Nam Ko Yai canyon mouth and its downstream depositional fan before and after the 8/11 event. The topographic apex of Nam Ko Yai alluvial fan had only minor changes between 1974 and 1996. A clear activeness of erosion and deposition was presumed to be from the 8/11 flow-flood event.

Figure 15

The expanded features of rectified orthophotographs (1:25,000 scale) taken on 9 January 2002 in Figures 15 and 16 clearly show current traces and tracks of debris flood evidenced from the distinct and active alluvial fan deposit. The deposits mainly occurred on the northern bank of the alluvial fan area where the flood severely damaged houses and orchards dominantly seen in the 1974 aerial photograph and 1996 rectified orthophotograph.

In the multi-spectral Landsat 7 ETM+ imageries analysis, evidences of the alluvial fan deposit from the 8/11 event were analyzed using NDVI value. NDVI value was also used to detect the depositional locations on the alluvial fan (Fig. 16). Oblique aerial photographs taken after the flood were used to characterize the extent of the deposit and validate analyzed result. The high value of NDVI change (56-107) in Figure 16 generally conformed the areas of the most serious damage in Figure 17.

Figure 16

Figure 17

The oblique aerial photographs of the severely damaged settlement areas (Fig. 1) illustrate characteristics and extent of a large volume of an active alluvial fan deposit. The flood levels were established from mud traces on house walls and trees. The highest level of the debris flood, 190-200 cm above the ground level, was located in the most severely damaged zone at locations A and B (Fig.17). The two locations faced the straight course of Nam Ko Yai stream before the channel changed direction abruptly further downstream. Here, the flood jumped over-bank to destroy houses and orchards and claim lives.

In step 2, a subsequent detailed and site-specific analysis of the hazard within the active depositional area was characterized. The multi-temporal aerial images and oblique aerial photographs clearly illustrate the typical morphology of an alluvial-fan landform where the village is situated. The landform is a section of stream gradient where long-term channel migration and sediment accumulation became markedly less confined than upstream. Below, gradients of the lower part of the older alluvial fan are gentler than those at the fan apex, as was noted from the wider spacing of contour lines in Figures 15 and 16. The topographic apex of this active alluvial fan was located at the point where the flow in the stream channel become unconfined and less certain, and thus is coincident with the hydrological apex.

The results of the resistivity survey investigated along the lines NK 01 – NK 05 (Fig. 18) to identify the local three-dimensional geology (thickness and depth of the older alluvial deposits), revealed four sedimentary units at a total depth of less than 100 m below the ground surface. The lowest unit was semi-unconsolidated sediments or weathered rocks of at least 70 m thick to the west with the bed top at a depth of about 30 m below ground surface (Fig. 18), and much thinner, less than 10 m to the east, with the bed top be noted at a depth of about 80 m below the ground surface. The overlying second unit was semi-unconsolidated sediments with trapped water in the bed openings. Thickness was 25-70 m and increased to the east. Its shallow horizon was 5 m below ground surface in the west to about 10-20 m to the east. These two lower units are never exposed near the site, but are at surface in the surrounding hills. The third unit was unconsolidated sediments with trapped water. Thickness was in the range of 5-30 m. The thickest part of this third unit was near the NK 03 line in the central part, where the depth to the top of the unit was from a few meters down to 15 m below the ground surface further to the east. The fourth and uppermost unit was of unconsolidated sediments with a thickness of a few meters in the west to 10 m in the east. The fourth unit was commonly exposed on the ground surface along all survey lines, except in the east where it was completely covered by recent topsoils.

Figure 18

A detailed field study of the previous alluvial fan deposits in the fourth unit was conducted along a 5x70 m eroded bank of Nam Ko Yai stream near where the resistivity survey had been performed. Seven stratigraphic profiles were studied to reveal sedimentary sequences in both terms of vertical and lateral stratigraphic correlation. The location map of the measured stratigraphic columns and the line of resistivity survey points are shown in Figure 19 and the actual profiles in Figure 20.

Figure 19

Figure 20

In the observed sections, the lowest sedimentary unit of the older alluvial fan deposits was a debris flow unit of floating texture, unsorted, and un-stratified material that was exposed in the stream-bed only in the eastern part. The coarse-grained fluvial unit of clast-supported texture and fining-upward graded bedding was transitionally deposited on top of the debris flow unit, especially in the middle part, and extended westward (upstream). This coarse-grained fluvial unit was the thickest in the western part and became thinner to the east. The uppermost part of this eroded-bank profile was a fine-grained fluvial and debris flood unit that was dominantly deposited to form a sharp contact on top of the coarse-grained fluvial unit. The uppermost unit is thicker to the east, especially in the eastern part. The representative and complete detailed sedimentary and stratigraphic characteristics in vertical succession are shown in Figure 21, from bottom to top, the debris flow unit, the coarse-grained fluvial unit, and the fine-grained fluvial and debris flood unit, respectively.

Figure 21

The overall interpreted subsurface characteristics of resistivity survey lines generally conformed to the normal alluvial fan deposits. The third sedimentary sequences unit repeated in the resistivity survey should be the same as the older alluvial fan deposits in this eroded bank profile as evidenced from the depth and thickness variation from the west to the east. The upper part of the third unit is clearly of the older fan deposits composing of the coarse-grained fluvial unit, debris flow unit, and fine-grained fluvial and debris flood unit.

Significant evidences of the previous debris floods found in the eastern part of uppermost fine-grained fluvial and debris flood unit were two preserved wooden debris fragments, one at the lower part (location PLW) and the other at the upper part (location PUW) as shown in Figure 22. These preserved wooden debris were dated by radiocarbon dating method to have the absolute ages of deposition between 2,618 +/-35 years before present and post-1950, respectively. From these radioactive dating results, it is strongly confirmed that this is an active alluvial fan and that debris flow-flood process had occurred at least twice before the 8/11disastrous event.

Figure 22

Debris flow-flood event reconstruction

The results of the study methods were used to reconstruct the 8/11 event as follows.

The debris flow probably began as a shallow circular landslide on the western and northern steep mountain slopes of Nam Ko Yai sub-catchment after a continuous heavy rainfall period for at least 10 days (before 8/11) that weakened the material with the increasing weight. It thus became highly movable down-slope. The colluvial soils and rock debris of Pw Formation and Pk Formation flew down the forest-covered 30° (or steeper) slopes from a high elevation (800-1,500 m) during the peak of heavy rainfall. This could be the primary source area for the debris (Fig. 23). The debris flow continued further over the central undulated valley area to the main channel of Nam Ko Yai stream. As Nam Ko Yai sub-catchment plain was extensively deforested during the last decade with only few trees left over its overbank flat land, the large quantity of plant debris observed must have come from the upslopes. The debris flow was capable of exerting tremendous lateral forces on obstruction in the flow path, as evidenced from the impact of entrained, large boulders in the highest velocity along the main channels of the first order and second order sub-catchments in the steep slope areas.

These high velocity flows severely snapped off a large number of trees, removed trunks from hillsides and over channels, and mixed with re-eroded soils of the detached-landslides at the steep banks down along the main channels to the central area of moderate-to-gentle slope. This could be the potential secondary source area (Fig. 23) where debris incorporated into the primary debris flows to form a significant volume through the run-out zone or transport zone of the sub-catchment.

Figure 23

With supporting study results on the soil engineering properties, the highly weathered rocks of Ls Formation with its thick residual or colluvial soils appeared to influence the slope failures on the hillsides and debris flows in the channels. These almost undrained clayey soils with increasing load pressure and less internal shear strength would have caused the mass movement beyond the critical load pressure.

Additionally, the previously-mentioned physical nature of the source areas and run-out zones to the flow-flood occurrence, the amount and intensity of precipitation falling, steep hill slopes and long-running sinusoidal stream channel were key factors as well. Ten days of continuous rainfall to the cumulative peak on 8/11 triggered the landslides and flow-flood in these zones of weak materials.

During these landslides and the flow- flood processes, a temporary natural dam might have built up somewhere in the causeway of this stream, most probably near Tad Fa waterfall. The temporary natural dam could have been formed when debris of plant remains, trees, soils and boulders both from several previous and the 8/11 events were locked at this specific location, forming a reservoir upstream. Then another powerful debris flow-flood followed to break this dam, perhaps with surges up to 10 m high to send water and debris flowing further down to destroy the village on the alluvial fan.

After this serious debris flow-flood occurrence in the year 2001 that completely traversed and removed the former sediments along the channels, it should take many more years to let the factor conditions to build up again. The plant debris and sediments are reduced at present. The relatively higher amount of rainfall in the following year 2002 in the same area did not result in a serious flow-flood event except a mild flash flood.

Figure 24

Conclusion

The disastrous 8/11 debris flow-flood event was not the work of the unusual high amount of rainfall alone, as previously theorized. Instead it was the work of combined factors from the steep terrain characteristics underlain by specific soils with natural moisture close to the liquid limit that could not be drained, and with specific land cover with time-delay for accumulation of debris and sediments. This combination of factors could also cause debris flow-flood accompanied with a high amount of precipitation. The damage could be made greater by a temporary natural landslide dam forming at locations within the stream course, followed by destruction of the dam under the weight of impounded water. The areas down below, especially the settlements on the distinctive alluvial fan, will always be in danger if no proper caution or preinvestigation is employed.

