Application of Unmanned Aerial Vehicle (UAV)-Acquired Topography for Quantifying Typhoon-Driven Landslide Volume and Its Potential Topographic Impact on Rivers in Mountainous Catchments

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Abstract: Landslides are highly erosional processes that dominate sediment mobilization and reshape landscapes in orogenic belts. Therefore, quantifying and characterizing landslide volume is essential to disaster prevention and understanding landscape evolution in mountainous rivers. Progressive development of the structure-from-motion (SfM) and multi-view stereo (MVS) photogrammetric techniques and Unmanned Aerial Vehicles (UAV) provides low-cost and high-resolution digital elevation models (DEMs), compared to traditional aerial photogrammetry at the same resolution. In this study, we quantified landslide volume and change in river channel volume at meter-scale accuracy for the Laishe River catchment of southern Taiwan from 2009 to 2015, which provides reliable data for discussing sediment transport and morphological response. The observations indicate that Typhoon Morakot in August 2009, induced a landslide volume of 31.63 million (M) m³, which is equal to 87% of the six-year sediment production. Typhoon Morakot also caused the deposition of 8.2 M m³ in the Laishe River. Additionally, this study demonstrates the feasibility of using UAVs to quantify the migration of landslide material and changes in channel area and volume, and the detection of landslide dams. In conclusion, two sources of images, especially those by UAVs, were used to decipher the consequence and potential hazard, social impact, and morphological changes in a mountainous river.

Keywords: unmanned aerial vehicles; LiDAR; landslide volume; geohazards; typhoon Morakot

1. Introduction

Landslides are highly erosional processes that dominate sediment mobilization and reshape landscapes in orogenic belts [1,2]. As a driving force between lithosphere and hydrosphere, landslides cause considerable material transport into fluvial systems, which may affect the ecological environment [3,4], nutrient/carbon transport [5–7], and also affects socioeconomic activities, i.e., food production [8,9]. Traditionally, the quantification and characterization of typhoon-derived landslide volumes at the catchment scale has relied on in-site surveys or satellite images [10–14]. However, it is limited by the manpower, lack of equipment, steep topographic settings, road interruptions,
and timeliness/completeness of satellite image acquisition; therefore, it is not feasible to conduct a comprehensive survey immediately after a typhoon event.

Progressive development of structure-from-motion (SfM) photogrammetric techniques and Unmanned Aerial Vehicles (UAVs) [15,16], which provide low-cost and high-resolution digital elevation models (DEMs) can be constructed using remote-controlled UAV surveys. Additionally, UAV-driven images can be corrected using ground control points, such as data from light detection and ranging (LiDAR) and real-time kinematic Global Positioning System (RTK-GPS), which can then be given high-precision spatial information [17,18]. UAVs can be applied to many fields such as disaster relief [19–21], studies of active tectonics [22–24], and studies of fluvial processes [25–27]. The advantages of the extensive, fast image acquisition capability provide a great opportunity to map landslides in mountainous river regions [28–32].

Typhoon Morakot in 2009, induced precipitation of 2686 mm in three days in Pingtung County and 2517 mm in Kaohsiung City [33], causing severe landslides in the mountainous areas of southern Taiwan [34–36]. Among the landslide-affected areas, the Laonong River catchment had the largest landslide area and the highest new landslide ratio [37]. Meanwhile, the upstream regions of the Linbian River, Laishe River became potential debris flow source areas, which continue to experience landslides. The threat of landslides not only affects the economic production, lives, and safety of mountain villages, but also affects the ability to preserve ecological resources and to conserve soil and water resources. Undoubtedly, the Laishe River catchment is one of the most highly landslide-affected areas after Typhoon Morakot. Therefore, it may provide an opportunity to examine the applicability of UAVs in quantifying the typhoon-derived landslide volume of the mountainous catchment. In this study, the images Digital Mapping Camera (DMC), of ADS40, LiDAR, and UAVs are integrated to decipher the consequences and the potential hazards. This study constructs DEMs before and after Typhoon Morakot, as well as the subsequent periods. With the datasets, it is possible to quantify the landslide volume and conduct further analysis of the morphological changes in the Laishe River catchment. The result can provide not only the geospatial dataset of the hazards, but also the essential geomorphologic, hazard mitigation, and planning information.

