DEBRIS FLOW MODELLING AND EARLY WARNING SYSTEM FOR DISASTER RISK REDUCTION IN KUNDASANG AREA, SABAH

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DEDICATION

This thesis is dedicated to my father, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my mother, who taught me that even the largest task can be accomplished if it is done one step at a time.

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ABSTRACT

Landslides are recurring geological disasters resulted in many human- and economic losses, even so with the rapid urbanization and extreme climate. Approximately, 21,000 landslides – debris flows were recorded in Malaysia. There are many uncertainties in the underlying root causes, understanding triggering factors, and ways to reduce local risk in a changing environment. Even more challenging to prepare a cost-effective Early Warning System (EWS) and to enhance resilient communities in a tectonically active region. This study aims to develop an integrated framework for debris flow EWS with the case study in Mesilau watershed, Kundasang, Sabah. These are the three objectives; (i) to map and characterize the debris flow induced by the 2015 Ranau earthquake, (ii) to model and simulate the debris flow runout, and (iii) to develop an integrated framework for debris flow EWS, in supporting local disaster risk reduction and resilience strategy. The study started by characterizing the watershed and landslide areas using the Geographic Information System. The results showed that the earthquake stripped at least 1.44 km^2 of vegetation cover within the upstream of Mesilau watershed, and increased the Stripped Earth Material (SEM) by 1.32 km^2. Thus, the increased SEM contributed to the temporary landslide damming formation. Next, critical rainfall, discharge, and hydrographs were extracted using the empirical method, and Hydrological Modelling System to understand the triggering factor for debris flow event. The extractions suggested the breaching of temporary landslide dam was due to the rainfall intensity of 14.2 mm/h, and 7-days critical rainfall that exceeded 66.3 mm. Hence, remobilized the temporary landslide dam, and initiated the debris flow that travelled for 18.6 km to Liwagu Dam, Ranau town. The extracted parameters were imported into the HyperKANAKO software to model and simulate the best-fit debris flow runout. The obtained best-fit debris flow runout was utilized to estimate the debris flow velocity and the lead time to evacuate. The best-fit simulation results suggested that the debris flow velocity as 12.5 m/s, with the suitable discharge at 550 m^3/s. The result indicates that the required lead time for the community to evacuate is 4.5 min before the debris flow arrives at Mesilau village. These simulation results were validated through the field evidence, image correlations, expert and local judgments. Subsequently, the debris flow EWS was designed by referring to the TAKUWA's guideline. All the obtained scientific results were then used to gain societal inputs by understanding demands and needs for people-centered EWS via structured EWS surveys and open-ended interviews. The societal inputs highlight that the EWS is critically needed for Mesilau watershed, as the area is prone to the earthquake and cascading geohazards (i.e., debris flows). In conclusion, the proposed integrated framework for debris flow EWS is aligned to Malaysia's commitment to increase the access to multi-hazard EWS and disaster risk information (Target G) of the Sendai Framework for Disaster Risk Reduction 2015 – 2030.

ABSTRAK

Tanah runtuh adalah bencana geologi berkala, yang mengakibatkan kehilangan nyawa, dan kerugian ekonomi, ditambah lagi dengan pembandaran yang pesat, dan iklim yang melampau. Hampir 21,000 tanah runtuh – aliran debris telah direkodkan di Malaysia. Terdapat banyak ketidaktentuan berkenaan punca asas, pemahaman faktor pencetus, dan kaedah pengurangan risiko setempat di dalam persekitaran yang berubah. Bahkan lebih mencabar untuk menyediakan Sistem Amaran Awal (EWS) dengan penjimatan kos, dan untuk meningkatkan daya tahan komuniti di persekitaran tektonik aktif. Kajian ini bertujuan untuk menghasilkan satu kerangka bersepadu EWS aliran debris, dengan kajian kes di lembangan Mesilau, Kundasang, Sabah. Tiga objektif disenaraikan; (i) untuk memetakan dan mencirikan aliran debris yang disebabkan oleh gempa bumi Ranau 2015, (ii) untuk membuat model dan simulasi aliran debris, dan (iii) untuk menghasilkan kerangka bersepadu EWS aliran debris, bagi menyokong pengurangan risiko bencana setempat, dan strategi berdaya tahan. Kajian dimulakan dengan pencirian lembangan dan tanah runtuh dengan menggunakan Sistem Maklumat Geografi. Hasil kajian mendapati gempa bumi telah memusnahkan 1.44 km^2 litupan tumbuhan di kawasan hulu lembangan, dan telah meningkatkan Bahan Bumi Terlucut (SEM) sebanyak 1.32 km^2. Peningkatan SEM telah menyumbang kepada pembentukan empangan tanah runtuh sementara. Seterusnya, hujan kritikal, aliran air, dan hidrograf diekstrak menggunakan kaedah empirikal dan Sistem Pemodelan Hidrologi bagi memahami faktor pencetus aliran debris. Pengekstrakan hujan mencadangkan keruntuhan empangan tanah runtuh sementara adalah disebabkan oleh intensiti hujan sebanyak 14.2 mm/j, dan hujan kritikal selama 7 hari yang melebihi 66.3 mm. Justeru itu, menggerakkan empangan tanah runtuh sementara dan menghasilkan aliran debris sepanjang 18.6 km ke empangan Liwagu, Pekan Ranau. Parameter yang terhasil dimasukkan ke dalam perisian HyperKANAKO bagi memodelkan dan mensimulasikan aliran debris yang terbaik. Hasil simulasi yang terbaik kemudiannya digunakan bagi mengganggarkan halaju aliran debris dan masa evakuasi yang diperlukan. Hasil simulasi terbaik mencadangkan halaju aliran debris adalah 12.5 m/s, dengan bacaan aliran air 550 m^3/s. Hasil kajian juga menunjukkan masa evakuasi yang diperlukan oleh komuniti adalah 4.5 minit sebelum aliran debris tiba di Kampung Mesilau. Simulasi ini dibuktikan melalui bukti lapangan, korelasi imej, penilaian pakar dan tempatan. Seterusnya, reka bentuk EWS aliran debris dibina dengan merujuk kepada panduan TAKUWA. Kesemua hasil kajian saintifik yang terhasil digunapakai bagi mendapatkan input masyarakat dengan memahami tuntutan dan keperluan EWS berasaskan komuniti melalui kaji selidik EWS berstruktur, dan temu ramah. Input sosial menunjukkan bahawa EWS aliran debris amat diperlukan bagi lembangan Mesilau kerana ia terdedah kepada gempa bumi dan bencana susulan (aliran debris). Kesimpulannya, kerangka kerja bersepadu EWS aliran debris seperti yang dicadangkan adalah seiring dengan komitmen Malaysia bagi meningkatkan akses kepada EWS pelbagai bahaya, dan maklumat risiko bencana (Sasaran G) Kerangka Sendai Pengurangan Risiko Bencana 2015 – 2030.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

1D	-	1-Dimensional
2D	-	2-Dimensional
3D	-	3-Dimensional
AGS	-	Australian Geomechanics Society
BN	-	Bayesian Network
CMD	-	Command-line Interpreter
CS	-	Cross-Section
DEM	-	Digital Elevation Model
DPPC	-	Disaster Prevention and Preparedness Centre
DRR	-	Disaster Risk Reduction
DSM	-	Digital Surface Model
DTM	-	Digital Terrain Model
EM-DAT	-	International Disaster Database
EWS	-	Early Warning System
FCC	-	False Colour Composite
FOV	-	Field of View
GIS	-	Geographic Information System
GLC	-	Global Landslide Catalog
GPS	-	Global Positioning System
HDD	-	Hard Disk Drive
HEC-GeoHMS	-	Hydrologic Engineering Centre's Geospatial Hydrologic Modelling
HFA	-	Hyogo Framework for Action
HiCBDRR	-	High-Impact Community-based Disaster Risk Reduction
HRDEM	-	High Resolution Digital Elevation Model
IDNDR	-	International Decade for Natural Disaster Reduction
IDRM	-	International Workshop and Field Practice on Disaster Risk Reduction
IDW	-	Inverse Distance Weighted
IFSAR	-	Interferometric Synthetic Aperture Radar
IGI	-	Integrated Geospatial Innovation
ISDR	-	International Strategy for Disaster Risk Reduction
JICA	-	Japan International Corporation Agency
JMG	-	*Jabatan Mineral dan Geosains*
LEWS	-	Landslide Early Warning System
LiDAR	-	Light Detection and Ranging
LR	-	Long-Range
MACRES	-	Malaysian Centre of Remote Sensing
MEA	-	Ministry of Economic Affair
MLC	-	Maximum Likelihood Classification
MMD	-	Malaysian Meteorological Department
MNR	-	Mesilau Nature Resort
Mw	-	Magnitude Weight

NADMA	-	National Disaster Management Agency
NASA	-	National Aeronautics and Space Administration
NDMO	-	National Disaster Management Office
NDVI	-	Normalized Different Vegetation Index
NGO	-	Non-Governmental Organization
NIR	-	Near Infrared
NNC	-	Nearest Neighbour Classification
NSC	-	National Security Council
OBIA	-	Object-based Image Analysis
PBRC	-	*Pemetaan Bahaya dan Risiko Cerun*
PFA	-	Probability of False Alarm
POD	-	Probability of Detection
PWD	-	Public Work Department
RAM	-	Random Access Memory
RVI	-	Ratio Vegetation Index
SDGs	-	Sustainable Development Goal
SEM	-	Stripped Earth Material
SFDRR	-	Sendai Framework for Disaster Risk Reduction
SPSS	-	Statistical Package for Social Sciences
SSD	-	Solid State Drive
SSL	-	Sutera Sanctuary Lodge
STDRR	-	Science and Technology for Disaster Risk Reduction
TB	-	Terrabyte
TINs	-	Triangulation Irregular Network
TLS	-	Terrestrial Laser Scanning
TWI	-	Terrain Wetness Index
UNDRR	-	United Nation for Disaster Risk Reduction
UNESCO	-	United Nations Educational, Scientific and Cultural Organization
USGS	-	United State Geological Survey

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Problem Background

Landslides depicted as one of the recurring geological disasters resulted in many human- and economic losses around the world. The International Disaster Database (EM-DAT) recorded at least 378 cases of major landslides from the year of 1998 until 2017 (CRED, 2018). Approximately, about 4.8 million people were affected, with 18,414 deaths were reported globally (CRED, 2018). Besides, the landslides have been placed as the top five disasters that caused the impacts to the economy and environment with the total loss of 8 billion US dollars (CRED, 2018).

Aside from the EM-DAT, the National Aeronautics and Space Administration (NASA) also published the "Global Landslides Catalogue" (GLC) dated from 2007 until 2017 (Kirschbaum and Stanley, 2018). Statistically, 10,804 cases of landslides were recorded around the world regardless of sizes, impacts or locations. 8,369 from the total landslides have been recorded as zero fatality (white dots), while the colour dots (pink, red and maroon) indicate the total fatalities (Figure 1.1). Both the EM-DAT and NASA databases have proven that the landslide disasters were a serious threat to human life and possibly led to the destruction of properties, and deaths.

Rahman & Mapjabil (2017) highlighted at least 21,000 landslide prone-areas were recorded in Malaysia. Approximately, 76% of landslides were recorded in Peninsular, whereas the remaining 34% was reported in East Malaysia (Figure 1.2). Majority of the landslides were induced by; the rainfall, mass movement, storm, flood, and earthquake to name a few. The examples for the rainfall-induced landslides were such as in; Genting Sempah (1995) (Sum *et al.*, 1996; Abd Rasid, 2006; Chigira *et al.*, 2011), Pos Dipang (1996) (PWD, 2009; Abdullah *et al.*, 2015), and Simunjan (2002) (Hashim and Among, 2003; Singh *et al.*, 2014); mass movement-induced landslide was such as in; Kuala Lumpur (1993) (Gul *et al.*, 2017; Kazmi *et al.*, 2017); storm-induced landslide such as in Keningau (1996) (JICA, 2015); flood-induced landslide in Malacca (2006) (Chan, 2012); and earthquake-induced landslide in Sabah (2015) (Tongkul, 2016; USGS, 2018).