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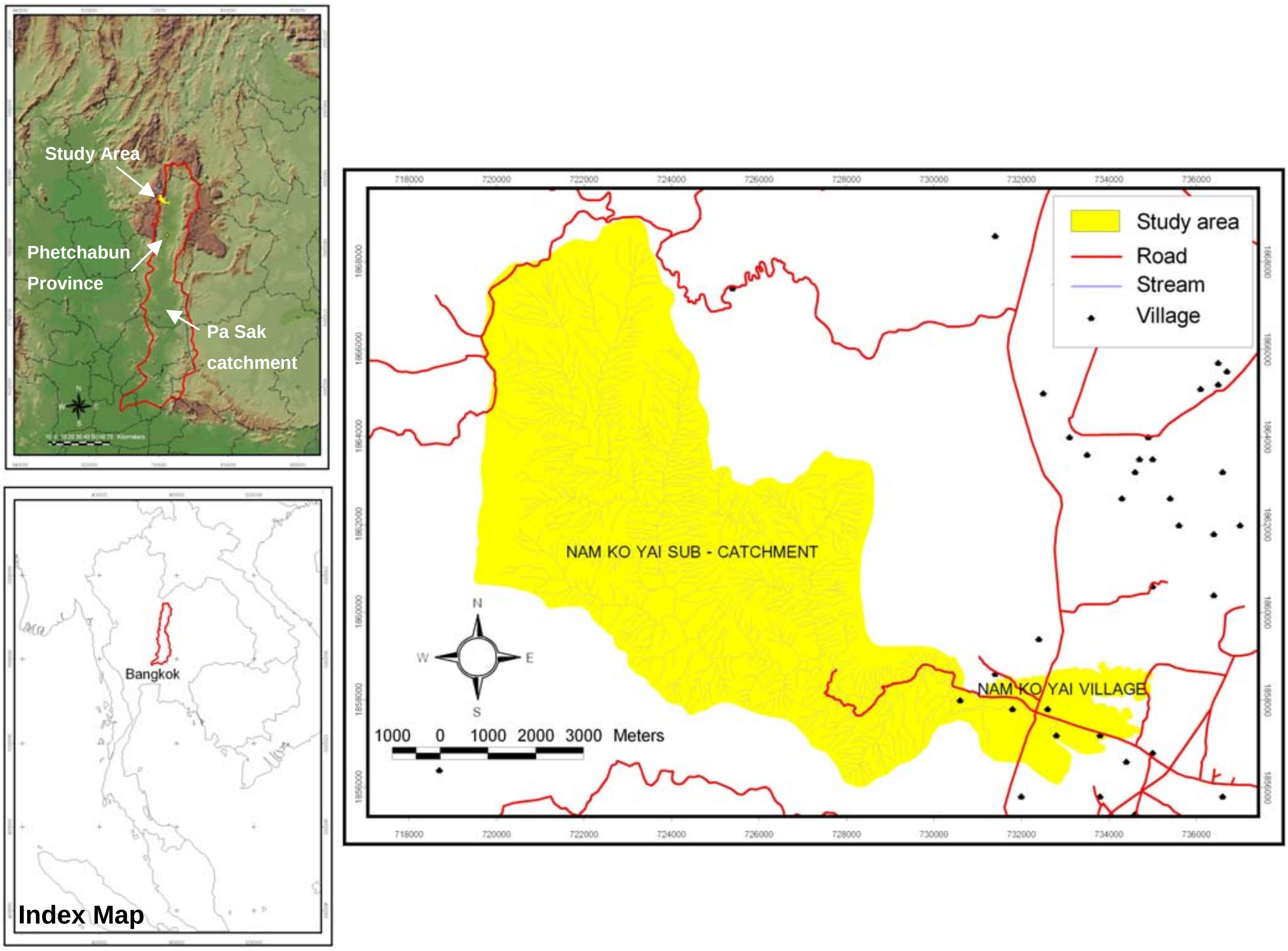


Fig. 2 Geographical location map of the study area in Pa Sak catchment, central Thailand. The coordinates are according to the Universal Transverse Mercater projection with 47 North Zone in Indian 1975 ellipsoid

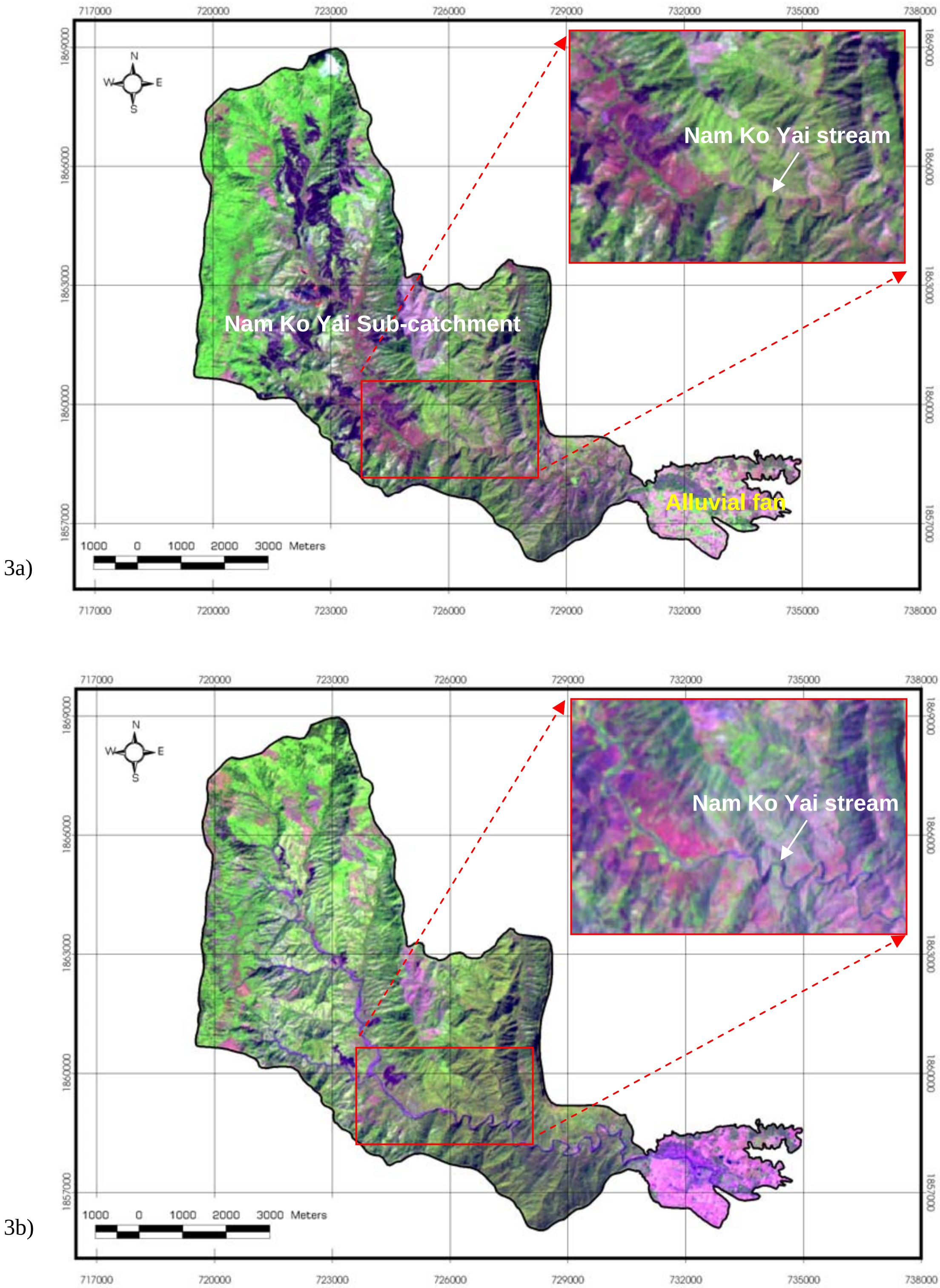


Fig. 3 3a) False color composite of Landsat 7 ETM+ (R=5, G=4, B=3) of the study area acquired on 5 January 2001 (before the debris flow and debris flood occurrence); and
3b) false color composite of Landsat 7 ETM+ (R=5, G=4, B=3) of the study area acquired on 21 November 2001 (after the occurrence) that show the distinctively changed features, especially in the main channels of Nam Ko Yai stream and its alluvial fan just below the canyon mouth