2. Material and Methods

2.1. Geomorphological and Geological Setting

The study area comprises the Laishe River catchment area of 69.8 km² in Pingtung County, southern Taiwan (Figure 1). The catchment originated from the western flank of the Central Mountain Range (CMR). The region experiences a tropical monsoon climate with an average annual precipitation of 4109 mm, (1980–2009) measured from Xinlaiyi and Taiwu stations and calculated using the Thiessen’s polygon method [38].

The typical landscape of the Laishe River is a valley region. Based on image interpretations and on-site investigations, it was found that the landslides are caused by incision and lateral erosion of the river. This process widens the river valley and steepens the hillslopes, resulting in the current topographical features of the Laishe River, including landslides near the riverbank, which has a series of river terraces and alluvial fans. The Laishe river is mainly composed of the Lushan formation, and only a part of the upstream area sits in the Bilushan Formation. Because the Lushan Formation is composed of a thick layer of argillite, slate, phyllite, and thin sand and shale interbed, the topographic change in the Laishe River catchment area is considerable; therefore, it is divided into six sub-sections based on the characteristics of landslides and channelized erosion, to understand the detailed changes in hillslopes and main channels (Figure 1a).
Figure 1. Location and geological background of the study site. (a) Color-shaded relief map showing the geographic location of the study site. UP3: upstream 3; UP2: upstream 2; UP1: upstream 1; EV: east village; WV: west village; YL: Yilin; TW: Taiwu: TW, a meteorological station. (b) Geological map of the sample site in this study; the square areas denote the Unmanned Aerial Vehicles (UAV) survey area in this study and the colors denote the various missions in the UAV survey.

2.2. Typhoon Morakot

Typhoon Morakot occurred from 7–9 August 2009 and caused at least 619 deaths and 76 disappearances in Taiwan. Agricultural losses exceeded USD 55 million. It was the worst casualty typhoon in Taiwan’s history [33]. The observed data from Taiwu Station show that the total precipitation was 1402 mm (8 August) and the maximum precipitation for the second consecutive day was 2146.5 mm (7–8 August). Simultaneously, the maximum daily rainfall in the Laishe River catchment area was 1427 mm [38]. The heavy rains led to the Laishe River flood and caused large-scale deep-seated
landslides, which damaged 120 houses and roads up to 3 km, and produced more than 15 m high sediment deposits in the Laishe River [39].

2.3. DEM Acquisition

2.3.1. Data Sources

The airborne LiDAR DEM data were provided by the Satellite Survey Center, Depart of Land Administration, Ministry of the Interior, and Central Geological Survey, Ministry of Economic Affairs. Airborne LiDAR technology produces effective data for obtaining large-area and high-resolution digital terrain features with the characteristics of rapid measurement, and lower unit cost [40]. Therefore, airborne LiDAR technology has been widely applied on slope hazard mapping, disaster prevention, interpretation of large-scale landslide areas, and changes in sediment transport in river channels [40,41] and survey of agriculture and forestry resources [42,43]. With the assistance of GPS, and IMU (Inertial Measurement Unit), each reach LiDAR return have positioning data. LiDAR data are composed of dense point clouds. The higher point cloud density can be used to build a high-density DEM.

The LiDAR DEM acquired in 2010 was used in this study. The grid spacing size was 1 m. Overlapping between swaths was greater than 40%. The point density of the areas where the elevation below 800 m is higher than 2 points/m², whereas the elevation above 800 m is higher than 1.5 points/m². The TWD97 coordinate system is used. The external error evaluation of airborne LiDAR is to select a certain proportion of ground control points and LiDAR data for comparative analysis to evaluate the overall accuracy. Ground control areas were selected from bare land, dwarf vegetation (short grass, dwarf trees, tea gardens, etc.), sheltered forests, densely covered forest, metropolitan areas, etc. Each category selects about 30 points for the precise measurement of RTK-GPS or total station. The elevation difference between ground point and LiDAR DEM is mostly within 10 cm [44].