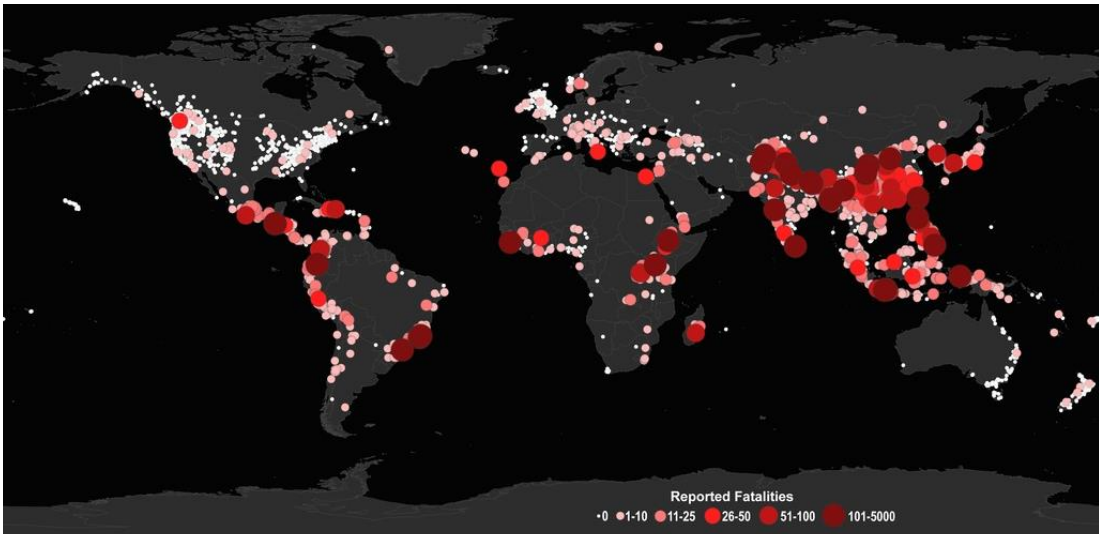

Figure 1.1 Global Landslide Catalogue (GLC) from NASA database that recorded landslides around the world with colours (white, pink, red, maroon) indicating the number of fatalities in the area (Kirschbaum and Stanley, 2018).

Figure 1.2 Landslide-prone areas (red polygon) as depicted in the National Slope Master Plan 2009-2023 (PWD, 2009).

Recently, the Mw 6.0 Ranau earthquake on 5th of June 2015 has been recorded as one of the strongest earthquakes, since Mw 6.2 Lahad Datu earthquake in 1976 (Tongkul, 2016; USGS, 2018). The earthquake was the fatal geophysical related disaster in the recent history of Malaysia. Many cascading geohazards were induced within the vicinity of Mount Kinabalu, the first UNESCO World Heritage Site in Malaysia (Hall *et al.*, 2008; Cottam *et al.*, 2013; Tongkul, 2016; Rosli *et al.*, 2020b). This includes; the rock avalanches, rock falls, landslides, and debris flows. A total of 18 climbers perished due to the rock falls along the summit trail, with 137 others were injured on the summit area (Shah, 2015; Tongkul, 2016; Abd Razak *et al.*, 2018).

The preliminary analysis by Tongkul (2016) suggested at least 1,500 hectares of earth surfaces were stripped off during the earthquake, and produced many earth materials accumulated on the upstream area. Hence, resulted in the formation of the temporary landslide dam that later breached and remobilized as debris flow (Tongkul, 2016; Rosli, 2020a). Two of the determined debris flow areas after the 2015 Ranau earthquake includes; the Mesilau watershed, Kundasang, and Kedamaian watershed, Kota Belud, Sabah. The impacts were experienced mostly by the community residing near the river (Rosli *et al.*, 2020a). For example, the Mesilau village (a village located within the midstream of Mesilau river), and Polumpung Base Camp (a recreational site located within the downstream of Kedamaian river).

To date, the debris flow induced by the earthquake and prolonged rainfall have received less observations among Malaysian researchers. In fact, Malaysia has no dedicated national policy, integrated framework, or standard operating procedures to address this sediment-related disaster in a holistic manner (Rosli *et al.*, 2020b). Moreover, a very limited Early Warning System (EWS) related to the debris flows were installed or published in this seismically active region, Sabah. This might be due to the lack of scientific studies, deep understanding, engagement with the affected communities, and risk reduction strategies to reduce the current risk, and preparing for the future risk. Therefore, this study aims at developing an integrated framework for debris flow EWS, in supporting local disaster risk reduction (DRR) and resilience strategy. A case study of debris flow induced by the earthquake and prolonged rainfall in the Mesilau watershed was selected for the purpose of this study.

This study implied a “multi-disciplinary” research to better analyse the past debris flow event, and a way forward to utilize the outputs for DRR. The “multi-disciplinary” refers to the different types of analysis including the scientific, and social analysis. The scientific analysis was conducted to obtain the scientific evidence of the past debris flow event, while the social analysis was performed to gather the EWS inputs from the local community and stakeholders. Both outputs were then correlated to achieve the final outcomes in terms of the proposed integrated framework. The final outcomes also aims to increase the national and local DRR strategies by 2020 (Target E), and to increase the availability and access to multi-hazard EWS and disaster risk information to people by 2030 (Target G) (UNDRR, 2017). The Target E emphasizes on developing the integrated EWS framework, whereas the Target G underlines the awareness, and knowledge for the community by making the research outcomes, and EWS framework visible and accessible to the public. Both the “Target E” and “Target G” are in line with Malaysia’s commitment to achieve the global target of The Sendai Framework for Disaster Risk Reduction (SFDRR) 2015 – 2030 (UNDRR, 2017).

1.2 Problem Statements

The Mw 6.0 Ranau earthquake dated on 5th of June 2015 has attracted many researchers to conduct comprehensive research in various fields within the study area. For example, the post-earthquake landslide inventory (Bibi *et al.*, 2017; Habibah, 2017), landslide susceptibility (Asmadi, 2018), and landslide hazard and risk (JMG, 2017). However, the researches focused only on the mapping in Kundasang area, whereby Habibah (2017) and Asmadi (2018), did a detailed landslide inventories and susceptibilities in the Mesilau river respectively. Despite the several studies conducted, very limited studies have emphasized the debris flow. To date, a brief report on the debris flow impacts were documented by Tongkul (2016). However, the discussions on the debris flow characteristics, processes, and DRR remained elusive. Therefore, the need for this study is timely and of utmost importance, since to date there are no scientific debris flow studies carried out in the Mesilau watershed.

This study becomes challenging since the source area of Mesilau watershed was located in the highly elevated, steep, and rugged topography. Mapping approach through the conventional geological survey was inadvisable without the preliminary assessments on the source area. This may be due to the possibilities of rock avalanches, and rock falls that probably risked the researcher's life during the field observation. Thus, resulted in the difficulty of field data collection, field evidence, and field mapping to physically characterize the source area. Characterizing the source area is essential for debris flow modelling (Iverson, 1997; Rengers *et al.*, 2016; Gong *et al.*, 2020). Therefore, the complexity in debris flow modelling is escalated since the mapping accessibility is limited, and in an area of high risk to a rock fall hazard. Given the difficulty of data collections, dangerous mapping, and limited access to the upstream area, this study investigates the suitable mapping approaches, by utilizing the advanced geospatial datasets available for the study area.

An intensive literature review and series of interviews were preliminary conducted to collect the past debris flow information, and available spatial datasets closest to the debris flow event. The preliminary findings identified the study area was having the limited datasets due to its high-altitude geographic locations, and located in the rural area. The limited datasets include; the unavailable rain gauge station in the Mesilau village, outdated Digital Terrain Model (DTM) of before the debris flow event, and dense cloud cover resulting in void filling the datasets. These conditions resulted in the uncertainties to determine the usable datasets for further processing. In overcoming the limitations, the extensive data collections regardless of open-sources or commercials are conducted.

The debris flow studies in Malaysia have received numbers of research in recent years. For example, the earliest cases of debris flow in Peninsular Malaysia (Tan and Ting, 2008), the rainfall intensities that initiated the debris flow (Jamaludin *et al.*, 2014), the triggering mechanisms of the debris flow (Norhidayu *et al.*, 2016), and the identification of debris flow within the initiation area (Lay and Pradhan, 2019). Even so, very few researchers attempted to simulate the debris flow runout due to the aforementioned uncertainties, limited datasets, and complexity in parameters. The closest attempt for debris flow modelling that emphasized on the hydraulic physical model was reported by Zainol and Awahab (2018). In fact, no simulation studies were carried out in the Mesilau watershed. Globally, the simulation studies have proven to support and provide scientific evidence of the past event, and predict the future event (Christen *et al.*, 2010; Hussin, 2011; Quan, 2012; Nakatani *et al.*, 2016). Therefore, this study employs the simulation analysis, despite the uncertainties, and complex parameters in analysing the debris flow in the Mesilau watershed, and utilizes the outputs for DRR.

The absence of scientific studies to provide evidence-based decision making has made the study difficult to achieve the DRR. Many studies around the globe have demonstrated the advantages of scientific studies to quantify the risk from the local to the national scale (Dai *et al.*, 2002; Van Western *et al.*, 2006; Liu and Miao, 2018). Besides, the scientific studies also have been beneficial to the stakeholders, practitioners, and local communities to understand the local risk and way forwards in planning for the suitable DRR. Thus, improving their awareness and preparedness in facing the future hazards and risks (Makia, 2012; Klimeš *et al.*, 2019). To date, there are no publications related to the debris flow DRR available in Malaysia. This was due to the lack of debris flow events, and social engagements. In the support of scientific studies and debris flow DRR, this study also considers societal inputs by engaging with the community and stakeholders. The societal input is considered to gain more inputs related to the DRR suitable for future debris flow in the Mesilau watershed.

The debris flow in the Mesilau watershed was chosen for this study because of several factors. This includes; (i) the existence of closest element-at-risk near the Mount Kinabalu and the Mesilau river, (ii) well-known as the touristic demanding areas (Rosli *et al.*, 2020b), and (iii) on-going land-use developments to satisfy human needs (Mohd Kamal *et al.*, 2019). The closest element-at-risk in the watershed area was known as the Mesilau village, where several homestays were collapsed, and a connecting bridge was destroyed. The further social study by Chong *et al.*, (2019) described the local incomes increased drastically after the earthquake and debris flow event. This shows that the village received high numbers of tourists every year. Thus, resulted in the increase of land-use developments to build homestays and resorts within the village. The evidence as described have proven that the Mesilau village is highly exposed towards the future earthquake and debris flow hazard. Due to this, an integrated framework for debris flow DRR is significantly needed to reduce the current risk, and prepare for the future risk.

1.3 Research Aim and Objectives

The aim of this study is to develop an integrated framework for debris flow EWS, in supporting local DRR and resilience strategies. The aim is achieved by emphasizing the multi-disciplinary research including; the scientific and social study. To achieve the aim, three research objectives are constructed as follows;

1. To map and characterize the debris flow induced by the 2015 Ranau earthquake
2. To model and simulate the debris flow runout
3. To develop an integrated framework for debris flow EWS, in supporting local DRR and resilience strategy

1.4 Research Questions

For solving the research aim and objectives, six (6) research questions have been constructed, and listed as follows;

1. To map and characterize the debris flow induced by the 2015 Ranau earthquake
    a) What are the datasets used to characterize the debris flow?
    b) What is the significance of mapping and characterizing the debris flow area?
2. To model and simulate the debris flow runout
    a) How to model the debris flow induced by earthquake, and rainfall in a poorly treated data, inaccessible terrain, and mountainous environment?

b) How to validate the simulation runout with the actual past event?