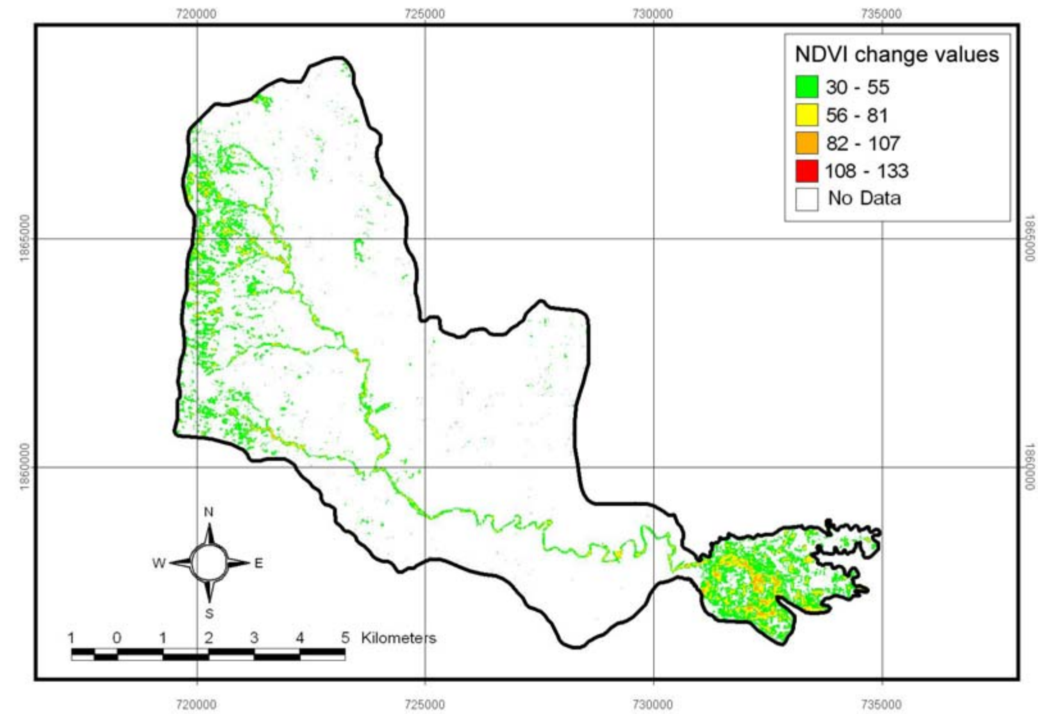
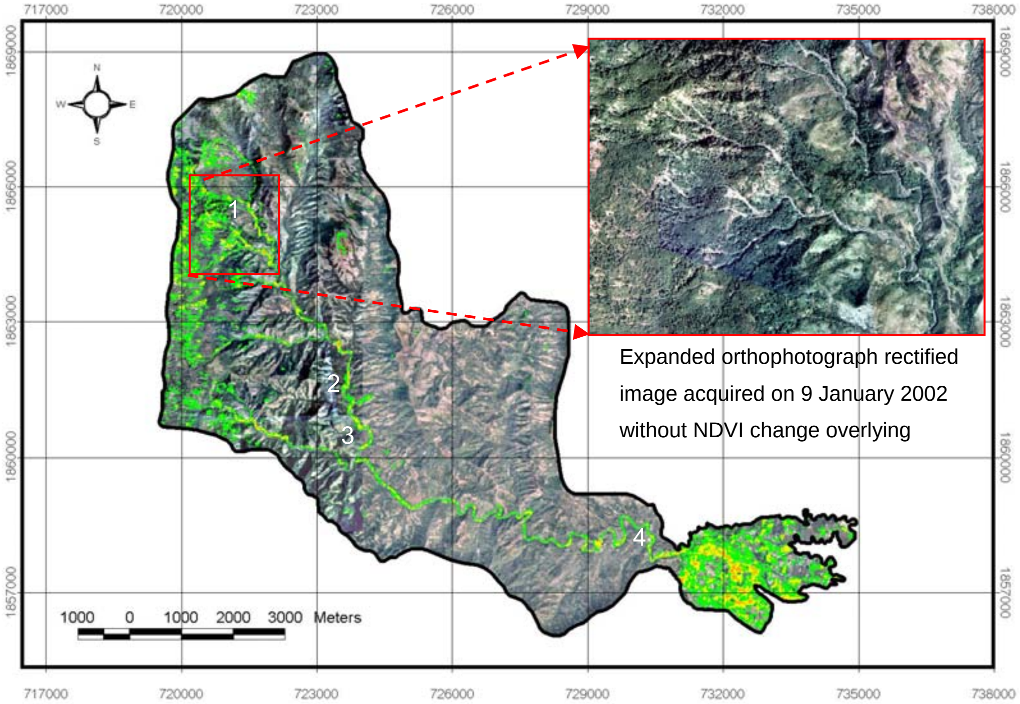


Fig. 4 The resulted significant change detection of NDVI showing scar-scouring and depositional locations in Nam Ko Yai sub-catchment and its alluvial fan that are caused from the 8/11debris flow-flood occurrence

5a)



5b)

Fig. 5 5a) The significant change of NDVI (from Fig. 4) overlain on the orthophotograph rectified image acquired on 9 January 2002 (after the debris flow-flood occurrence); and 5b) the photographs of four locations (number referred to the location in the map) taken a few days in Nam Ko Yai sub-catchment after the 8/11 event showing the ground truth evidences

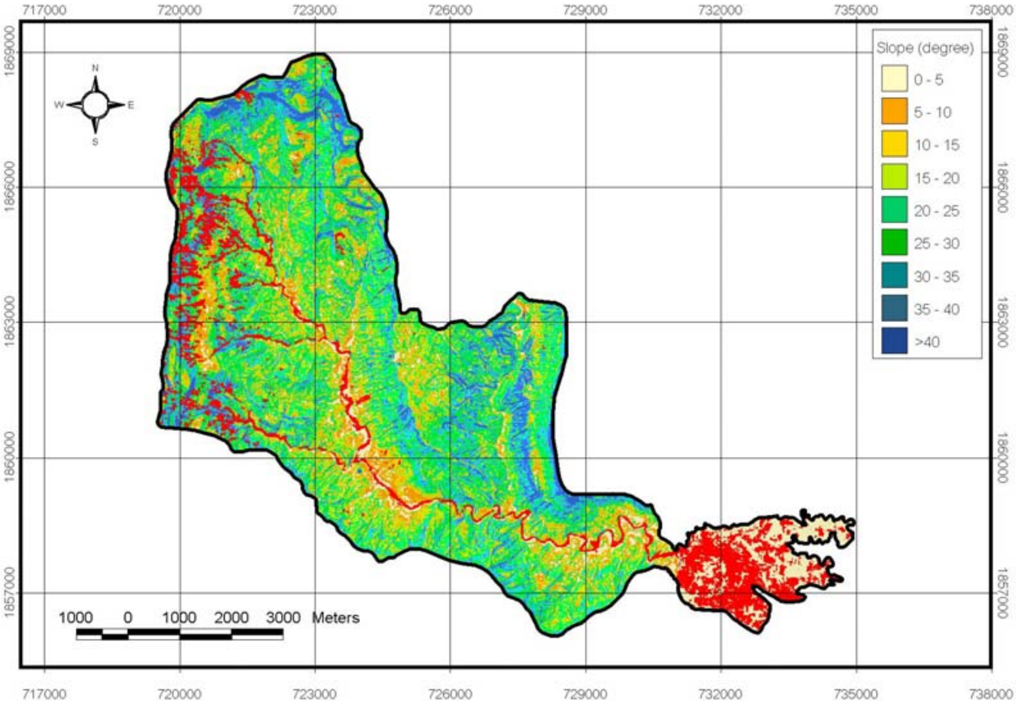


Fig. 6 Slope map overlain with scars-scouring and depositional locations (in red) in the study area

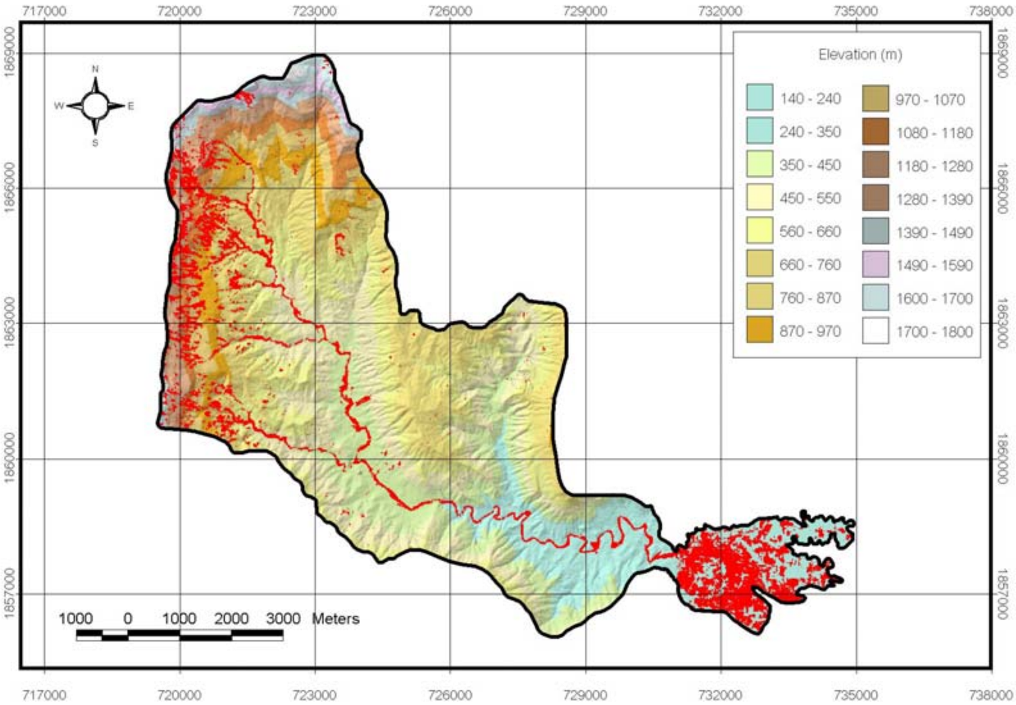


Fig. 7 Elevation map overlain with scar-scouring and depositional locations (in red) in the study area