The images before Typhoon Morakot were provided by the Aerial Survey Office, Forestry Bureau, Council of Agriculture, Executive Yuan, and were obtained from an airborne platform with an Airborne Digital Sensor ADS40 airborne camera or Z/I Imaging DMC. The Airborne Digital Sensor ADS40 is a commercially available airborne camera developed by Leica. It can provide five spectral bands (Panchromatic, R, G, B, NIR), three panchromatic CCD lines, four multispectral CCD lines, a 12-bit dynamic range CCD chain, 14-bit Resolution A/D converter, 16-bit data channel, and get true color 3D data in photogrammetry. The DMC system developed by Intergraph that provides four multispectral (R, G, B, NIR), 3k × 2k camera heads, CCD frame sensor technology delivers the best geometric accuracy, and 12-bit per pixel radiometric resolution ensures exceptional image clarity. Data acquisition of images after Typhoon Morakot was performed using the Skywalker X8 carry with Nikon D800E with a fixed lens of 50 mm focal length. In addition, the average rainfall intensity of the 1st survey period is 120.04 mm/rainy days and the rainfall intensity of 2nd and 3rd survey period are 45.50 and 41.97 mm/rainy days, respectively. The rainfall intensity caused by typhoon Morakot is 3 times more than the regular periods and this observed difference may cause the measurable difference of topographic process. The detailed information of the image source is shown in Table 1.
Table 1. Information on the image source.

| Date            | Camera | Coverage Area (km\(^2\)) | GSD \(^1\) (cm) | DEM Grid Spacing (m) | Platform | AGL \(^2\) (m) | Average Rainfall Intensity (mm/rainy days) |
|-----------------|--------|---------------------------|-----------------|---------------------|----------|---------------|---------------------------------|
| 10 April 2009   | DMC    | 80                        | 30              | 2                   | Aircraft | 4004          | -                              |
| 28 August 2009  | ADS40  | 32                        | 15              | 2                   | Aircraft | 4000          | 120.04                         |
| 2010 LiDAR      |        |                           |                 |                     | Aircraft | 4000          | -                              |
| 23 January 2015 | Nikon D800E | 67.5                      | 15              | 0.17                | UAV      | 1500–3000     | 45.50                          |
| 6 November 2015 | Nikon D800E | 69.8                      | 15              | 0.20                | UAV      | 1500–3000     | 41.97                          |

\(^1\) Ground sampling distance; \(^2\) Above ground level.

2.3.2. DEM Construction

In this study, UAV has been used for 2 missions, which were carried out in January and November 2015. A total of 3529 images were captured for the first time, with a survey area of 67.5 km\(^2\). The second flight mission was completed in November. A total of 1697 images were captured, with a survey area of 69.8 km\(^2\). The Overlay and Sidelap are >80% and >60%, respectively. The Pix4Dmapper software developed by the Swiss Pix4D company was used in this study. The aerial photographs taken by the UAVs were exported to the Pix4Dmapper to build DEMs for calculations of landslide volume and change in river channel depth in based on structure-from-motion (SfM) and multi-view stereo (MVS) photogrammetric techniques [45,46], then analysis by ArcGIS application. The principle of the Pix4Dmapper model production is split into the following five steps [47]: (1) search for feature points in the images; (2) aerial triangulation adjustment to reconstruct the precise position and camera direction; (3) verification of feature points and calculation of 3D coordinates; (4) interpolation of feature points to construct an irregular triangular mesh to obtain DEMs and building a dense 3D model to increase the spatial resolution of the triangular mesh; (5) projection images on DEMs to make orthophotos.

To reduce such discrepancies, ground control points (GCPs) should be used. However, the study area is situated on high relief mountainous range, the access is limited, so, only part of GCPs situated on the valley closed to the village are available. It is believed that airborne LiDAR has the best quality [44,48]. Alternatively, we focused on the geomorphic changes, only the difference is a major concern, thus the relative precision of the datasets is feasible for such analysis. Caused by inaccessibility and availability, distinct topographic features are chosen from the airborne LiDAR dataset. In this study different GCPs have been used for DEM production. Figure 2 denotes the distribution of GCPs. The control points were assigned based on the permanent points within the landscapes, such as the intersection of roads and mountain peaks (Figure 2). Especially for leveling control, the area was selected first without a significant change within the DEMs.
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Figure 2. Distribution of ground control points (GCPs) of digital elevation models (DEMs). The dots denote the sampling point in this study and the colors denote various missions of the surveys.