3. To develop an integrated framework for debris flow EWS, in supporting local DRR and resilience strategy

    a) To what extend the results from the mapping, characterizing, and modelling processes help in formulating the integrated framework?

    b) How the debris flow EWS supports the local DRR and resilience strategies?

1.5 Significance of Study

The past debris flow events around the world have recorded a high number of fatalities and major destruction towards any element-at-risks located within the downstream area. For example, the debris flow in Sichuan, China (2003) that killed 51 people (N. S. Chen *et al.*, 2005), Wenchuan, China (2008) that killed nearly 1600 people (Wu *et al.*, 2010; Wang *et al.*, 2014), Hiroshima, Japan (2014) that killed 74 people (Fawu *et al.*, 2015) and Putumayo, Columbia (2017) that killed 409 people (Petley, 2019). In fact, Malaysia also recorded a high number of fatalities with the human losses of 302, and 100 others remained unfound (Borneo, 1996; PWD, 2009; JiCA, 2015). The event was induced by a typhoon recorded in Keningau, Sabah (1996) (Borneo, 1996; PWD, 2009; JiCA, 2015). Thus, remarked as the fatal geological disasters in Malaysia. To date, 23 debris flow events were recorded across Malaysia, and very few emphasized on the event in the Mesilau watershed, Kundasang. Therefore, this study has taken the first initiative to analyse the past debris flow induced by the earthquake, followed by the prolonged rainfall within this area, in better understanding the past event, as well as providing scientific evidence in preparing for the future event.

Besides, understanding any disasters, including debris flow has become one of the initiatives to achieve the first "Priority in Action" of "The Sendai Framework for Disaster Risk Reduction (SFDRR) 2015 – 2030" (United Nations for Disaster Risk Reduction, 2015). The conducted analysis such as; mapping the watershed area, modelling the past event, and gathering EWS inputs from various stakeholders and local communities have given a better understanding towards the disaster risk, and way forwards for DRR. Additionally, the understanding also provided an evidence-based decision making for the government, district, and local community to prepare for the future hazard and risk. Thus, leading the study to achieve the other three priorities of SFDRR, including; "Strengthening the disaster risk governance to manage disaster risk", "Investing in disaster risk reduction for resilience", and "Enhancing disaster preparedness for effective response and to 'Build Back Better' in recovery, rehabilitation and reconstruction" (UNDRR, 2015).

This study becomes more significant as there is no integrated early warning system framework available within this area. Extensive literature reviews as well as interviewing the local communities were conducted to determine the existence of EWS. The preliminary findings highlighted no EWS has been installed within this tectonically active region. This statement was also validated by the interview session with the local government such as; The Department of Mineral and Geoscience of Sabah (JMG Sabah). Hence, opening a research gap for this study to design a suitable people-centred EWS framework based on the scientific and social studies conducted. According to the USGS earthquake archives, the Ranau district has experienced three earthquakes greater than Mw 5.0 within the 50-year records from 1965 until 2015. The earthquakes were dated in 1966 (Mw 5.3), 1991 (Mw 5.2), and 2015 (Mw 6.0), with the approximate return periods for every 24 to 25 years (Tongkul, 2016; USGS, 2018). By taking the return period as the issue, it has been predicted that the future earthquake could possibly trigger in another 24 or 25 years from 2015. The return period was also highlighted by Tongkul (2016); and Abd Razak *et al.* (2018). Hence, increasing the possibilities of the future cascading geohazards, including debris flow. Therefore, the needs for this study are essential to analyze the past event, predict the future event, and plan for the suitable DRR measures. As quoted by Doe (1983), *"The Past is the key to the Future"*. Thus, to study the debris flow event in a tectonically active region is relevant since there is a possibility of a large earthquake that may initiate a debris flow. In addition, a guidance for future researchers on the methodologies conducted can also be applied from this study.

The debris flow in the Mesilau watershed was described as the first ever event induced by the earthquake and prolonged rainfall recorded in Malaysia. The event was different with the other reported events where the triggering factors were mostly rainfall, and less triggered by the storm. Though the event did not cause any fatalities, the impacts were still observed along the channelized river. Geographically, three element-at-risks were affected within the watershed area, namely as; Mesilau village (i.e., collapse of homestays, destroyed bridge), Naradau village (i.e., damaged bridge), and Ranau town (i.e., accumulated log within the Liwagu Dam). From these three element-at-risks, the Mesilau village was the most affected village, as it was; (i) located close to the foot slope of Mount Kinabalu, (ii) a close living community near the river, and (iii) known as the touristic demanding areas. Hence, making the village highly exposed towards the future event as well. This statement has provided a strong justification to select this area as a case study due to the existence of closest element-at-risks near the source area, and the river.

1.6 Scope of Study

The conducted analysis for this study focused on the Mesilau watershed only. Despite the other reported events across Malaysia, this event was considered as a non-common event, where it was triggered by the earthquake followed by the prolonged rainfall. The study area covered the channelized Mesilau river from the foot slope of Mount Kinabalu until the Liwagu Dam, Ranau town. The channelized river was selected in order to understand the landslide damming formation within the upstream area, and debris flow mobilization processes to the downstream area.

The scope of the study started with collecting the geospatial datasets through the available remotely-sensed datasets from the archives and commercial platforms. This study considered the high-resolution datasets to produce the more accurate outcomes. The datasets include; the satellite images, digital elevation model (DEM), and rainfall dataset. However, the available high-resolution datasets were limited since the area was located in a rural and highland area. Therefore, the data collections were acquired based on the closest date available to the earthquake and debris flow event. For example, the available DEM before the debris flow event dated on 2008.

The second scope of the study was the conducted analyses towards the obtained datasets. The three aforementioned datasets were utilized to derive the hydro-geomorphological causal factors, extract the hydrologic watershed parameters, extract the parameters for debris flow modelling, characterize the landslides dam, and analyze the critical rainfall. Due to the time constraint, the analyses were limited to the available processing platforms, such as; eCognition 9.3, ArcGIS 10.8, QGIS 2.8, HyperKANAKO.

The third scope of the study was related to the debris flow modelling. Globally, there were many modelling software that have been developed by various researchers across the world. The details of the developed models were presented in the literature reviews under the debris flow modelling section. For this study, the selected model software was the HyperKANAKO model developed by Nakatani *et al.* (2016). The HyperKANAKO was selected as it was in line with the JICA's project. The contract-license was received from Professor Nakatani, Kyoto University, Japan. The simulation was conducted along the channelized Mesilau river from the source of initiation, until the depositional area. However, the analyses and interpretations were limiting to the area in the Mesilau village only. Due to the time constraint, few of the parameters were set as default as suggested by the developer.

Next, the fourth scope of the study was focusing on gathering the societal inputs for DRR from the local community and stakeholders. This study only emphasized the interview and questionnaire methods in validating the past debris flow event, and in obtaining the suitable DRR measures for the localized area. To obtain the societal inputs, this study involved several community-based programs conducted by Universiti Teknologi Malaysia (UTM) Kuala Lumpur in Kundasang, Sabah. Two of the involved programs include; Science and Technology for Disaster Risk Reduction (STDRR 2019), and "*International Workshop and Field Practice on Disaster Risk Management* (IDRM)".

Finally, the fifth scope of the study was to develop the integrated framework for debris flow as the final product for this study. The base of the integrated framework was referred to the people-centered Early Warning System (EWS) published by UNDRR (2006). Both scientific and social findings were correlated in developing the framework. Since the selected study area is prone to the earthquake and cascading geohazards, therefore the proposed framework aims to reduce the future debris flow hazard induced by the earthquake.

1.7 Description of Study Area

In general, the study site is a rural area situated within the North-western Coast of Borneo Island, Sabah. The state consisted of five divisions, namely as; Tawau, Kudat, Sandakan, Interior, and West Coast (Jesselton, 2000). From these five divisions, the study area belongs to the West Coast division, with the total approximate area of 7,588 km^2 (10.3%) from the total area of Sabah state (Jesselton, 2000). Precisely, the study area is located within the Ranau district that covers 2,978 km^2 (4%) from the total area of the West Coast division. The area is mostly popular with its highest mountain in Malaysia, known as Mount Kinabalu, and has been officially gazette as Malaysia's First UNESCO World Heritage site, under the Kinabalu National Park in the year of 2000 (Hall *et al.*, 2008). The panoramic view of Mount Kinabalu is shown as in Figure 1.3. Most of the land is covered with the tropical rainforest (State Government of Sabah, 2018).

Figure 1.3 The panoramic view of Mount Kinabalu, taken at Maragang Hill.

The mountain was a part of the uplifting process due to the tectonic plate compression during the middle of the Miocene period (Cottam *et al.*, 2010) (Figure 1.4). Hall *et al.* (2008) justified the uplifting of Mount Kinabalu as the results of either the delamination of the lithosphere, or a break off of a subducted slab. Currently, the highest summit of Mount Kinabalu was 4,095 m from the mean sea level (Hall *et al.*, 2008). However, the mountain was expected to arise at a long-term rate of 0.5 mm every year as the uplifting rate was approximately 7 mm (Hall *et al.*, 2008). As the elevation rises to the summit, the tropical rainforest landscape changes to the subalpine range. Due to its high altitude, the temperature of this area dropped to 10°C at night, making it one of the coolest places in Sabah (Malaysia Travel Information Centre, 2012).

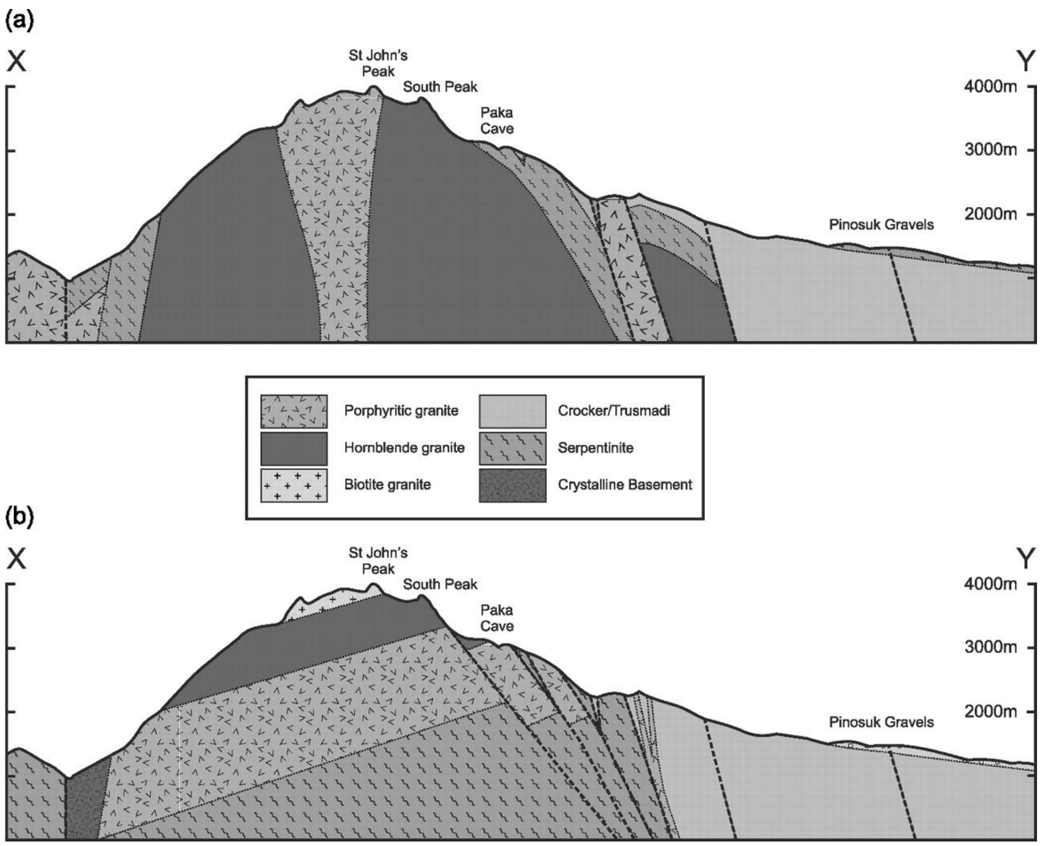

Figure 1.4 The cross-sectional of uplifted Mount Kinabalu due to the tectonic plate compression in the middle of Miocene period (Cottam *et al.*, 2010).

