School of GeoSciences

Dissertation for the degree of

MSc in Geographic Information Science

Daniel Hunn

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Part I: Research Paper
Contents

Contents ................................................................................................................. i  
List of figures ................................................................................................. ii  
List of tables .................................................................................................... iii 
List of abbreviations .......................................................................................... iii  
Abstract ............................................................................................................ iv  

1. Introduction ................................................................................................. 1  
  1.1 Research question and aims ........................................................................ 2  

2. Background and context ............................................................................... 3  
  2.1 Accuracy and availability of topographic data ............................................. 3  
  2.2 DEM merging ............................................................................................. 4  
  2.3 Existing DEM merging methods ................................................................. 5  
  2.4 Lahar flow characteristics ......................................................................... 5  

3. Study area ..................................................................................................... 6  
  3.1 Panabaj ....................................................................................................... 6  
  3.2 October 2005 lahar ..................................................................................... 6  
  3.3 Development since the event ..................................................................... 7  

4. LaharFlow methodology ............................................................................... 8  
  4.1 Data pre-processing I ................................................................................ 8  
  4.2 Source conditions ...................................................................................... 9  
  4.3 Flow parameters ....................................................................................... 9  
  4.4 Results and discussion I .......................................................................... 10  

5. DEM merging methodology .......................................................................... 13  
  5.1 Data pre-processing II ............................................................................. 13  
  5.2 Existing methods ...................................................................................... 13  
  5.3 Proposed method ..................................................................................... 14  
  5.4 Results and discussion II ....................................................................... 16  

Page i
List of figures

Figure 1  Comparison of flow channels in 30m SRTM and 5m AW3D datasets ...... 3
Figure 2  Towns and volcanos around Lake Atitlán ...................................... 6
Figure 3  Path of hurricane Stan over Central America ..................................... 7
Figure 4  Lahar inundation extents in Panabaj .................................................. 8
Figure 5  Flow source and channels ................................................................. 9
Figure 6  Results of the calibrated LaharFlow model, using 10m AW3D data ....... 10
Figure 7  Results of the calibrated LaharFlow model, using 30m SRTM data ...... 11
Figure 8  Intersection and Union of simulated and measured inundation areas ..... 12
Figure 9  Solids concentration through the AW3D modelled flow ..................... 12
Figure 10 East and West halves of DEM area ................................................... 13
Figure 11 Flow chart of the *DBlend* methodology ......................................... 14
Figure 12 Comparison of channels in AW3D and resampled SRTM datasets ...... 15
Figure 13 Comparison of flow channels in the West HR merging scenarios .......... 15
Figure 14 Comparison of flow channels in the East HR merging scenarios .......... 16
Figure 15 Intersection (orange) and Union of AW3D-based (purple) and blended
      DEM-based (blue) inundation areas ...................................................... 17
Figure 16 Depictions of volcanic or lahar hazards in Guatemala ......................... 19
Figure 17 Hazard maps produced through participatory mapping exercises .......... 20
Figure 18  Shaded relief map of the Atitlán area using AW3D elevation data ........ 21
Figure 19  Blender Map depicting AW3D-based flow model over Panabaj .......... 22

List of tables

Table 1  Total area of union and intersection between the inundation area
simulated using complete AW3D data and the area simulated using
blended DEMs .......................................................... 18

List of abbreviations

ADECCAP  Asociación de Desarrollo Comunitario del Cantón Panabaj
ALOS    Advanced Land Observing Satellite
AW3D
DEM    Digital Elevation Model
DSM    Digital Surface Model
DTM    Digital Terrain Model
GIS    Geographic Information System / Science
GPU    Graphics Processing Unit
HR     High Resolution (topographic dataset)
JAXA   Japan Aerospace Exploration Agency
KML    Keyhole Markup Language
LiDAR  Light Detection and Ranging
LR     Low Resolution (topographic dataset)
PRISM  Panchromatic Remote-sensing Instrument for Stereo Mapping
SRTM   Shuttle Radar Topography Mission
TIN    Triangular Irregular Network

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Abstract

With the development of new technologies and methods for collecting elevation data, high resolution DEMs are becoming increasingly available, though limitations can often leave datasets incomplete. This project set out to assess methods for merging together multiple DEMs with varying resolutions for use in overland flow modelling.

The study area for this project is Panabaj, Guatemala which saw significant loss of life and property as a result of a lahar flow in October 2005. In the years since, the population has begun to rebound, leading to an increased number of people at risk of a similar event.

The first stage of this project was to recreate the 2005 lahar using the LaharFlow software using a complete 10m DEM, informed by on-site measurements and observations made soon after the lahar event. Following this, a number of DEMs would be produced using various merging techniques, combining 10m AW3D data with 30m SRTM data, across two scenarios where the high resolution data was used in either the Western or Eastern half of the flow area. By running the same LaharFlow parameters over these merged DEMs, and comparing results from models running on complete and merged DEMs, the effects of the merging techniques on overland flow simulations were be assessed.

The results showed that the three DEM merging methods yielded similar results, however models where high resolution data was used in the Western half (containing the inundation area and flow terminus) yielded consistently better results, indicating that the accuracy of topographic data is plays a greater role in shallower areas where the flow is slower.