3. Results

3.1. Accuracy of DEMs

ArcGIS application was used to convert the selected area of DEMs into point files to obtain the elevation of each point and to calculate the mean and standard deviation (SD) (Table 2). It was decided that three times the standard deviation would be used as the allowable error range, which further removed the outlier value for calculating landslide volumes and changes to the channel depth. In addition, Table 2 indicates that the comparison of the survey errors of all regions in each period without including the river change and landslide area. Overall, the control point densities spaced from 0.05–1.0 pts/m² and the mean of the vertical bias between surveyed DEMs and airborne LiDAR space was from −0.13–0.65 m. To quantify the extreme typhoon-event-induced landslide volume, the authors believe that less 1 m of survey error is acceptable on a catchment scale.

Table 2. Vertical bias between survey DEMs and LiDAR DEM.

| Date          | Control Point Density (pts/m²) | Vertical Bias (m) |        |        |        |
|---------------|--------------------------------|-------------------|--------|--------|--------|
|               |                                | Mean              | SD     | Maximum| Minimum|
| 10 April 2009 | 0.25                           | 0.65              | 7.2    | 22.25  | −20.95 |
| 28 August 2008| 0.05                           | 0.65              | 4.8    | 15.05  | −13.75 |
| 23 January 2015| 0.99                          | 0.47              | 4.8    | 14.87  | −13.93 |
| 6 November 2015| 1.00                          | −0.13             | 4.2    | 12.47  | −12.73 |

3.2. Landslide Volume and Change in River Channel Volume

The landslide volume and sediment budget of the Laishe River channel is shown in Tables 3 and 4, respectively. The location of the six sub-sections, upstream 3 (UP3), upstream 2 (UP2), upstream 1 (UP1), east village (EV), west village (WV), Yilin (YL), and Taiwu (TW) are denoted on Figure 1a. The abbreviation of the six sites is used afterward. Overall, the total landslide volume was approximately 36.16 million (M) m³ from April 2009 to November 2015, and the landslide volume decreased from upstream to downstream (Table 3). Furthermore, the total landslide volume was
approximately 31.63 M m$^3$, which also shows a decrease from upstream to downstream. More than 80% of the landslide volume was produced from the upstream area. Moreover, the ratio of landslide volume in two periods ranged from 9.09% to 133.33%. Except for WV, all the ratios of landslide volume were over 77%, which means Typhoon Morakot dominated the landslide volume over a six-year period. Additionally, the >100% ratio in EV and YL may indicate that the recovery of landslide scars was measurable, for example, for vegetation recovery. However, the deposited volume was relatively lower than the landslide-induced erosion; only 0.49 M m$^3$ at EV and 0.06 M m$^3$ at YL.

Table 3. Landslide volume.

|         | UP3 | UP2 | UP1 | EV | WV | YL | Total |
|---------|-----|-----|-----|----|----|----|-------|
| Area (M m$^3$) | 1.2 | 1.45 | 1.19 | 0.8 | 0.17 | 0.17 | 4.97  |
| Date     | 10 April 2009–6 November 2015 | 11.73 | 10.07 | 8.47 | 5.50 | 0.22 | 0.18 | 36.16 |
| Volume (M m$^3$) | 10 April 2009–28 August 2009 | 9.12  | 9.01  | 7.25 | 5.99 | 0.02 | 0.24 | 31.63 |
| Ratio (%) | 77.75 | 89.47 | 85.60 | 108.91 | 9.09 | 133.33 | 87.47 |

Table 4. Topographic change in the river depth.

|         | UP3 | UP2 | UP1 | EV | WV | YL |
|---------|-----|-----|-----|----|----|----|
| Date     | 10 April 2009–6 November 2015 | −5.44 | 6.55 | 5.47 | 6.91 | 4.02 | 3.26 |
| Change in Height Difference (m) * | 10 April 2009–28 August 2009 | −2.33 | 13.79 | 11.10 | 8.14 | 2.84 | 2.54 |
| Ratio (%) | 42.83 | 210.53 | 202.93 | 117.80 | 70.65 | 77.91 |

* negative value represents erosion and a positive value represents deposition.