The chosen area for this study is situated within the Southeast flank of Mount Kinabalu, Kundasang, Sabah. To be specific, the area of interest is located along the channelized Mesilau river, covering the foot slope of Mount Kinabalu, until the

Liwagu Dam, Ranau town (Figure 1.5). The latitudes are recorded from 06°05'02.0" and 05°57'34.6", while the longitudes are recorded from 116°32'53.3" and 116°41'01.6". Geographically, many villages are observed in Kundasang town, with Mesilau village as the closest village to the foot slope of the mountain. Kundasang town and its villages have been popularly known for its market that open seven days a week, with the businesses related to the fresh vegetables, and fruits (Dambul and Buang, 2008; Asmadi, 2018). Besides, the Mesilau village offers many attraction places, such as; the Mesilau Golf Club, Desa Cattle Farm, Mini Strawberry Farm Mesilau, Mesilau Cat's Village, Maragang Hill, and Sosodikon Hill. Thus, making the village as one of the top visited places either by the local or international tourist. The common population in this area is mainly native Dusun and a small portion of other races (Sarman *et al.*, 2000; Kamarudin *et al.*, 2016).

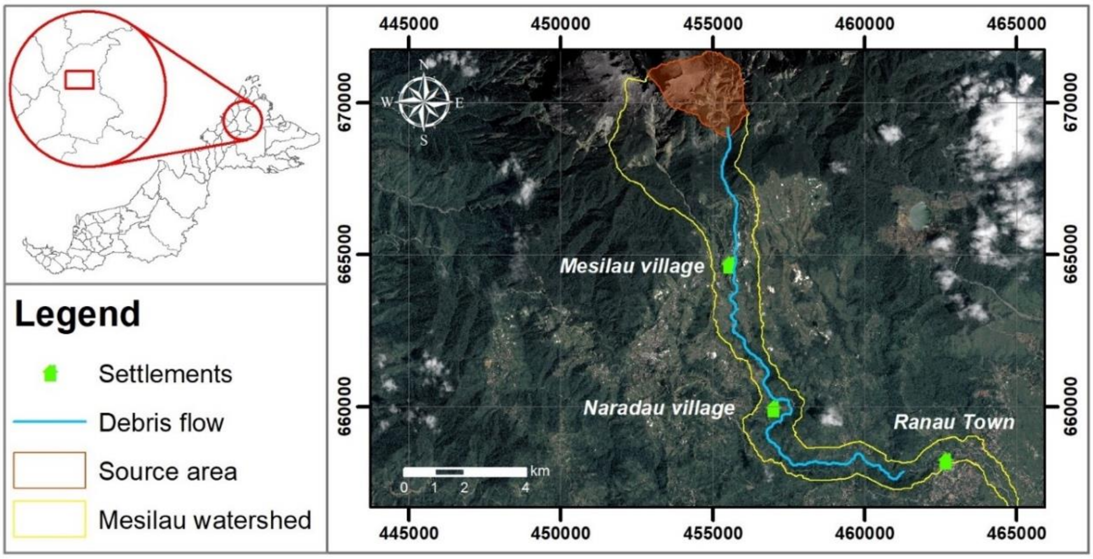

Figure 1.5 The overall map of the study area within Mesilau watershed.

Geologically, the study area was associated with the weak geological materials, and many active faults that induced many landslides within any existing slope profile. As highlighted in Figure 1.6, five lithologies were identified within the watershed area, namely as; Serpentinite, Crocker Formation, Trusmadi Formation, Granite, and Pinousok gravel (Kirk, 1968; Jacobson, 1970; Hall *et al.*, 2008; JMG, 2010). The Pinosouk gravel was the dominant lithology within Mesilau village, whereas the Granite, and Serpentinite was the most observed lithologies within the source area. The Pinosouk gravel comprises of poorly consolidated gravels of various compositions. This can be observed by its rounded big boulders in the Mesilau village (Figure 1.7). Additionally, two major active faults were determined within this area, known as Lobou-Lobou fault, a left lateral strike faulting N20E, and Mensaban fault that was trending Northwest-Southeast (Tjia, 2007). Both evidence of the weak geological materials, and active faults have categorized the area as the high geohazard-prone areas (Sharir *et al.*, 2017; Tongkul, 2017; Roslee and Tongkul, 2018).

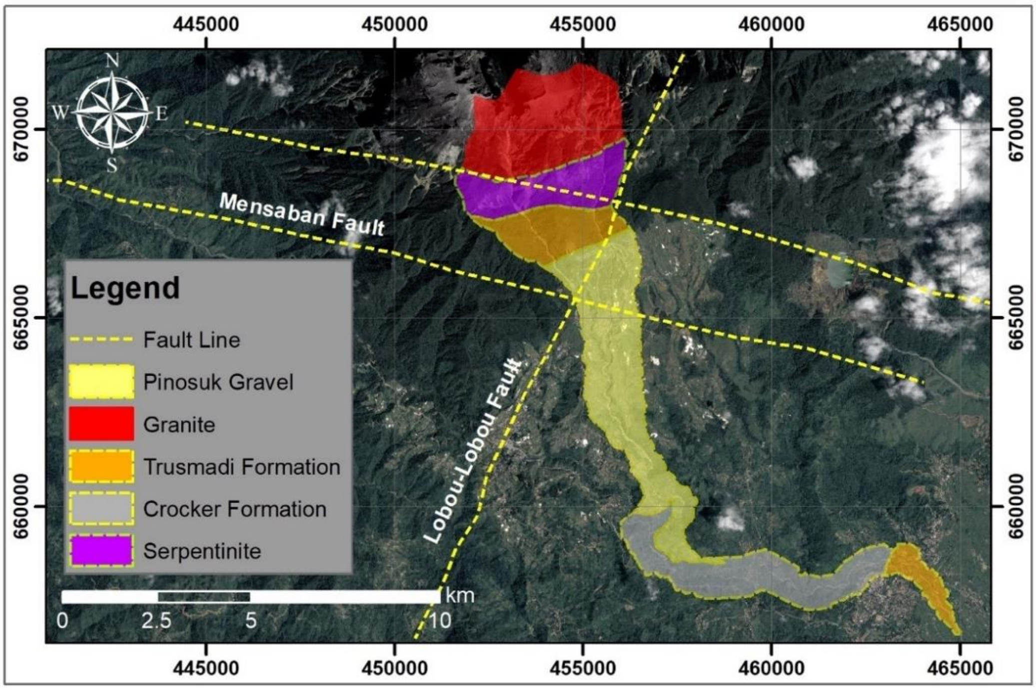

Figure 1.6 The derived geological map of the study area within Mesilau watershed (Kirk, 1968; Jacobson, 1970; Hall *et al.*, 2008; JMG, 2010).

Figure 1.7 The evidence of rounded big boulders representing the Pinosuk gravel.

The Mw 6.0 Ranau earthquake dated on 5th June 2015 was the fatal geo-physical related disaster in the recent history of Malaysia. The earthquake induced many cascading geohazards including rock falls, landslides, and debris flows in the vicinity of UNESCO World Heritage site, Mount Kinabalu. As described by Tongkul (2016) and USGS (2018), the earthquake epicentre was located in the highland of Kundasang town, and was triggered by the slip of Lobou-Lobou fault at a shallow depth of 10 km. The direct impacts have perished 18 climbers due to the rock falls along the summit area, with 137 others remained injured and stranded along the trail (Tongkul, 2016). In addition, the earthquake stripped lots of earth surfaces resulting in the landslide occurrences within Mount Kinabalu. Thus, accumulating the earth materials on the upstream channel forming a temporary landslide dam. The following days of prolonged rainfalls then initiated a cascading geohazard known as debris flows. Two of the well-reported damages from the event includes; the collapse of homestay into the Mesilau river (Figure 1.8) (NST, 2015; The Star, 2015), and the destructed bridge from Mesilau Village to Mesilau Nature Resort (Figure 1.9) (Min and Hwee, 2015). Theoretically, the concept was similar to the Gorkha earthquake resulting to the accumulation of landslides, and later, remobilized the materials as debris flow (Rosser *et al.*, 2016).

Figure 1.8 The collapse of homestay into the Mesilau river due to the earthquake induced landslides (*source from* NST, 2015; The Star, 2015).

Figure 1.9 The destroyed connecting bridge to the Mesilau Nature Resort (MNR) due to the debris flow (Min and Hwee, 2015).

1.8 Thesis Structure

The thesis consisted of five chapters beginning with the introduction (Chapter 1), followed by the literature review (Chapter 2), research methodology (Chapter 3), results and discussion (Chapter 4), and finally conclusion and recommendations (Chapter 5). The whole structure of this thesis can be referred to Figure 1.10.

The Chapter 1 introduces the topic and central idea of this thesis. Chapter 1 consisted of eight subchapters starting with; the problem background, problem statements, research aim and objectives, research questions, significance of study, scope of study, description of study area, and finally thesis structure. The introductory subchapter began with the issues regarding the landslides around the world. Then, the scopes are narrowed down into the cases in Malaysia, with the details focusing on the debris flow in the Mesilau watershed.

The Chapter 2 is the chapter of reviewing all the literature related to the study. Chapter 2 is the crucial chapter where the author needs to conduct an extensive review, reading, and watching the video documents in order to obtain the overall understanding and extract the debris flow information that has been published by various researchers across the world. This chapter mainly consisted of eight main topics, that started with; the Disaster Risk Reduction (DRR) and its published frameworks, landslides, debris flow, mapping techniques, image classification, debris flow modelling, social survey, and global published debris flow framework.

The Chapter 3 discusses the methodological structures applied in order to achieve the overall aim and research objectives of this study. The scopes have been divided into eight major subchapters, that are; the data collections and data sources, data pre-processing, data processing and data analysis, field mapping, debris flow modelling, debris flow warning system, survey data analysis, framework design and development.

The Chapter 4 is the chapter of presenting the results, and discussing the findings obtained. Chapter 4 highlights the major contribution of this study as the assessments, understanding, and outputs are presented in this chapter. The results that are discussed in this chapter includes; the hydro-geomorphological factors, channel profiles, object-based image analysis (OBIA), landslide recognition and inventory mapping, characterizations of landslide dam, discharge and hydrographs, debris flow modelling, people-centered early warning system, interview response, correlation of outputs, design of framework, justification of framework, and finally, the discussions.

Lastly, Chapter 5 concludes the whole analysis performed in this study. Besides, the improvements, and recommendations were also presented to improve the outcomes in the future. Purposely, the Chapter 5 summarizes the research work conducted, and how the future researchers can improve the findings from this study.