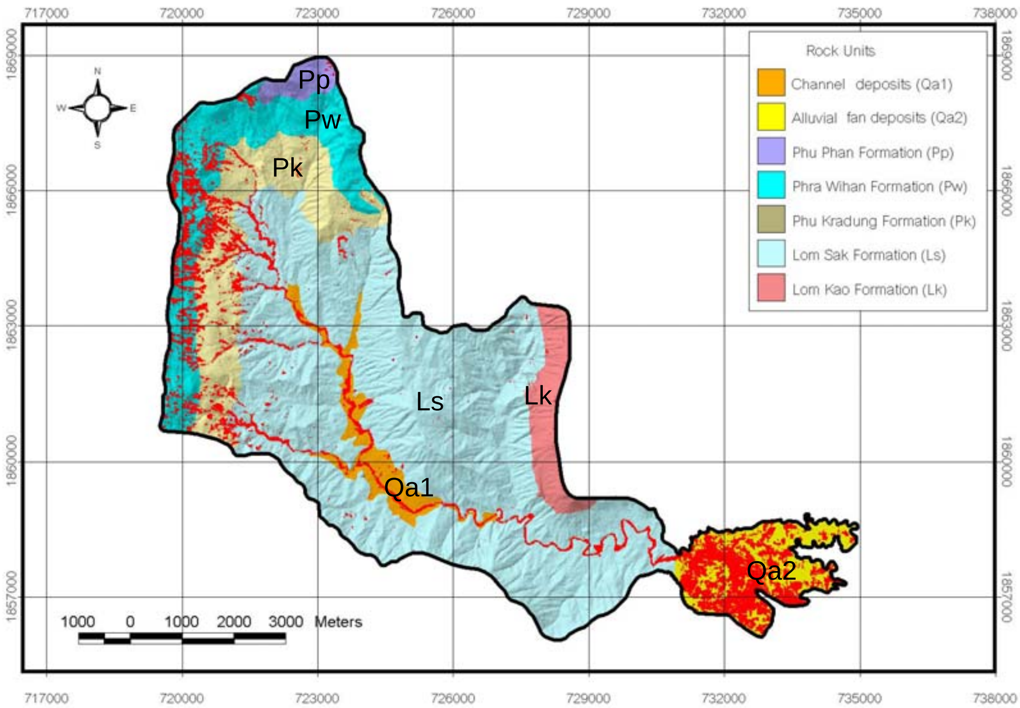


Fig. 8 Rock unit map overlain with scar-scouring and depositional locations (in red) in the study area

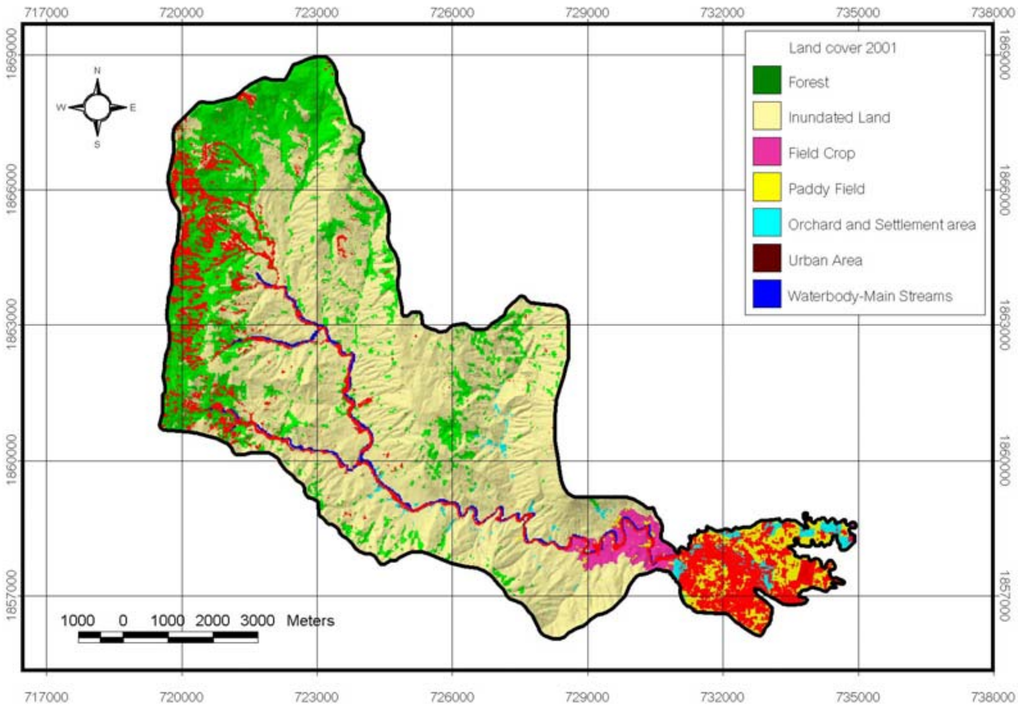


Fig. 9 Land cover map overlain with scar-scouring and depositional locations (in red) in the study area

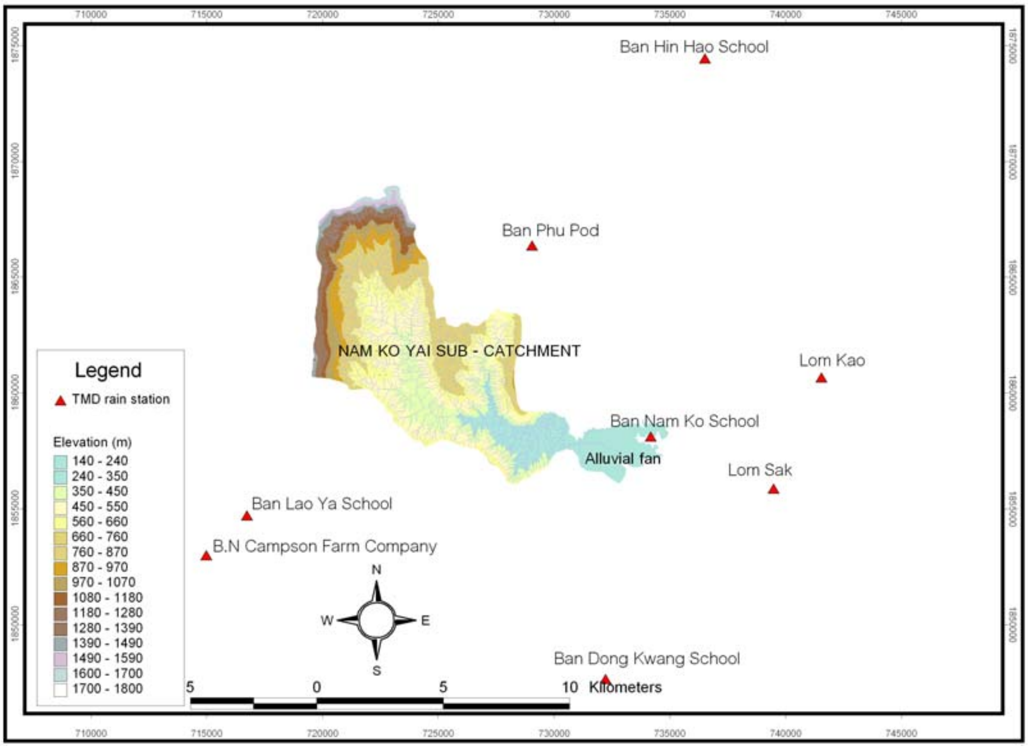


Fig. 10 Location of seven TMD (Thai Meteorological Department) rainfall measurement stations (red triangles) near the study area

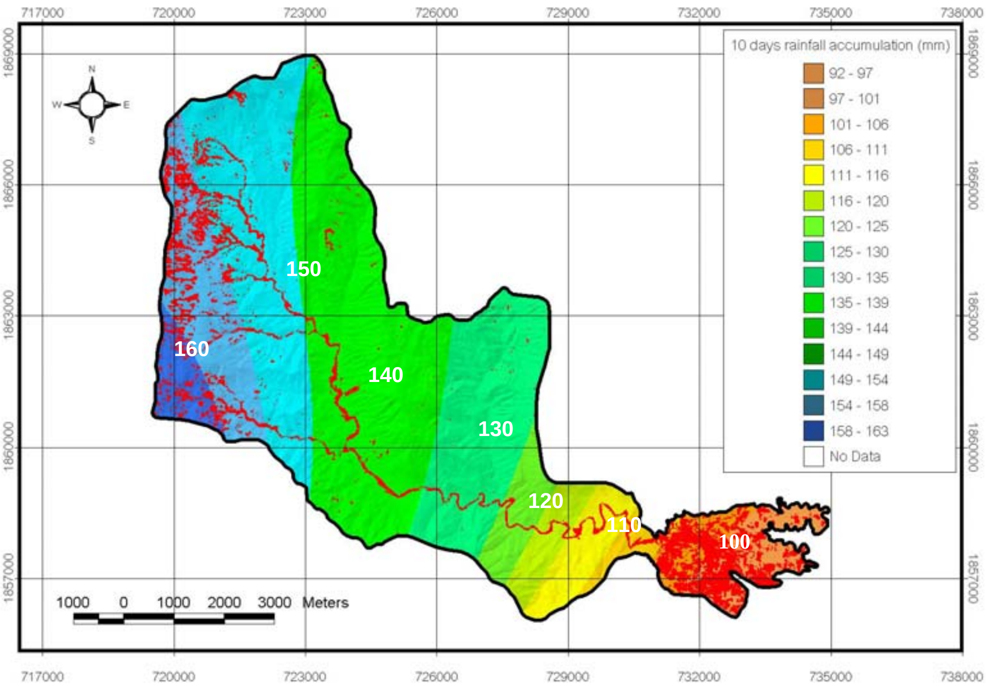


Fig. 11 Rainfall accumulation in the period of 1-10 August 2001 (before the 8/11 debris flow and debris flood occurrence) overlain with scar-scouring and depositional locations (in red) in the study area