For the distribution of landslides (Figure 3a), four landslides with a hundred meter in length in UP3, two of which were old landslide areas (Mark 1 and 2) were used. Landslides continued to expand by subsequent typhoon-induced erosion, such as headward erosion (Mark 3). Additionally, hillslopes along the river channel were severely eroded due to river flow, causing lateral erosion-induced landslides from several meters to several tens of meters (Mark 4). The erosion pattern of UP2 was similar to UP1, a headward erosion and lateral erosion induced landslide (Mark 5–8). By combining the landslide material of UP3 and UP2 that accumulated with the river, UP2 had the largest sediment deposition in the catchment. Among the three landslides with a kilometer in length in UP1, two were caused by headward erosion (Mark 9) and one was in an old landslide area (Mark 10). The resulting lateral erosion led to the continuous expansion of the scale of landslides from 20–80 m (Mark 11). There were also many lateral erosions along the river channel. Two of these landslides were prominent, with lateral erosion mixed with headward erosion (Mark 12) and lateral erosion of the Neishe River (Mark 13). The landslides in WV were affected by two creeks (Mark 14). Although the creeks above the WV were not as severely eroded as the upstream area, they extended to the ridge and there was continuous collapse damage to the residential area. This was not as obvious, relatively, as the lateral erosion of the river channel in YL. The only factor that needed to be noted here was a potential debris flow (Mark 15) below the YL village. Typhoons Haitang and Talim in 2005, Kemi in 2006, Morakot in 2009, and Fanabee in 2010 were all followed by disasters.
Figure 3. Distribution of height changes obtained from the DEM by the UAV survey (a) 10 April 2009–28 August 2009 (b) 28 August 2009–6 November 2015. Blue dots denote the outlet of Laishe River.

In this study, we did not have a field survey of landslide and channel depth, but the evaluation of accuracy provides centimeter to the meter-scale resolution of DEMs, and therefore the data should be expanded to support the observation results. As for a long-term topographic change in the river channel (after Typhoon Morakot), UP3 was the only river section that showed erosion. Due to the steep channel gradient, the landslide material after the typhoon was transported to the middle and lower reaches of the flood. Therefore, the erosion in UP3 was higher than the deposition. The channel area was approximately $0.09 \text{ km}^2$, average channel height change was $5.44 \text{ m}$ (Table 4), and the highest height difference was $30–35 \text{ m}$. The deposition at UP3 was $0.07 \text{ M m}^3$, erosion volume was $0.58 \text{ M m}^3$, and the total amount of erosion was $0.51 \text{ M m}^3$ (Table 5). From UP2, the channel was shown to be experiencing accumulation, the channel area was approximately $0.11 \text{ km}^2$, average height difference was $6.55 \text{ m}$ (Table 4), highest height difference was $25–30 \text{ m}$, deposition volume was $0.97 \text{ M m}^3$, the erosion volume was $0.24 \text{ M m}^3$, and the total amount of deposition was $0.73 \text{ M m}^3$ (Table 5). In UP1, several creeks converged to the main channel. The landslides caused substantial deposition downstream of the confluence and well as widening of the channel. The channel area was approximately $0.24 \text{ km}^2$, average height difference was $5.47 \text{ m}$ (Table 4), the highest height difference was $30–33 \text{ m}$, deposition volume was $1.75 \text{ M m}^3$, erosion volume was $0.42 \text{ M m}^3$, and the total amount of deposition...
was 1.33 M m$^3$ (Table 5). In EV, two large landslides near the upstream and above the residential area formed the largest deposition in the catchment. The river channel area was approximately 0.24 km$^2$, average height difference was 6.91 m (Table 4), the highest deposition depth was 15–20 m, deposition volume was 1.83 M m$^3$, erosion volume was 0.14 M m$^3$, and the total amount of deposition was 1.69 M m$^3$ (Table 5). In WV, the downstream section of the Laishe River, sediments from upstream had gradually slowed down, and there was no large-scale landslide. The channel area was approximately 0.18 km$^2$, average deposition depth was 4.02 m (Table 4), highest deposition depth as 8–10 m, deposition volume was 0.77 M m$^3$, erosion volume was 0.03 M m$^3$, and the total amount of deposition was 0.74 M m$^3$ (Table 5). In YL, the gentlest channel of the Laishe River catchment, the channel area was approximately 0.14 km$^2$, average height difference was 3.26 m (Table 4), highest height difference was 8–10 m, deposition volume was 0.45 M m$^3$, erosion volume was less than 0.01 M m$^3$, and the total amount of deposition was 0.44 M m$^3$ (Table 5).