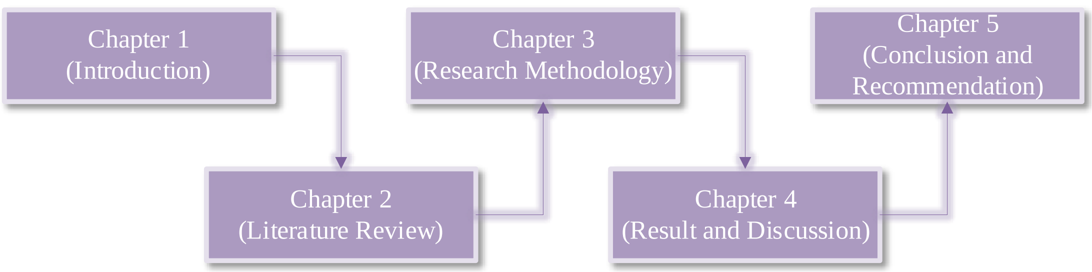

Figure 1.10 Flowchart of the thesis structure.

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Appendix A The people-centred Early Warning System (EWS) survey.

UTM
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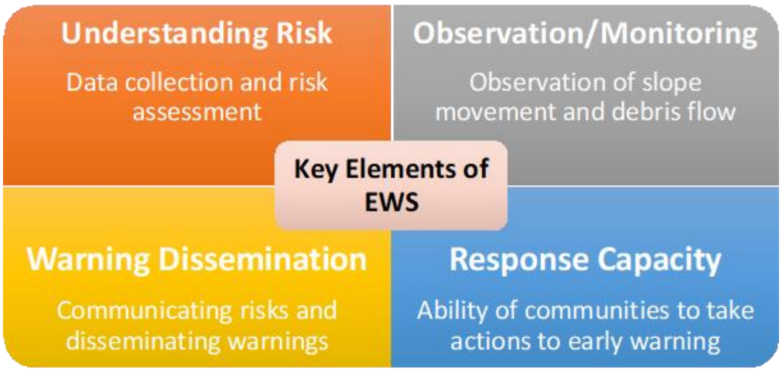
STAKEHOLDER'S SURVEY FORM

SURVEY ON THE UNDERSTANDING AND READINESS OF STAKEHOLDERS IN DEBRIS FLOW DISASTER RISK REDUCTION AND WAY FORWARD IN DESIGNING AN INTEGRATED FRAMEWORK FOR EARLY WARNING SYSTEM (EWS)

Sir/Madam,

This survey is conducted to study the level of understanding and readiness of department/agency in debris flow disaster risk reduction, in the past and in the present, along with the suggestions/opinions in implementing an integrated framework for early warning system (EWS) to reduce the future debris flow risk. There are four sections to this Q&A, based on the four objectives in this form as depicted in the figure below. The outputs will be used to propose an integrated framework for debris flow within the tectonically active region in Malaysia.



The survey requires your honest response and if you do not know the answer to a question, please leave the answer blank or choose "Do not know". All response, and answer will be confidential and will only be used for research purposes only.

Thank you for your time and cooperation.

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SECTION A: PERSONAL INFORMATIONS AND RESPONDENT BACKGROUND
Please tick (/) which relevant to you.

A.1 Gender:
- [ ] Male
- [ ] Female

A.2 Age: _____ years

A.3 Contact information (email, mobile#):

A.4 Highest Education:
- [ ] Lower Secondary School (PMR)
- [ ] Higher Secondary School (SPM)
- [ ] Pre-University (Foundation/Diploma/Matric/STPM)
- [ ] Tertiary Education (Degree)
- [ ] Master/PhD
- [ ] Others: ______________________

A.5 Which department/agency that you are currently working for?
____

A.6 How long have you been working in this department/agency? _______ years

A.7 What is the type of disasters you ever experienced with?
- [ ] Flood
- [ ] Landslides
- [ ] Earthquake
- [ ] Debris Flow

A.8 Have you ever been involved in disaster management operation?
- [ ] Yes
- [ ] No

SECTION B.1: RISK KNOWLEDGE ON DEBRIS FLOW
Tick (/) for the appropriate answer

B.1.1 In general, do you know the existence of landslide hazards induced by the Sabah Earthquake on 5th June 2015?
- [ ] Yes
- [ ] No

B.1.2 If yes, where do you think is the most vulnerable landslide areas after the 2015 Sabah earthquake? (Please tick two of the dominant areas)

- ☐ Kota Kinabalu
- ☐ Kundasang
- ☐ Ranau
- ☐ Kota Belud
- ☐ Sandakan
- ☐ Keningau
- ☐ Lahad Datu
- ☐ Don't know
- ☐ Others: _______________

B.1.3 Do you know the existence of debris flow hazards after the 2015 Sabah Earthquake?

- ☐ Yes
- ☐ No

B.1.4 If yes, do you know any location(s) in which debris flow (mud flow) disaster had occurred?

- ☐ Mesilau River
- ☐ Kedamaian River
- ☐ Padas River
- ☐ Melangkap River
- ☐ Don't know
- ☐ Others: _______________

B.1.5 Do you know the existence of landslide hazard and risk map developed in 2016 by the Projek Pemetaan Bahaya dan Risiko Cerun?

- ☐ Yes
- ☐ No

B.1.6 If yes, did you or your organization take any actions for disaster management?

Please specify your actions (by location): ____________________________

B.1.7 Where do you get your information about landslide/debris flow risk?

- ☐ Newspaper
- ☐ Radio/TV
- ☐ Research papers
- ☐ SNS (e.g. Whatsapp, Facebook, etc)
- ☐ Government
- ☐ Experts (e.g. workshops, seminar)
- ☐ Others: _________________

B.1.8 From your opinion, what are the factors contributing to the debris flow initiation?

- ☐ Geomorphology (e.g. steep slopes)
- ☐ Hydrology (e.g, rainfall)
- ☐ Geology (e.g. weak materials)
- ☐ Don't know
- ☐ Others: ____________________

SECTION B.2: KNOWLEDGE ON EARLY WARNING SYSTEM
Tick (/) for the appropriate answer

B.2.1 Do you know any existing Early Warning System (EWS) in Malaysia?

☐ Yes ☐ No

B.2.2 If yes, what is the EWS type that you have ever known?

☐ Flood ☐ Tsunami
☐ Landslide ☐ Debris flow

Please specify the location or type of EWS: ________________________

B.2.3 If yes, where did you get your information about the contents of EWS?

☐ Newspaper ☐ Radio/TV
☐ Research papers ☐ SNS
☐ Government ☐ Experts (e.g. workshops)
☐ Others: ___________________

B.2.4 If no, do you know of any working EWS outside of Malaysia?

☐ Yes ☐ No

What is this EWS? _____________________________

B.2.5 Have you been involved in developing or installing an EWS? If yes, what have you done?

☐ No ☐ Yes – Please describe:

B.2.6 What are the challenges in developing and operating an EWS?

☐ Cost ☐ Time
☐ Installation ☐ Expertise
☐ Maintenance ☐ Others: _______________

B.2.7 In your opinion, how critical is it to install EWS in Kundasang Sabah for reducing debris flow disaster risk?

☐ Not Critical ☐ Less critical
☐ Critical ☐ Very critical

B.2.8 What kind of EWS is suitable to be installed in Kundasang Sabah?

☐ Full-spec EWS by government (e.g. SAIFON)

☐ Low-cost, small-scale community-based EWS

☐ Others: ________________________

B.2.9 Which organization(s) should design and install the EWS in Kundasang Sabah?

Please specify: ____

B.2.10 What do you think the important elements when designing a debris flow EWS in Kundasang Sabah?

☐ Inventory of past debris flow	☐ Record of rainfall
☐ Risk map of potential debris flow	☐ Debris flow simulation
☐ Know the elements-at-risk	☐ Others: _____________

B.2.11 Which organization(s) should be responsible for each of the debris flow EWS components?

a. Risk data and assessment: ________________________________

b. Observation/Monitoring: ___________________________________

c. Communication/Dissemination: ______________________________

d. Response Capability Building: ______________________________

SECTION C: OBSERVATION/MONITORING

Tick (/) for the appropriate answer

C.1 In your opinion, what is the suitable method in monitoring a debris flow event?

- ☐ CCTV
- ☐ Rainfall station
- ☐ Wire sensor
- ☐ Vibration sensor
- ☐ Drone
- ☐ Others:___________________________

C.2 Does your organization play a role in monitoring a debris flow event?

- ☐ Yes
- ☐ No

C.3 If yes, what are the actions/methodologies used to monitor the debris flow event?

Please specify: ____

C.4 Does your organization work with local stakeholders for making on-site real time monitoring?

- ☐ Yes
- ☐ No

C.5 If yes, who are the local stakeholders who do the monitoring?

- ☐ Fire Department
- ☐ Village Leader
- ☐ Police
- ☐ District Officers
- ☐ Civil Defense Force
- ☐ Others: __________________________

SECTION D: WARNING DISSEMINATION AND COMMUNICATION

Tick (/) for the appropriate answer

D.1 From past experiences, how are disaster information disseminated during disaster events?

- ☐ Mosque Speaker
- ☐ Phone call/FAX
- ☐ Email
- ☐ Radio/TV Broadcast
- ☐ SNS
- ☐ Others: _________

D.2 Based on your answer in D.1, how well did the community react to the EWS messages?

- ☐ No action
- ☐ Some action
- ☐ Very reactive
- ☐ Not sure

D.3 In your opinion, how fast and effective were the disaster information disseminated?

- [ ] Not effective
- [ ] Less effective
- [ ] Effective
- [ ] Very effective

D.4 At what percentage do you think the disaster information reached the community?

- [ ] 0 – 25%
- [ ] 25 – 50%
- [ ] 50 – 75%
- [ ] 75 – 100%

D.5 For answers (in D.4) below 50%, what do you think was the reason for the low percentage?

- [ ] Distrust in information
- [ ] Late in dissemination
- [ ] Ignored the information
- [ ] Others: ______________

D.6 In your opinion, what is the effective medium that can be used to warn the local communities about the possible debris flow disaster? (Please rank in numbers 1-6)

- [ ] Siren (speaker)
- [ ] SNS
- [ ] Email
- [ ] Phone call (incl. SMS)
- [ ] News (radio/TV)
- [ ] Others: _______________

D.7 What is the communication level of your organization with local government and communities?

- [ ] Low
- [ ] Medium
- [ ] High
- [ ] Very High

SECTION E: RESPONSE CAPABILITY

Tick (/) for the appropriate answer

E.1 How do you evaluate the general response capability of communities to EWS messages in Malaysia?

- [ ] Low
- [ ] Medium
- [ ] High
- [ ] Very High

E.2 What are the first steps that can be taken in improving the response and preparedness towards debris flow risk?

Please suggest: ____

E.3 What kind of programs and activities should be implemented for communities in reducing the debris flow risks?

Please suggest: ____

E.4 Who do you think should lead or initiate capacity building programs related to debris flow disaster response?

- [ ] Federal government
- [ ] State government
- [ ] District office
- [ ] NGOs/CBOs
- [ ] Universities
- [ ] Others ____________________________

E.5 What specifically can be done by your organization to implement the programs suggested in E.3?

Please suggest: ____

E.6 How often do the evacuation drills be conducted in Kundasang?

- [ ] Once a year
- [ ] Every 6M
- [ ] When needed
- [ ] Other: ____________________________

E.7 Have you ever been involved in debris flow disaster response operation?

- [ ] Yes
- [ ] No

E.8 If yes, what were your roles in debris flow disaster response operation?

Please write your actions: ____

Appendix B The procedures to extract the hydrologic watershed model, using the ArcHydro, and Hec-GeoHMS.