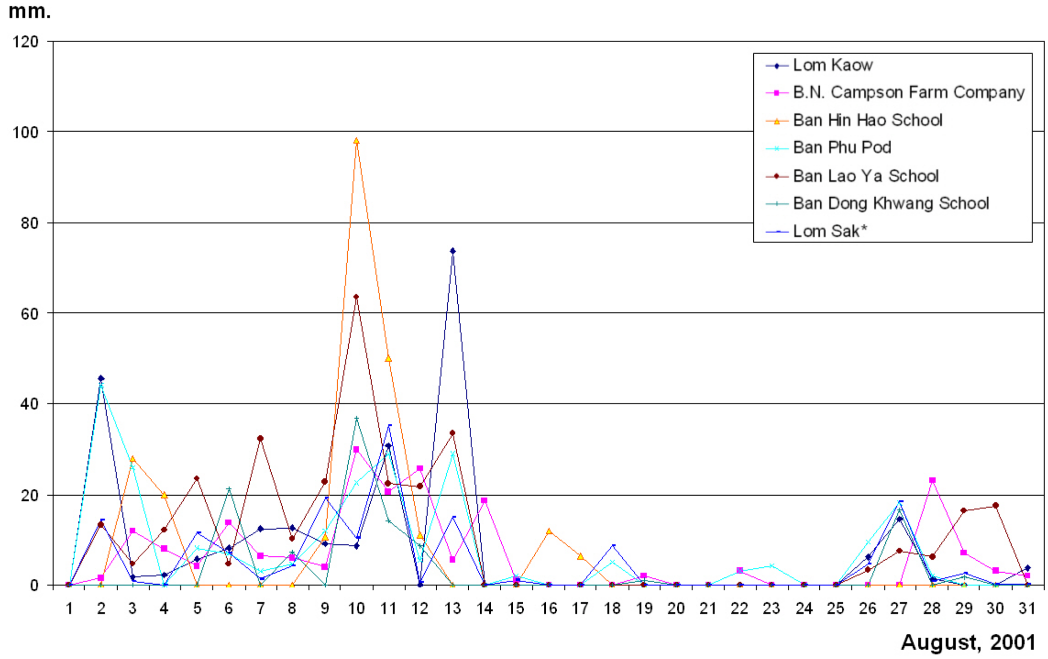


Fig. 12 The graph showing the pattern distribution of rainfall measurements in August 2001 recorded from the seven locations (Fig. 10) near the study area

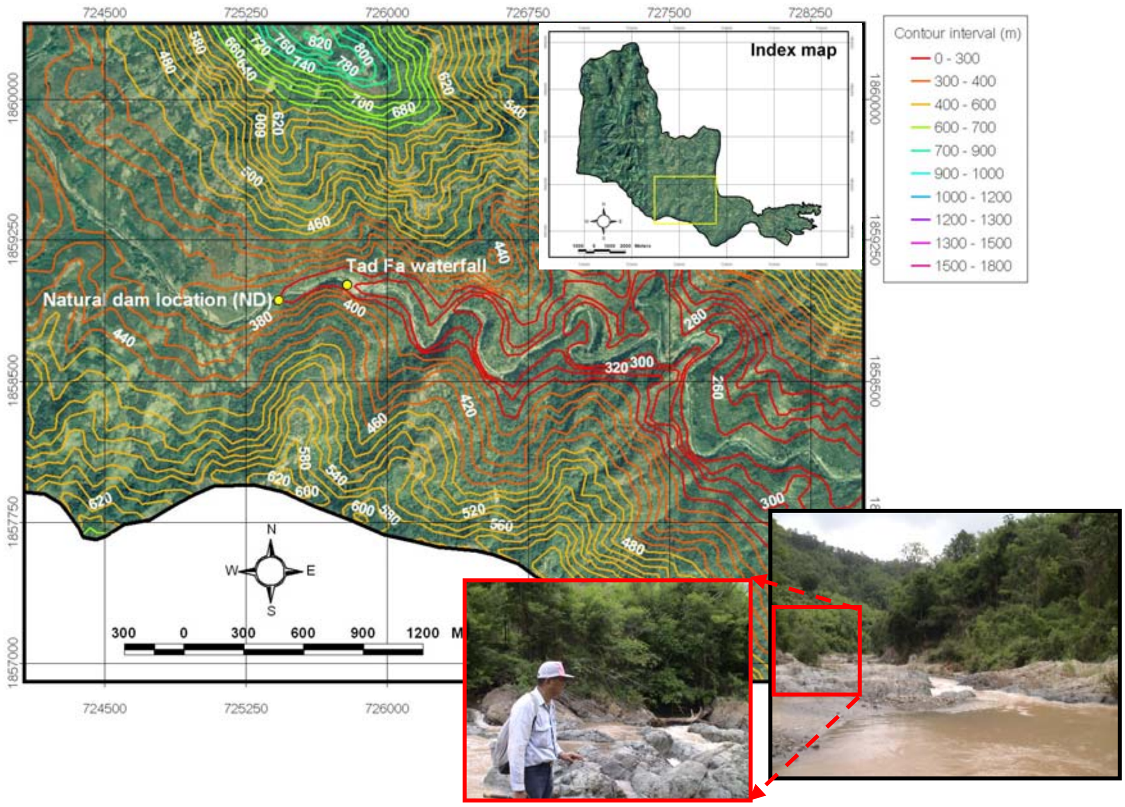


Fig. 13 The orthophotograph rectified image (1:25,000 scale, January 9, 2002 after the 8/11 event) overlain with the contour intervals (20 m) showing the specific configuration of Nam Ko Yai stream located in the lower central part of the study area proposed to be the natural dam location (ND) in front of the location of Tad Fa waterfall

Fig. 14 The oblique aerial photograph (taken on 22 August 2001, 11 days after the event) along the channel of Nam Ko Yai stream with the high sinuosity characteristic illustrating the debris flow-flood track along plant debris and soils had been strongly eroded and transported from its banks before reaching the canyon mouth outlet of the stream

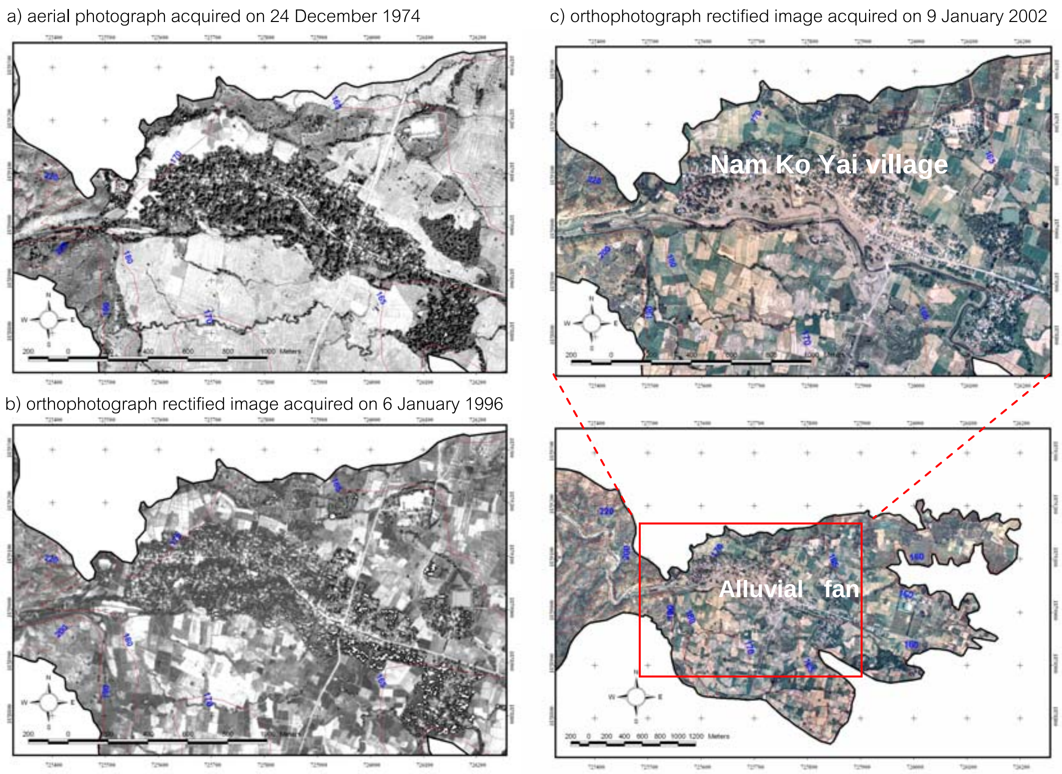


Fig. 15 The multi-temporal low-altitude images of aerial photograph and orthophotograph (with contour intervals in red line) acquired on three different periods: a) 24 December 1974, b) 6 January 1996, and c) 9 January 2002 showing the distinct identification of the topographic apex of Nam Ko Yai stream in the alluvial fan that was slightly modified from 1974 until 1996. Pronounced and still active changes are evident following the 8/11debris flow-flood