| Date                  | UP3 | UP2 | UP1 | EV  | WV  | YL  | Total |
|-----------------------|-----|-----|-----|-----|-----|-----|-------|
| 10 April 2009–6 November 2015 | −0.51 | 0.73 | 1.33 | 1.69 | 0.74 | 0.44 | 4.44  |
| 10 April 2009–28 August 2009     | −0.28 | 2.57 | 2.80 | 2.40 | 0.54 | 0.29 | 8.32  |
| Ratio (%)              | 54.90 | 352.05 | 210.53 | 142.01 | 72.97 | 65.91 | 187.39 |

* negative value represents erosion and a positive value represents deposition.

In addition, for the event-scale topographic changes of the river channel (Table 5) in UP3, the average height difference was 2.33 m (42.83% of the long-term average) and the total amount of deposition was 0.28 M m$^3$ (54.90% of the long-term average). At UP2, the channel showed accumulation, with an average height difference of 13.79 m (210.53%), and total depositional amount of 2.57 M m$^3$ (352.05%). From UP1 to YL, the decreasing average height difference was 11.0 (202.93%), 8.14 (117.80%), 2.84 (70.65%), and 2.54 m (77.91%), and the total deposition amount was 2.80 (210.53%), 2.40 (142.01%), 0.54 (72.97%), and 0.29 (65.91%) M m$^3$. Overall, compared to the long-term average, Typhoon Morakot almost doubled the sediment input. In particular, the sections of UP2, UP1, and EV had double, and even triple the normal sediment input.

4. Discussion

4.1. Waste-Filled Valleys in a Mountainous River

Waste-filled valleys are defined as the river valleys that fill with weak diagenetic sedimentary rock [49,50], caused by glacial and fluvial deposition or even human activity. The geomorphic evolution of waste-filled valleys, such as braided rivers, meander belts, and erosional river terraces, can provide the opportunity for understanding the interaction among driving forces, landscape, and the anthroposphere. Indeed, the considerable sediment supply is critical in a mountainous river, and, therefore, geomorphic forces connecting hillslope and channel systems control the source supply of waste-filled valleys [51,52]. In orogenic belts, landslides dominate the sediment production or erosion rate in catchment scales [53,54]. Therefore, quantifying sediment input is essential for discussing the cause of waste-filled valleys. In this study, the time-series change of meter to decameter-scale landslide volume and river channel volume was documented after Typhoon Morakot.

After being affected by several typhoon events, the reach of UP3 was almost eroded due to the steep channel gradient. The reach of UP2 began to experience accumulation along the river channel to the downstream area. Based on the observed data of channel volume, the upstream area was eroded (UP3), and the midstream (UP2 and UP1) and downstream (EV, WV, and YL) experienced accumulation,
which was generally consistent with the recognized phenomenon that upstream erodes, midstream transports, and downstream accumulates sediment. Large-scale landslides have occurred in the middle and lower reaches cause by headward erosion, lateral erosion, and old landslides. From April 2009 to November 2015, the channel deposition volume was 4.4 M m$^3$ in the Laishe River, and over 36.12 M m$^3$ of the landslide volume was produced during this period. Therefore, considerable landslide volume stayed in the hillslope system or was transported downstream. In addition, river terraces encompass most of the life and all human activity in the mountainous area; however, the origin of river terraces is usually linked to the incision of the waste-filled valleys [55]. Therefore, the settlements built on these terraces may be located in historic flooding areas with the high potential risk of hillslope disaster.