1. On the first step, the user is required to install the extensions of ArcHydro, and Hec-GeoHMS, suitable with the version of the ArcGIS. The extensions can be downloaded from the link: http://downloads.esri.com/archydro/HECGeoHMS/
2. Once installed, the user must allow both of the extensions in the ArcGIS software, under the customize window > toolbars.
3. Both of the extensions are then popped out on the workspace, highlighting the parameters used by the extension.
4. The user is then required to import the DTM dataset for the watershed extraction.
5. The first procedure to extract the watershed model is by using the ArcHydro extension.
6. The steps are conducted in order from step 1 – 14, as shown in Figure B-1, and B-2. To note with, the output for each step is used for the next step. For examples, the output for step 1, is used in the step 2, while the output for step 2, is used in the step 3.
7. However, the ArcHydro extension has made the processing goes easier, where the user just required to execute the function without importing each output.

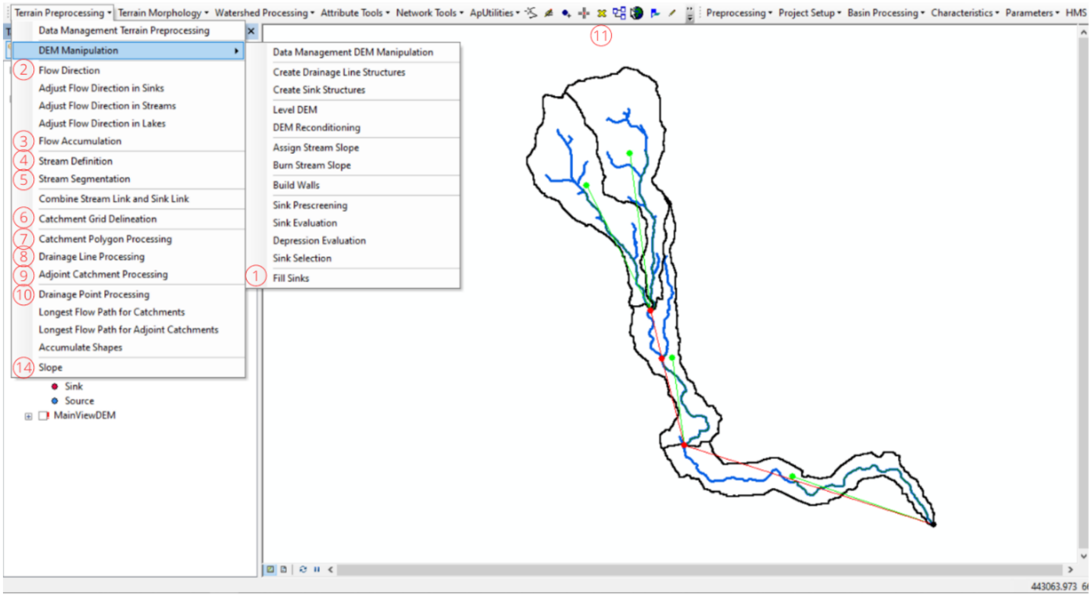

Figure B-1 The steps conducted in ArcHydro, under Terrain Processing (Step: 1 – 14).

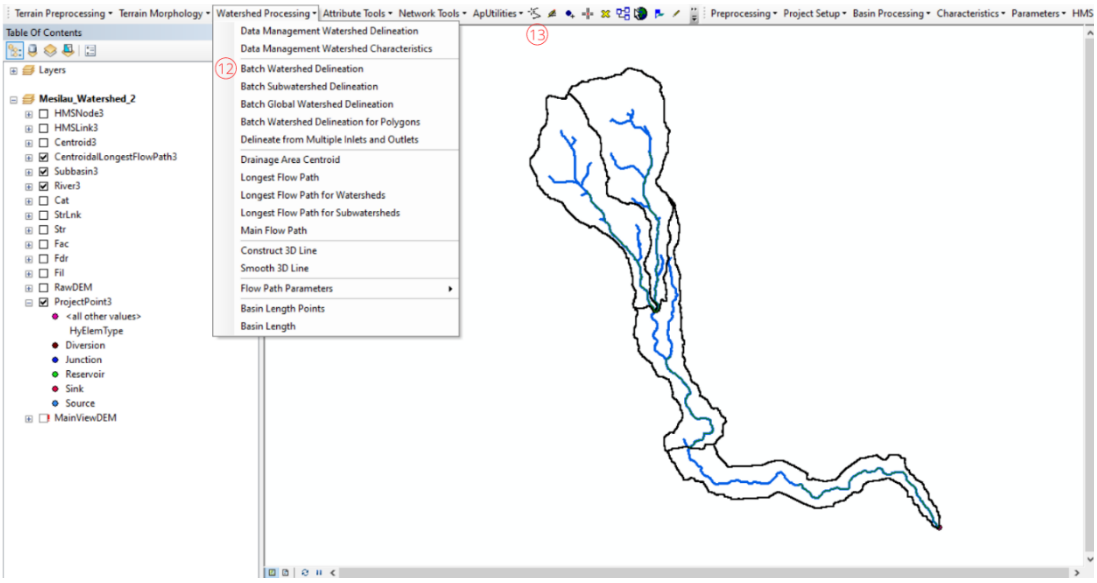

Figure B-2 The steps conducted in ArcHydro, under Watershed Processing (Step: 12 – 13).

8. The next step after all the ArcHydro steps have been conducted is to proceed with the steps in the Hec-GeoHMS.
9. Beforehand, the user must import all the produced outputs or parameters, under the Project Setup > Data Management (Step 15) (Figure B-3).
10. The steps conducted in the Hec-GeoHMS (step 15 – 39) are shown as in Figure B-4, Figure B-5, and Figure B-6 respectively.

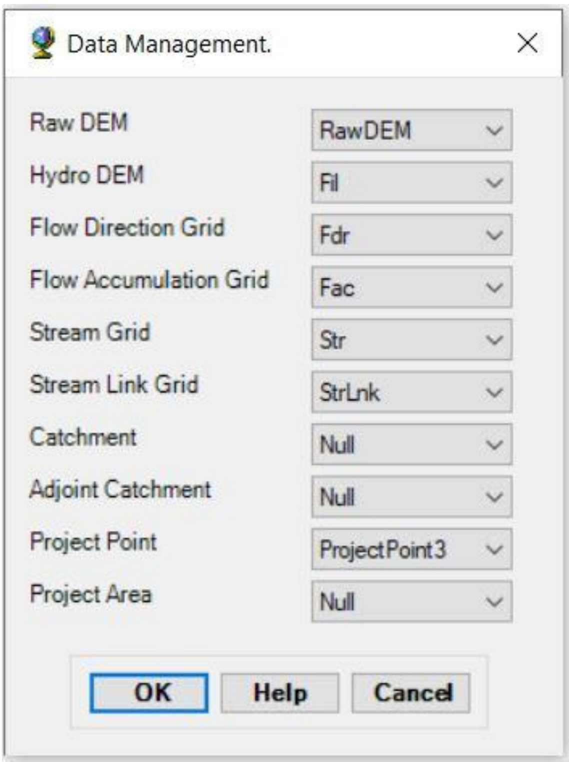

Figure B-3 The imported outputs/steps in the Project Setup > Data Management.

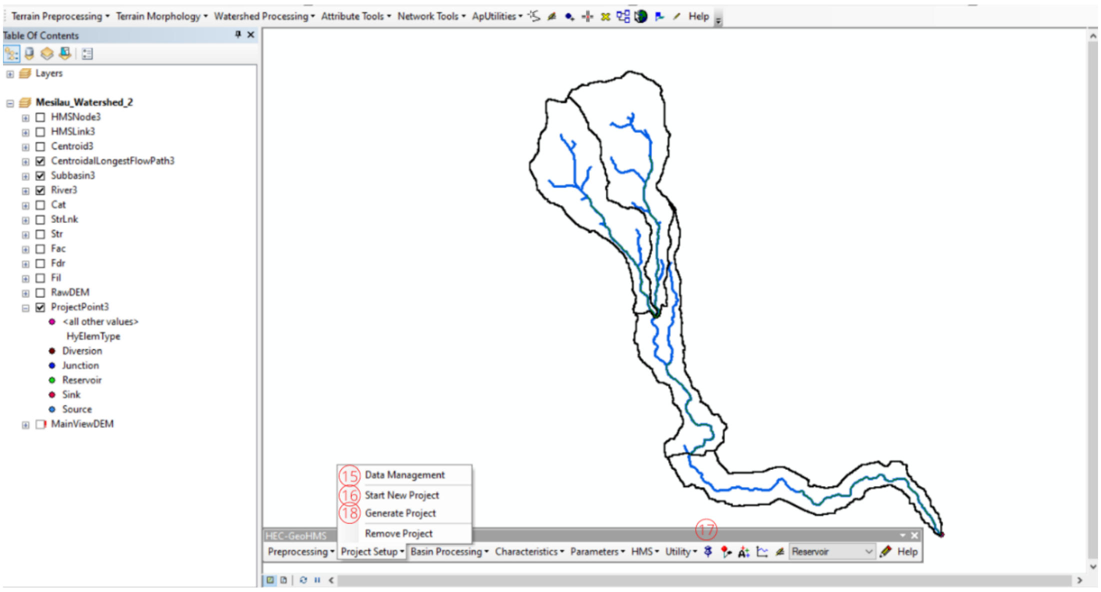

Figure B-4 The steps conducted in the Hec-GeoHMS, under Project Setup (Step: 15 – 18).

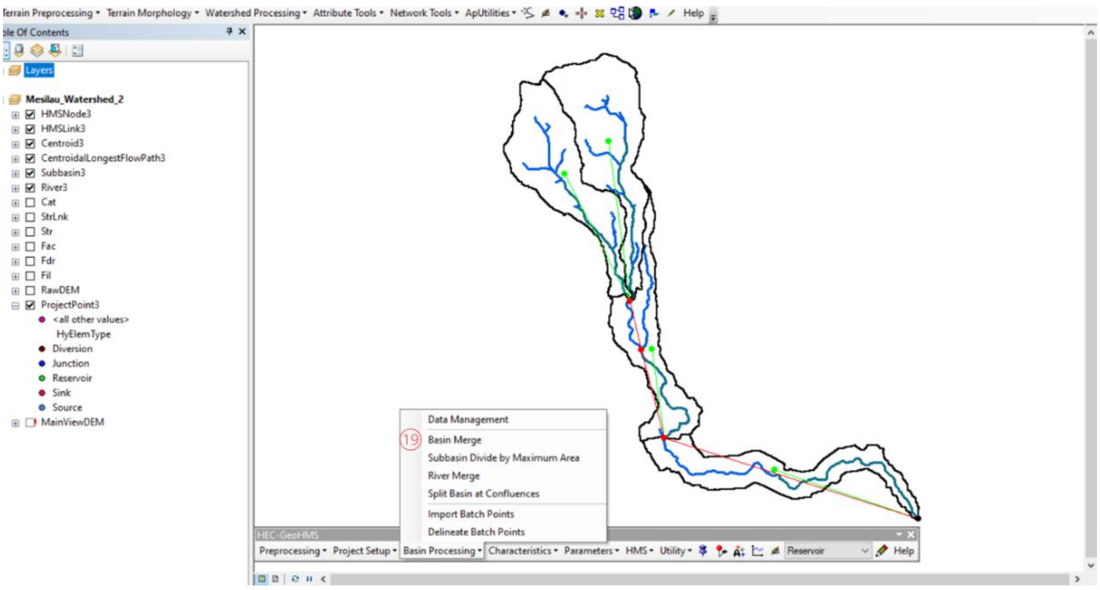

Figure B-5 The steps conducted in the Hec-GeoHMS, under Basin Processing (Step: 19).