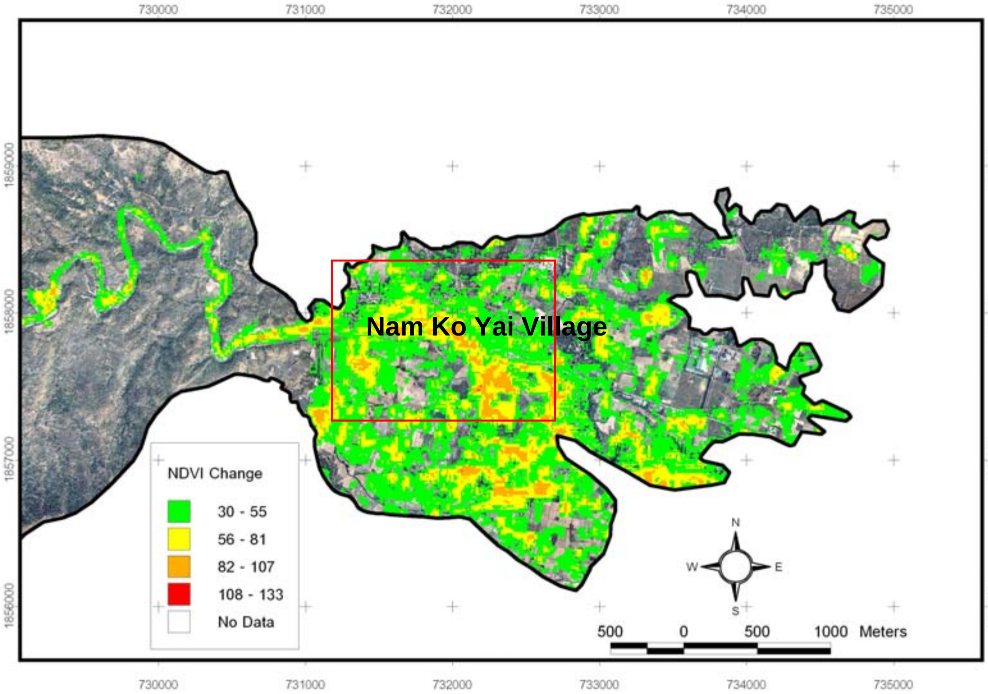


Fig. 16 The detection change of NDVI in the depositional location of the alluvial fan (expanded from Fig. 4) overlain on the orthophotograph rectified image (1:25,000 scale) acquired on 9 January 2002. The brown-colored zones are new traces of fan deposit after 1996

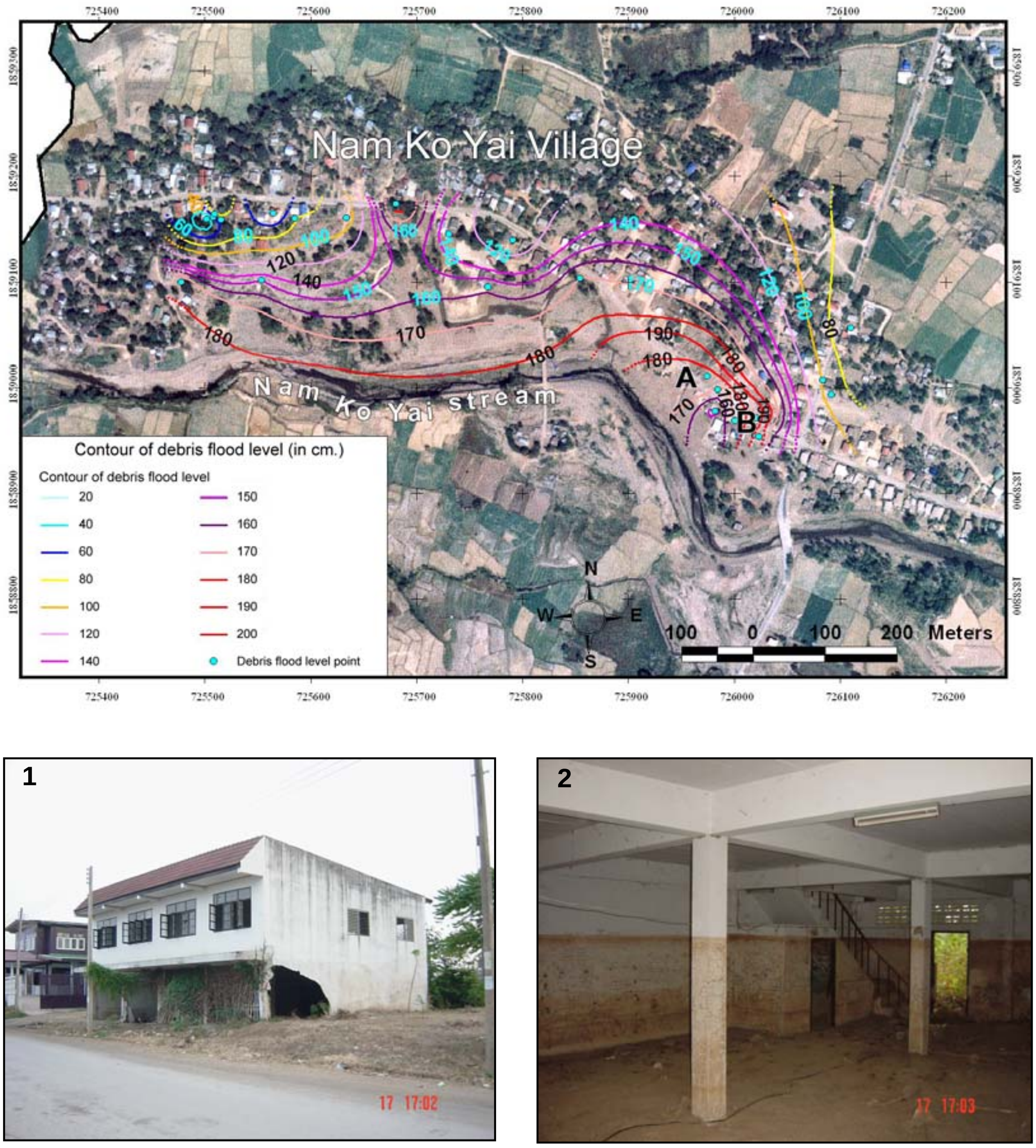


Fig. 17 The expanded orthophotograph rectified image (1:25,000 scale) acquired on 9 January 2002 (red outline in Fig. 16) showing the contours of debris flood levels (in cm) above the ground surface (detected from the thin brown film left at house-walls and trees) in the strongly damaged area of Nam Ko Yai village caused by the 8/11 debris flow-flood

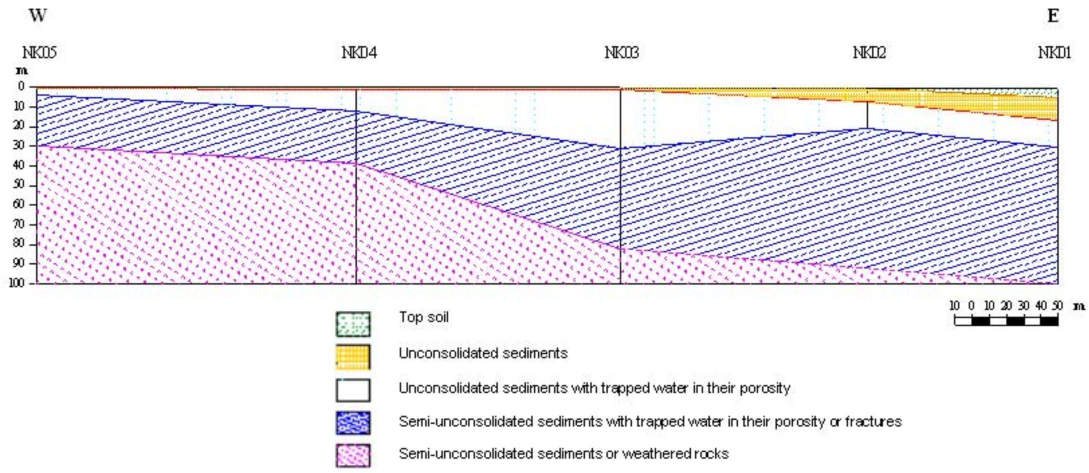


Fig. 18 The cross-section of the resistivity survey interpreted from the five survey points (NK 01 – NK 05 as shown in Fig. 19) that revealed four sedimentary units lying less than 100 m below ground surface