4.2. Change in the Laishe River Midstream

Large amounts of landslide material in the mountains are the main source of debris flows [56]. In particular, riverbank landslides can directly cause riverbed sedimentation and form landslide dams; subsequently, heavy rains may cause dam breaks, leading to downstream flooding. Monitoring channel platforms is essential for analyzing channel stability as well as improving river management. Three DEM periods were used in this study to clarify the dominant changes in the Laishe River due to Typhoon Morakot and multiple other events from 2009 to 2015. The height difference of the DEMs indicates that the channel change was the highest between April 2009 and 2010 (Figure 4a), during which, a deposition thickness of approximately 34 m can be observed (Figure 5). During this period, only Typhoon Morakot caused severe disasters in southern Taiwan. Therefore, the channel change during this period can be considered as a single event. From 2010 to January 2015, serious erosion of the river channel can be detected (Figure 4b). During this period, the typhoons affecting southern Taiwan were Meranti, Fanapi, Megi, Nanmadol, Talim, Saola, Tembin, Soulik, Trami, Kong-Rey, Usagi, Matmo, Fung-Wong, etc., considering the changes in the river channel during this period as the result of multiple typhoon events. In short, it is found that the changes in the Laishe River channel were mainly caused by Typhoon Morakot in 2009, which induced significant deposition in the middle of the Laishe River. However, the subsequent typhoons caused small incisions and sporadic landslides, and no obvious channel deposition. After Typhoon Morakot, the only erosional part in the middle reaches (Figure 4a marked by a black arrow), was a natural earth dam that blocked the main channel and formed a landslide dam. It can be seen that the area of the landslide dam is shrinking (Figure 4b). Although the landslide dam is located in the upstream area, far from the main downstream residential area, the danger posed by landslide dams cannot be eliminated. Once the outlet of a landslide dam is blocked and accumulated by runoff, the dam may break, which would cause specific harm to the safety of the lives and property of the downstream residents, i.e., the case in Xiaolin village [41,57,58]. After six years, the geomorphic change appears dynamic stable (Figure 4c). However, the height of the channel is still higher than the condition of pre-Morakot, and the landslide-induce volume still stored in the channel, which means the un cemented sediment could be the erosional material of the following typhoon events; Overall, the channel gradient in upstream, midstream, and downstream before typhoon Morakot are 14.4%, 6.1%, and 2.4%, respectively. After typhoon Morakot, the channel gradients in upstream, midstream, and downstream are 14.4%, 5.7%, and 2.69%, respectively (Figure 5a). Substantial landslide material remains stored in the channel (Figure 5b). The cross-section of the channel also proved the deposition of 10 m after typhoon Morakot and the incise more than 10 m in 2015 (Figure 5c). Nevertheless, the considerable erosion on Earth’s surface is not a single case. The measurable change was observed in the adjacent Laonong River catchment[59]. The Laonong River catchment was also suffering the typhoon Morakot in 2009, but the drainage area of the Laonong River is larger (1373 km$^2$). Using ADS40 images to establish a DEM to analyze the geomorphic changes in the Laonong River channel during Typhoon Morakot, the results show that the channel area increased from 13.78 M m$^2$ to 19.77 M m$^2$ after the event. The erosion volume of the main river channel is 31.19 M m$^3$, the accumulation volume is 147 M m$^3$, and the maximum deposited height in upstream reaches is about 30–40 m. The riverbank of low’ height change would also demonstrate the error
correction in this study is acceptable. The Earth’s surface system changes perpetually due to processes within and interactions amongst the solid Earth and the hydrosphere. The orogenic belt has significant landslides, which generate a large amount of sediment, nutrients \cite{60,61}, and carbon (e.g., \cite{62,63}) during erosion. Therefore, the role of the landslides in the supply behavior of the terrestrial cycle needs to be better understood. In addition, considerable landslide material affects the physical and chemical reactions in the fluvial ecosystem. The behavior of fluvial systems, including turbulence and migration, may result in accelerated exposures or burial for longer-term storage in the sediment. These processes are considered to have a significant impact on the global system.