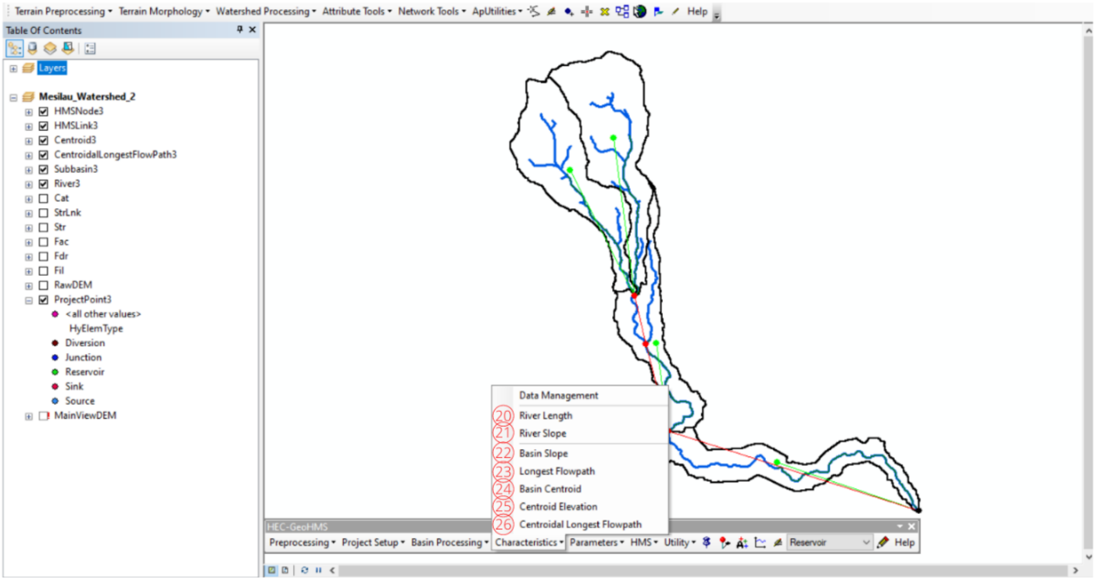

Figure B-6 The steps conducted in the Hec-GeoHMS, under Characteristics (Step: 20 – 26).

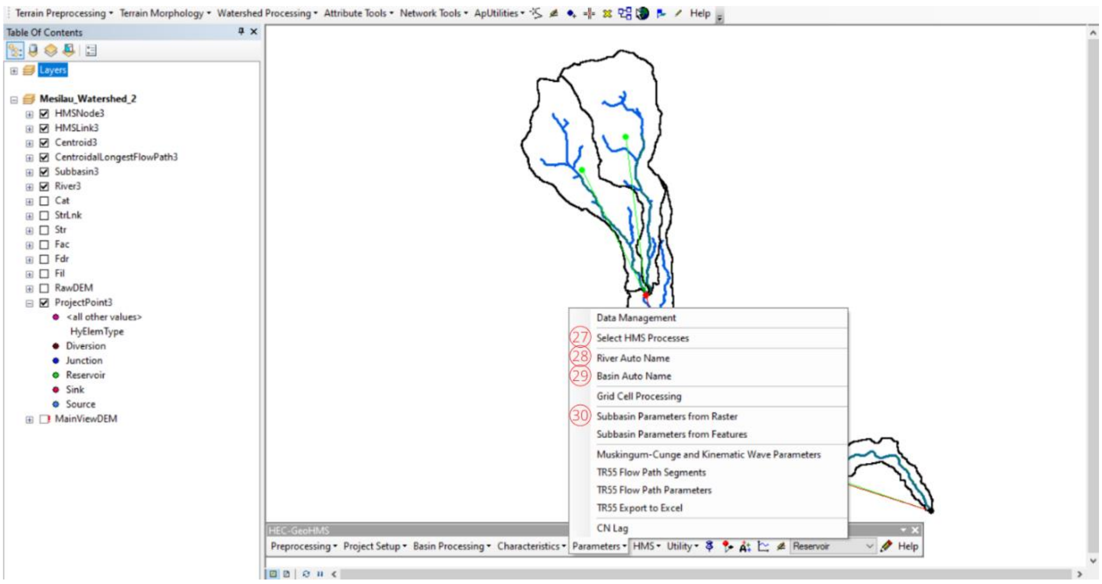

Figure B-7 The steps conducted in the Hec-GeoHMS, under Parameters (Step: 27 – 30).

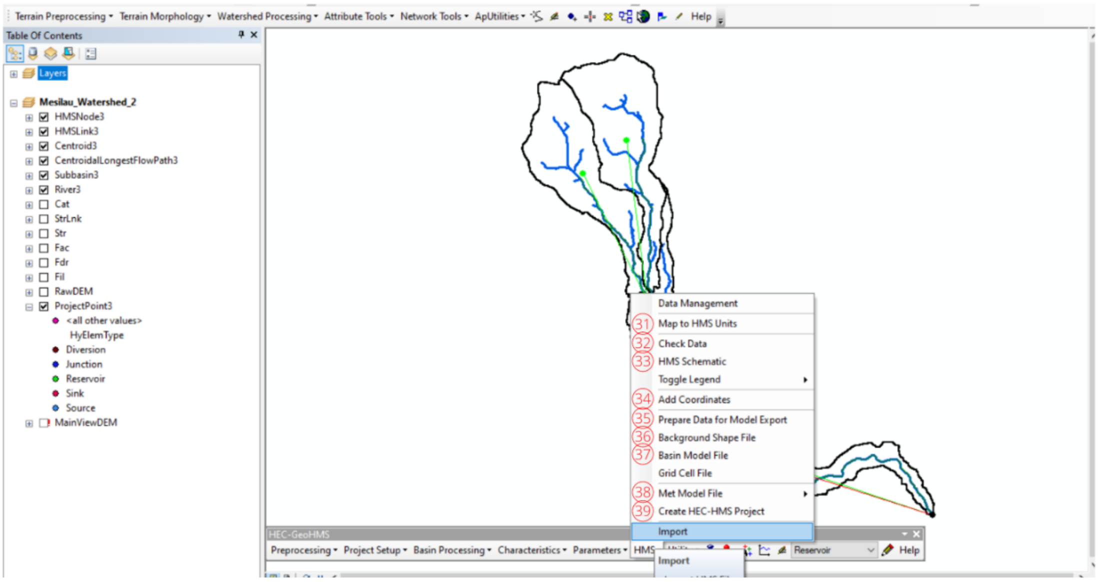

Figure B-8 The steps conducted in the Hec-GeoHMS, under HMS (Step: 31 – 39).

Appendix C The accuracy assessment results for; (A) before earthquake, and (B) after earthquake.

A. The detailed accuracy assessment results for before the earthquake are as follows.

A.1. The classification results with respect to the correct sampling points (CSP) (grey), the ground truth point (blue), and the total class (red).

	Classifications	Ref. SEM	Ref. Vegetation	Ref. Bare earth	Ground Truth
RAW	SEM	50	0	2	52
	Vegetation	0	49	1	50
	Bare earth	0	1	47	48
	Total Class	50	50	50	150

A.2. The CSP with respect to the total class.

	Classifications	Ref. SEM (%)	Ref. Vegetation (%)	Ref. Bare earth (%)
CSP	SEM	100	0	4
	Vegetation	0	98	2
	Bare earth	0	2	94
	Total	100	100	100

A.3. The commission results in representing the points that are incorrectly classified against the row.

	Classifications	Incorrect Points (Row)	Ground Truth	%
Commissions	SEM	2	52	3.9
	Vegetation	1	50	2
	Bare earth	1	48	2.1

A.4. The omission results in representing the point pixels that are incorrectly classified against the column.

	Classifications	Incorrect Points (Column)	Total Class	%
Omissions	SEM	0	50	0
	Vegetation	1	50	2
	Bare earth	3	50	6

A.5. The end result for the producer's accuracy assessment

Producer acc.	Classifications	CSP	Total Class	%
	SEM	50	50	100
	Vegetation	49	50	98
	Bare earth	47	50	94

A.6. The end result for the user's accuracy assessment.

User acc.	Classifications	CSP	Ground Truth	%
	SEM	50	52	96
	Vegetation	49	50	98
	Bare earth	47	48	97

A.7. The accuracy assessments summary for before the earthquake.

Summary	Classifications	User's accuracy (%)	Producer's accuracy (%)
	SEM	96	100
	Vegetation	98	98
	Bare earth	97	94

Overall classifications accuracy for before the earthquake: **97.3%**
Kappa Coefficient: **0.96**

B. The detailed accuracy assessment results for after the earthquake are as follows.

B.1. The classification results with respect to the correct sampling points (CSP) (grey), the ground truth point (blue), and the total class (red).

	Classifications	Ref. SEM	Ref. Vegetation	Ref. Bare earth	Ground Truth
RAW	SEM	46	0	3	49
	Vegetation	0	50	0	50
	Bare earth	4	0	47	51
	Total Class	50	50	50	150

B.2. The CSP with respect to the total class.

	Classifications	Ref. SEM (%)	Ref. Vegetation (%)	Ref. Bare earth (%)
CSP	SEM	92	0	6
	Vegetation	0	100	0
	Bare earth	8	0	94
	Total	100	100	100

B.3. The commission results in representing the points that are incorrectly classified against the row.

	Classifications	Incorrect Points (Row)	Ground Truth	%
Commissions	SEM	3	49	6.1
	Vegetation	0	50	0.0
	Bare earth	4	51	7.8

B.4. The omission results in representing the point pixels that are incorrectly classified against the column.

	Classifications	Incorrect Points (Column)	Total Class	%
Omissions	SEM	4	50	8
	Vegetation	0	50	0
	Bare earth	3	50	6

B.5. The end result for the producer’s accuracy assessment

	Classifications	CSP	Total Class	%
Producer acc.	SEM	46	50	92
	Vegetation	50	50	100
	Bare earth	47	50	94

B.6. The end result for the user’s accuracy assessment.

User acc.	Classifications	CSP	Ground Truth	%
	SEM	46	49	94
	Vegetation	50	50	100
	Bare earth	47	51	92

B.7. The accuracy assessments summary for after the earthquake.

Summary	Classifications	User's accuracy (%)	Producer's accuracy (%)
	SEM	94	92
	Vegetation	100	100
	Bare earth	92	94

Overall classifications accuracy for before the earthquake: **95.3%**
Kappa Coefficient: **0.93**

Appendix D The raw outputs for the people-centred survey, extracted using the SPSS software.