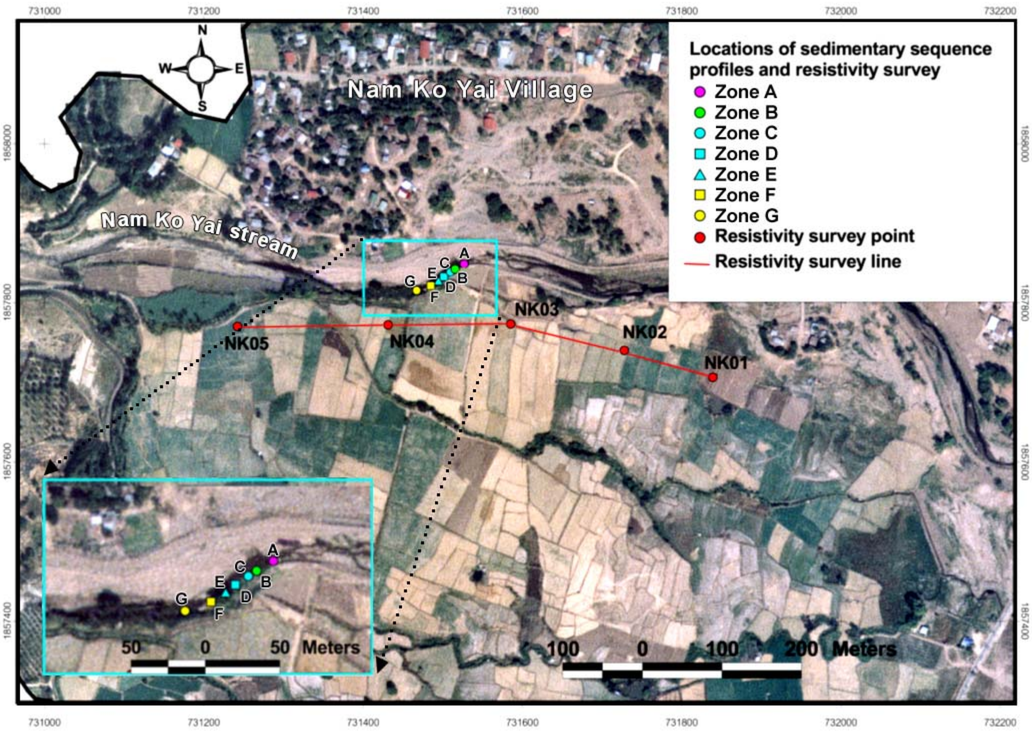


Fig. 19 The location map of seven measured stratigraphic profiles (A, B, C, D, E, F, G) along the eroded bank of Nam Ko Yai stream, and a line of five resistivity survey points (NK01 – NK05) used for investigating the stratigraphy, sedimentology and subsurface geology of the older alluvial fan deposits

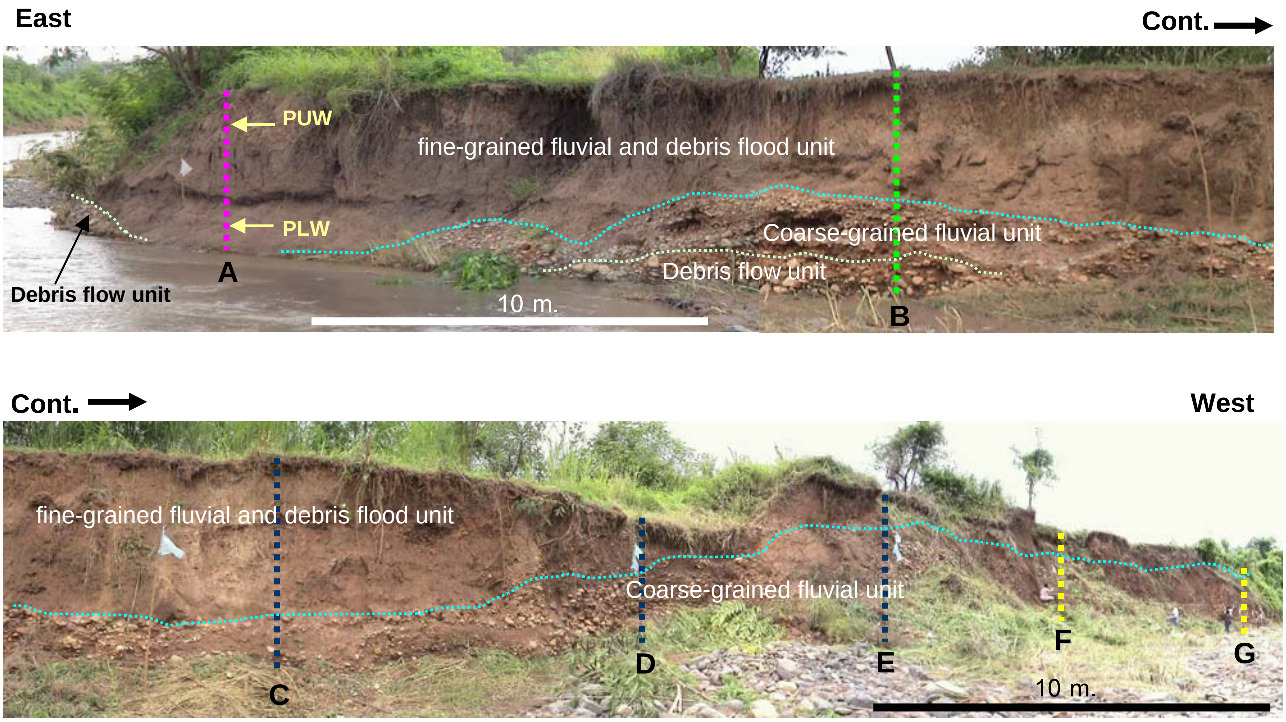


Fig. 20 The lateral and vertical stratigraphic characteristics of debris flow and debris flood deposits of older alluvial fan along the eroded-bank of Nam Ko Yai stream with the locations of those seven measured stratigraphic profiles (A, B, C, D, E, F, G)

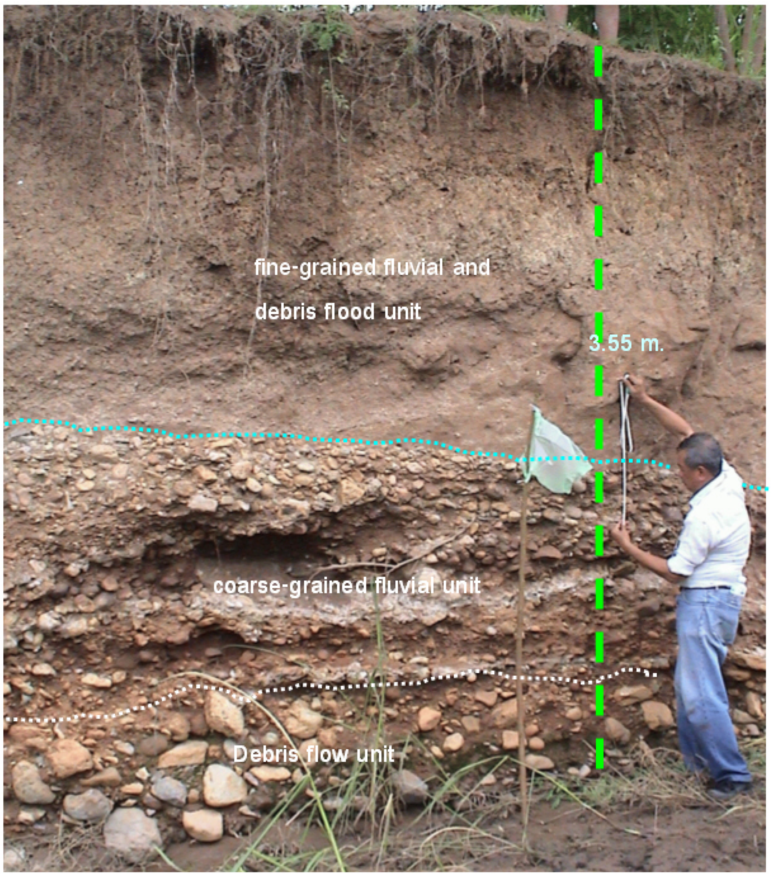


Fig. 21 The measured stratigraphic profile B showing the debris flow unit underlain by the coarse-grained fluvial unit with the transitional contact, and the uppermost fine-grained fluvial and debris flood unit overlying on top of the coarse-grained fluvial unit with a sharp contact