Figure 4. Distribution of height change obtained from the DEM by the UAV survey in a specific section (a) 10 April 2009–2010 (b) 2010–23 January 2015 (c) 23 January 2015–6 November 2015.
4.3. Integration of UAVs and Airborne LiDAR to Quantifying Landslide Volume

The study area belongs to the high mountain valley and, therefore, was hindered by the high-risk of data collection and uniform control point establishment. The accuracy of the DEMs could be improved, which facilitated confirmation with the local relief and volume calculation. Central Geological Survey, Ministry of Economic Affairs of Taiwan has also applied a similar method (geomorphometric analysis), using multi-phase LiDAR DEM data and DEM data from other image sources to analysis the landslide volume after adjustment, and using the LiDAR image before and after the typhoon season to calculate the sediment yield [40,48] and to evaluate topography changes [56,57]. The study focuses on the application of UAV photogrammetry on change in the landscape by considering LiDAR DEM with relatively precise 3D geoinformation. LiDAR DEM provides GCPs that cannot be measured on-site. Therefore, LiDAR DEM can also provide the benchmarks for comparison of surface change of the survey DEMs. We refer to the smallest relative vertical bias between LiDAR DEM and survey DEMs instead of absolute vertical bias in this study. When the volume of the landslide sediment or the sediment yield in the river channel needs to be calculated, the information can be quickly applied to the planning design and cost analysis of the landslide control project or river dredging project for post-disaster recovery. This study uses multiple images, including aerial images in grid spacing size of 2 m, LiDAR in grid spacing size of 1 m and UAS images in grid spacing size of cm-scale, all of which have been calibrated based on LiDAR, which is sufficient for the analysis of landslide disasters in Taiwan. In addition to analyzing the information of the affected area after the typhoon, the same technique can be used in land monitoring in meter-scale accuracy [55]. A large landslide material caused by Typhoon Morakot in the Laishe River catchment has remained in place. Heavy rain caused significant downstream sediment transport and the narrow upstream river channel easily formed a landslide dam, which facilitated confirmation with the local relief and volume calculation.
formed a landslide dam, which may cause a future disaster such as the historic case of the Xiaolin village [41,57,58]. Therefore, monitoring the changes in the river channel and landslides with the DEMs by regular UAV surveys, not only allows for the understanding of the sediment migration [55], but also ensures the safety of life and property in the downstream areas. Based on this case study, it is suggested that the UAV-acquired DEMs integrated with airborne LiDAR, can play an important role in quantifying and characterizing typhoon-derived landslide volumes and the potential topographic impact to a mountainous river.

5. Conclusions

In this study, multi-period high-resolution aerial photogrammetry images and self-photographed UAV photogrammetry data were used to quantify the landslide and channel sediment volumes to a meter-scale accuracy in the Laishe River catchment from 2009 to 2015, which provided reliable data for discussing sediment transport and morphological changes. From 2009 to 2015, a total of 36.16 M m$^3$ of landslide material were generated. Typhoon Morakot in 2009, caused 31.63 M m$^3$ of landslide sediment, which is equal to 87% of the six-year sediment production volume. From 2009 to 2015, the total depositional volume in the channel was 4.4 M m$^3$. Typhoon Morakot caused deposition of 8.2 M m$^3$, almost double the six-year channel volume input, which means about 3.78 M m$^3$ of sediment in the channel was removed from the observed area. Considering the spatial distribution of change in channel depth, the average erosion depth of the upstream channel was 8.5 m, the average deposition thickness of the middle channel was 5.5–6.5 m, and the average deposition thickness of the downstream channel was 3–6 m. This study used high-resolution DEMs to quantify landslide volume and channel erosion on long-term and event scales at the catchment scale.

This study emphasizes the potential of high-resolution topographic surveys. In particular, it demonstrated the feasibility of using UAVs to quantify the migration of landslide material and the changes in the channel area and volume. In addition, after Typhoon Morakot, the main channel of the Laishe River was blocked by a landslide in the upstream area, and a landslide dam was formed. Meanwhile, the UP2 area in this study also identified the possible location of the landslide dam. Regular monitoring of landslide and channel sediment can effectively determine the formation, location, and possible break form of landslide dams. Therefore, the results of this study have significant potential for application in the monitoring of threshold landscapes. As the intensity of social and economic activities gradually increase, the need for threshold landscapes will also increase. The results from this study would help ensure the security of the residents, and would, therefore, reduce the impact of natural disasters.

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