A. Respondents Demographic

[A.1] Gender

		Frequency	Percent
Valid	Male	32	68.1
	Female	15	31.9
	Total	47	100.0

[A.3] Age Range

		Frequency	Percent
Valid	20 - 29	3	6.4
	30 - 39	18	38.3
	40 - 49	15	31.9
	50 - 59	7	14.9
	> 60	4	8.5
	Total	47	100.0

[A.4] Respondent's Highest Education

		Frequency	Percent
Valid	Higher Secondary School (SPM)	1	2.1
	Pre-University (Foundation/STPM/Diploma/Matric)	2	4.3
	Tertiary Education (Degree)	22	46.8
	Master/PhD	22	46.8
	Total	47	100.0

[A.6] Range of Respondents Working Experience

		Frequency	Percent
Valid	< 5	12	25.5
	6 - 10	11	23.4
	11 - 15	13	27.7
	16 - 20	1	2.1
	> 21	10	21.3
	Total	47	100.0

[A.7] Rank of the Respondent Experiences in Disaster

				Percent of Cases
Valid	Flood	36	35.3%	76.6%
	Landslide	29	28.4%	61.7%
	Debris flow	20	19.6%	42.6%
	Earthquake	17	16.7%	36.2%
Total		102	100.0%	217.0%

[A.8] Respondent's Involvement in Disaster Management

		Frequency	Percent
Valid	Yes	29	61.7
	No	18	38.3
	Total	47	100.0

B. Knowledge of Landslide and Debris Flow

[B1.1] Respondent Knowledge on the Existence of the 2015 Sabah Earthquake

		Frequency	Percent
Valid	Yes	43	91.5
	No	4	8.5
	Total	47	100.0

[B1.2] Rank of the Vulnerable Landslide Area

				Percent of Cases
Valid	Kundasang	40	41.7%	87.0%
	Ranau	25	26.0%	54.3%
	Kota Belud	19	19.8%	41.3%
	Kota Kinabalu	9	9.4%	19.6%
	Lahad Datu	3	3.1%	6.5%
Total		96	100.0%	208.7%

[B1.3] Respondent Knowledge on the Cascading Debris Flow Hazard and Risk

		Frequency	Percent
Valid	Yes	40	85.1
	No	7	14.9
	Total	47	100.0

[B1.4] Rank of the Debris Flow Occurrences

				Percent of Cases
Valid	Mesilau river	34	39.5%	82.9%
	Melangkap river	26	30.2%	63.4%
	Kedamaian river	26	30.2%	63.4%
Total		86	100.0%	209.8%

[B1.7] Rank of the Retrieved Debris Flow Information

				Percent of Cases
Valid	Expert	30	21.0%	63.8%
	Newspaper	27	18.9%	57.4%
	SNS	23	16.1%	48.9%
	Radio and TV	23	16.1%	48.9%
	Government	22	15.4%	46.8%
	Research paper	18	12.6%	38.3%
Total		143	100.0%	304.3%

[B1.8] Rank of the Debris Flow Contributing Factors

				Percent of Cases
Valid	Hydrological factor	46	40.7%	97.9%
	Geomorphological factor	33	29.2%	70.2%
	Geological factor	30	26.5%	63.8%
	Human made	4	3.5%	8.5%
Total		113	100.0%	240.4%

B2. Knowledge of Early Warning System

[B2.1] Do you know any Existing Early Warning System (EWS) in Malaysia?

		Frequency	Percent
Valid	Yes	36	76.6
	No	11	23.4
	Total	47	100.0

[B2.2] Rank of the Common or Known EWS in Malaysia

				Percent of Cases
Valid	Flood	27	42.9%	75.0%
	Tsunami	25	39.7%	69.4%
	Landslide	8	12.7%	22.2%
	Debris flow	3	4.8%	8.3%
Total		63	100.0%	175.0%

[B2.3] Rank of the Retrieved EWS Information

				Percent of Cases
Valid	Expert	25	31.3%	71.4%
	Government	20	25.0%	57.1%
	Research paper	13	16.3%	37.1%
	Newspaper	10	12.5%	28.6%
	Radio and TV	7	8.8%	20.0%
	SNS	5	6.3%	14.3%
Total		80	100.0%	228.6%

[B2.4] Known of Any Working EWS outside of Malaysia?

		Frequency	Percent
Valid	Yes	15	31.9
	No	32	68.1
	Total	47	100.0

[B2.5] Respondent's Involvement in Installing EWS.

		Frequency	Percent
Valid	Yes	10	21.3
	No	37	78.7
	Total	47	100.0

[B2.6] Rank of the Challenges in Installing EWS

				Percent of Cases
Valid	Cost	38	30.4%	80.9%
	Maintainance	36	28.8%	76.6%
	Expertise	25	20.0%	53.2%
	Time	14	11.2%	29.8%
	Installation	12	9.6%	25.5%
Total		125	100.0%	266.0%

[B2.7] Respondent's Opinion in Installing EWS for Kundasang, Sabah.

		Frequency	Percent
Valid	Less critical	1	2.1
	Critical	16	34.0
	Very critical	30	63.8
	Total	47	100.0

[B2.8] Rank of the suitable debris flow EWS for Kundasang case

				Percent of Cases
Suitable debris flow EWS	Full spect, by government	29	50.0%	61.7%
	Low-cost, community-based program	29	50.0%	61.7%
Total		58	100.0%	123.4%

[B2.10] Rank of the Important EWS Elements

				Percent of Cases
Valid	Hazard and risk map	41	24.7%	87.2%
	Rainfall record	33	19.9%	70.2%
	Simulation of past event	32	19.3%	68.1%
	Inventory of past events	31	18.7%	66.0%
	Analysing element at risk	29	17.5%	61.7%
Total		166	100.0%	353.2%

[B2.11] (a) Rank of the Responsible Agencies for the Risk Assessment

				Percent of Cases
Risk assessment	JMG	28	46.7%	66.7%
	DID	15	25.0%	35.7%
	JMG	6	10.0%	14.3%
	JKR	5	8.3%	11.9%
	MCDF	3	5.0%	7.1%
	NADMA	3	5.0%	7.1%

Total		60	100.0%	142.9%

[B2.11] (b) Rank of the Responsible Agencies for the Observation and Monitoring

				Percent of Cases
Observation and Monitoring	JMG	15	27.3%	41.7%
	DID	13	23.6%	36.1%
	Local Community	8	14.5%	22.2%
	Local Authority	5	9.1%	13.9%
	MCDF	5	9.1%	13.9%
	MMD	5	9.1%	13.9%
	NADMA	2	3.6%	5.6%
	Sabah Parks	2	3.6%	5.6%
Total		55	100.0%	152.8%

[B2.11] (c) Rank of the Responsible Agencies for the Warning Communication and Dissemination

				Percent of Cases
Communication and dissemination	NADMA	18	40.0%	43.9%
	Local Authority	9	20.0%	22.0%
	Local Community	9	20.0%	22.0%
	DID	4	8.9%	9.8%
	JMG	3	6.7%	7.3%
	MMD	2	4.4%	4.9%
Total		45	100.0%	109.8%

[B2.11 (d) Rank of the Resposible Agencies for the Response Capability

				Percent of Cases
Response and Capability[a]	NADMA	14	31.1%	35.0%
	Local Authority	10	22.2%	25.0%
	MCDF	8	17.8%	20.0%
	JKR	5	11.1%	12.5%
	Local Community	4	8.9%	10.0%
	DID	3	6.7%	7.5%
	JMG	1	2.2%	2.5%
Total		45	100.0%	112.5%

C. Knowledge of Early Warning System

[C1] Rank of the Suitable Monitoring Methods

				Percent of Cases
Valid	Rainfall station	34	26.4%	72.3%
	Vibration sensor	32	24.8%	68.1%
	CCTV	28	21.7%	59.6%
	Wiring sensor	20	15.5%	42.6%
	Drone	15	11.6%	31.9%
Total		129	100.0%	274.5%

[C2] Does your organization play a role in monitoring a debris flow event?

		Frequency	Percent
Valid	Yes	11	23.4
	No	36	76.6
	Total	47	100.0

[C4] Respondent's Agencies that Worked with the Local Stakeholders for the Real-Time Monitoring

		Frequency	Percent
Valid	Yes	15	31.9
	No	32	68.1
	Total	47	100.0

[C5] Rank of the Responsible Local Stakeholders for the Real-Time Monitoring

				Percent of Cases
Valid	Village Leader	11	26.2%	61.1%
	District Officers	9	21.4%	50.0%
	Civil Defense Force	7	16.7%	38.9%
	University	6	14.3%	33.3%
	Police	5	11.9%	27.8%
	Fire Department	4	9.5%	22.2%
Total		42	100.0%	233.3%

D. Warning Dissemination and Communication

[D1] Rank of the Disaster Dissemination During the Past Event

				Percent of Cases
Valid	Mosque speaker	27	27.0%	42.6%
	Radio and TV	25	25.0%	66.0%
	Phone Call	24	24.0%	51.1%
	SNS	21	21.0%	44.7%
	Email	4	3.0%	8.5%
Total		100	100.0%	212.8%

[D2] Rank of the Well-Reacted EWS messages by the Community

		Frequency	Percent
Valid	Very reactive	10	21.3
	Some Action	24	51.1
	Not Sure	11	23.4
	No Action	2	4.3
	Total	47	100.0

[D3] The Effectiveness of the Disaster Information Disseminated.

		Frequency	Percent
Valid	Very Effective	2	4.3
	Effective	22	46.8
	Less Effective	21	44.7
	Not Effective	2	4.3
	Total	47	100.0

[D4] Percentage Level of the Disaster Information Reached the Community

		Frequency	Percent
Valid	0 - 25%	5	10.6
	25 - 50%	19	40.4
	50 - 75%	19	40.4
	75 - 100%	4	8.5
	Total	47	100.0

[D5] Rank of The Reasons for the Low Percentage as in D4

				Percent of Cases
Valid	Late in Dissemination	22	44.9%	64.7%
	Ignored the Information	17	34.7%	50.0%
	Distrust in Information	10	20.4%	29.4%
Total		49	100.0%	144.1%

[D6] Rank of the Effective Medium to Warn the Community

				Percent of Cases
Valid	Sirens	43	31.4%	91.5%
	Phone Call	30	21.9%	63.8%
	SNS	29	21.2%	61.7%
	Newspaper	26	19.0%	55.3%
	Email	9	6.6%	19.1%
Total		137	100.0%	291.5%

[D7] Respondent's Agencies Communication Level with the Local Government and Local Communities

		Frequency	Percent
Valid	Very High	6	12.8
	High	15	31.9
	Medium	18	38.3
	Low	8	17.0
	Total	47	100.0

E. Warning Dissemination and Communication

[E1] General Response Capability by the Community

		Frequency	Percent
Valid	Low	14	29.8
	Medium	25	53.2
	High	8	17.0
	Total	47	100.0

[E2] Respondent's Recommendation for the First Step to Improve the Local Responses

		Frequency	Percent
Valid	Education	27	57.4
	Community Engagement	10	21.3
	Early Warning System	9	19.1
	Data Sharing	1	2.1
	Total	47	100.0

[E3] Suggested Programs/Actions to be Implemented

		Frequency	Percent
Valid	Community Program	22	46.8
	Education	10	21.3
	School Education	3	6.4
	Simulation Drill	12	25.5
	Total	47	100.0

[E4] Rank of the Lead Agency for the Capacity Building Programs

	Percent of Cases

Valid	State governments	36	31.6%	81.8%
	District offcer	35	30.7%	79.5%
	Federal governments	22	19.3%	50.0%
	University	21	18.4%	47.7%
Total		114	100.0%	259.1%

[E6] Rank of the Suitable Evacuation Drill and Training

				Percent of Cases
Suggested Evacuation Drill	Every 6 months	26	59.1%	59.1%
	When Needed	10	22.7%	22.7%
	Once a Year	8	18.2%	18.2%
Total		44	100.0%	100.0%

LIST OF PUBLICATIONS

1. Rosli, M. I., Razak. K. A. and Mohd Kamal, N. A. (2021) 'Assessing Earthquake-induced Debris Flow Risk in the First UNESCO World Heritage in Malaysia', *Remote Sensing Applications: Society and Environment* (RSASE), pp. 1-10. (*Submitted Journal*).

2. Rosli, M. I., Asmadi, M. A., Che. Ros, F., and Marto, A. (2020) 'Assessing Debris Flow Risk in Tectonically Active Regions: A Technological Approach', in *Book Chapter 8 Volume 1: Advancing Disaster Risk Reduction for Societal Resilience.* (*Submitted Book Chapter*).

3. Rosli, M. I., Razak, K. A., Che Ros, F. and Ambran, S. (2020) 'Debris Flow Risk Reduction in Malaysia: From Science-Policy to Multi-Stakeholder Actions', *1,* pp. 123-142. (*Accepted*).