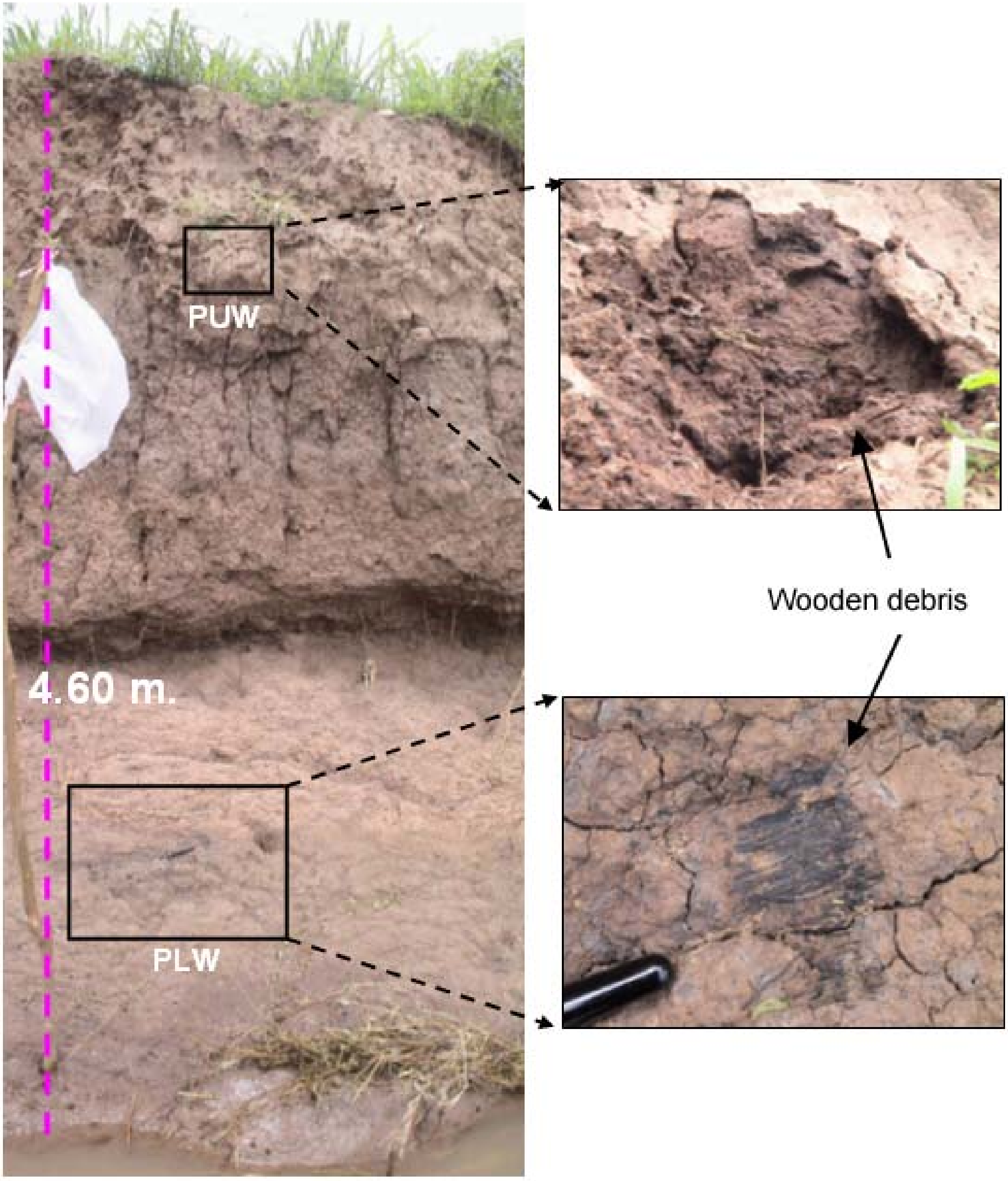


Fig. 22 The measured stratigraphic profile of the uppermost fine-grained fluvial and debris flood unit illustrating its general characteristics and two locations of preserved wooden debris at the lower part (location PLW) and upper part (location PUW)

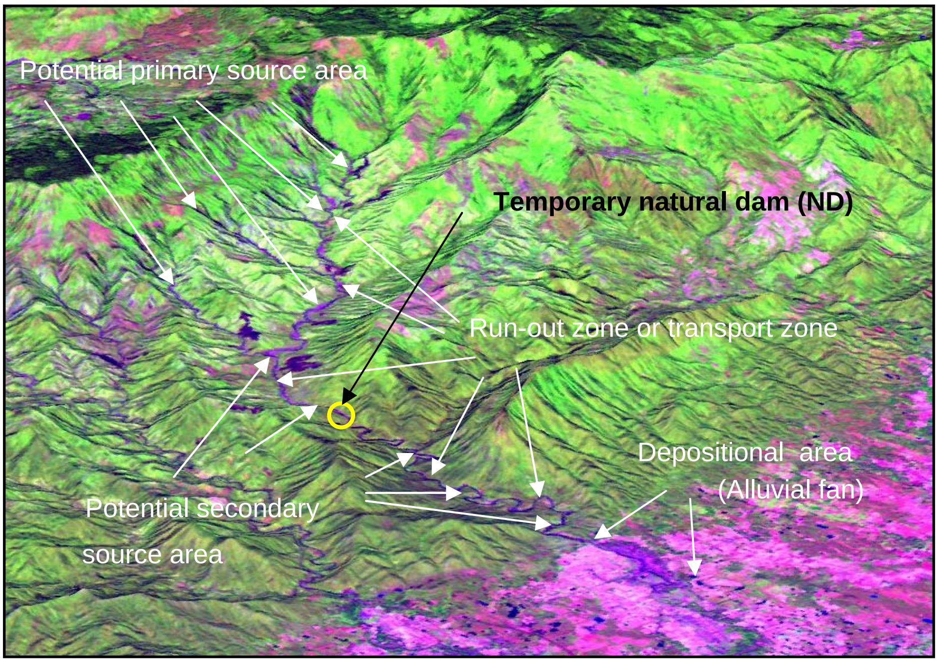


Fig. 23 Three-dimensional view of Nam Ko Yai sub-catchment and its alluvial fan modeled by overlying the false color composite of Landsat 7 ETM+ (R=5, G=4, B=3) acquired on 21November 2001 through the base-scale DEM showing the main features after the debris-flood occurrence with identified potential hazard zones of the potential primary and secondary source areas, the run-out zone or transport area, the proposed location of a temporary natural dam, and the depositional area

Table 1 Overview of the important input data themes discussed

Main theme	Sub theme	Made through
A. Debris flow and debris flood inventory map	A1. Scar-scouring & depositional locations	Multi-temporal image interpretation, Multi-temporal image classification, Field investigation
B. Geomorphological map	B1. Digital Elevation Model (DEM)	Topographic map, Existing photogrammetric-elevation data
	B2. Slope	With GIS from a DEM
	B4. Topographic shape	With GIS from a DEM ,Image interpretation, Field investigation
D. Geological map	D1. Rock unit	Existing geological map, Image interpretation, Field investigation
E. Soil map	E1. Soil unit	Existing soil properties map, Field investigation
	E2. Soil thickness	Existing soil properties map, Field investigation
F Land cover map	F1. Land cover	Multi-temporal image interpretation, Multi-temporal image classification, Field investigation
G. Hydrological map	G1. Sub-catchment characteristics	Topographic maps, DEM extraction, Field mapping
	G2. Drainage network	Topographic maps, DEM extraction
	G4. Rainfall intensity	Existing information, Inflow hydrograph analysis
H. Elements at risk map	H1.Settlement area	Image interpretation, Field investigation

1a)

1b)

Fig. 1 1a) Two oblique aerial photographs perceivably illustrating the characteristics and extension of a large volume of deposited sediments; and 1b) four closed-up photographs illustrating the seriously battered structural damage of houses, orchard trees and other infrastructures in Nam Ko Yai village caused by the fast-moving debris flow-flood occurrence on 11 August 2001 (8/11)

Table 2 The analytical results of some important soil engineering properties of the six soil samples collected from the weathered natural zone of volcanic complex of Lom Sak Formation (Ls) in the study area

Sample No.	Location	Percent Finer #200 (% clay and silt)	Natural Water Content, w_N	Plastic Limit, w_P	Liquid Limit, w_L	Plastic Index, PI = w_L-w_P	Activity, A = PI/%Clay)	Liquidity Index, LI = (w_N-w_P)/PI	C_u	Soil Type			Shear Strength (kPa)
										1*	2*	3*	
2-B	47 Q 0723290/ UTM 1860028	67.6	27.0	20.8	40.5	19.7	0.76	0.31	>5	Clay	CL	A-7-6 (Clayey soils)	40
3-B	47 Q 0723164/ UTM 1860126	87.1	44.9	29.2	54.6	25.4	0.53	0.62	>5	Clay	CH	A-7-6 (Clayey soils)	10
6-B	47 Q 0722980/ UTM 1860132	87.4	33.8	30.6	54.9	24.2	0.53	0.13	>5	Clay	CH	A-7-6 (Clayey soils)	93
7-B	47 Q 0722937/ UTM 1860140	77.3	34.4	25.4	45.6	20. 2	0.67	0.44	>5	Clay	CL	A-7-6 (Clayey soils)	22
10-B	47 Q 0722609/ UTM 1860196	62.0	26.7	24.7	38.4	13.7	0.62	0.15	>5	Clay sand	CL	A-6 (Clayey soils)	87
1-A	47 Q 0728840/ UTM 1858259	38.1	21.8	17.4	24.20	6.8	0.31	0.65	>5	Clay sand	ML	A-4 (Silty soil)	9

Note:

1. Classification of The Mississippi River Commission
2. Classification of of Unified Soil Classification System

   CL – inorganic clays of low to medium plasticity, gravelly clay, sandy clays, silty clays, lean clays.

   CH – inorganic clays of high plasticity, fat clays

   ML – inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plassticity.
3. AASHTO Soil Classification System