In order to facilitate engagement with the local and external stakeholders with varying experience in using spatial data, Blender was used to attempt to produce more accessible model outputs, taking lessons learned from participatory mapping exercises in Guatemala.
Section 1 - Introduction

The combination of the effects of climate change and growing populations in hazard-prone areas is resulting in more frequent and severe disasters (UNISDR, 2002). This has been the case in Panabaj, near Lake Atitlán which, in the years since a deadly lahar event in October 2005, has seen a significant resurgence in its population and land use. Hence, there is significant need to improve and refine flow-modelling tools in order to better understand and prepare for future flow events (Hdeib et al., 2018).

Lahar flows can be considered among the most severe ground-based volcanic hazards due to a number of factors; their rapid and unpredictable mobilisation, high flow speeds, ability to carry large volumes of material, and their tenancy to follow existing river channels towards populated areas (Charbonnier et al., 2018). Among direct volcanic hazards, only tsunamis and pyroclastic flows are considered more lethal (Thouret et al., 2020).

Flow modelling is a vital resource for better understanding and preparing for lahars, as well as flow scenarios such as floods and avalanches. These models have a range of applications from understanding the hydraulic behaviour of a catchment or channel and supporting the design of mitigation strategies, to informing flood forecasting systems and risk maps that can play a significant role in planning and managing emergency responses (Leitão & de Sousa, 2018). The accuracy of a flow model relies, largely, on the quality of its input data; in the context of lahars, topography plays an important role, as overland flows are driven by gravity (Kervyn et al., 2008). The accuracy of a lahar flow model is, therefore, largely dependent on the resolution and accuracy of the DEM, although other parameters must be set correctly to simulate flow speeds and extents adequately.

With the advancement of data collection technologies and methodologies in recent years e.g. ground-based LiDAR and UAV-based photogrammetry, high resolution DEMs are becoming more easily accessible (Leitão et al., 2016b). However, many of these methods have physical and/or logistical limitations that can result in only partial coverage of a study site e.g. Andaru et al. (2021). This has created the need to develop methods to merge DEMs, for use in flow modelling, to take advantage of high resolution topographic data where it is available.

This dissertation aims to use idealised flow conditions to recreate the October 2005 lahar flow event in Panabaj using the LaharFlow model. This model will then act as a basis for testing methods of merging DEMs of differing resolutions. A further aim of this project is to make flow-modelling outputs more accessible for community engagement within Panabaj by combining 3D rendering capabilities with insight and experience from past participatory mapping projects.
1.1 Research question and aims

The key research question of this dissertation is:

Can DEMs of differing resolutions be merged for use in overland flow modelling, while ensuring minimal topographic disjuncture at the boundary between the two DEMs?

To answer this question, this dissertation has three key aims:

1. To use idealised flow conditions to recreate the October 2005 lahar flow event in Panabaj using the LaharFlow model.

2. To test various methods of merging DEMs and assess their ability to create a ‘seamless’ merge by comparing flow models run on complete and merged elevation datasets.

3. To utilise outcomes of previous participatory mapping projects to inform the design and production of map outputs that may be more accessible to local stakeholders.
Section 2 - Background and context

2.1 Accuracy and availability of topographic data

In order to facilitate accurate and reliable flow models, consideration needs to be applied when choosing which topographic datasets to use. Fanghui et al. (2019) state ‘resolution and accuracy of the DEM can affect the performance of volcanic mass flow models, the simulated flow paths, run outs and thicknesses’. As outlined by Capra et al. (2010) and Fanghui et al. (2019), certain physical features of a landscape, such as valleys and contours on a hill-slope, will be more accurately represented in a higher resolution topographic dataset, seen in figure 1. These topographic features influence overland flows; ensuring they are represented accurately is essential in producing reliable flow simulations.

Figure 1 Comparison of flow channels in 30m SRTM and 10m AW3D datasets (Author, 2022)

There are a number of factors that determine the ‘accuracy’ of topographic data. Firstly, the horizontal and vertical accuracy; this simply means how closely a single point in a topographic dataset represents a physical location either laterally or vertically. The second factor is the dataset’s resolution; In a raster-based topographic dataset, spatial resolution typically refers to the ground surface area covered by a single cell, i.e. a 30m resolution DEM cell represents a 30x30m ground area. Topographic datasets, such as SRTM and ASTER GDEM, are freely available and provide near global coverage at a moderate 30m resolution. Their accessibility and moderate resolution has made them common options for flow modelling e.g. Schneider et al. (2006).
This data may be sufficient for many applications, including flow-modelling in many environments, however, for flow models in areas with steep or rugged topographies — such as the landscape surrounding Lake Atitlán — Capra et al. (2010) recommend using an elevation dataset with a resolution of 5-10m. However, high-resolution elevation data, while beneficial for accurate flow modelling, may not be accessible for all or any of a chosen study site (Leitão & de Sousa, 2018).

In recent years there has been a growing interest in developing new technologies and exploring new methodologies for generating high-resolution topographic data that is both cost-effective and sufficiently flexible to enable frequent surveys. Examples of these technologies are the growing use of ground-based LiDAR systems and UAVs (Leitão et al., 2016a; Küng et al., 2011). However these technologies have limitations which can restrict the extent of their data capture, discussed further in the technical report (Author, 2022b). In a flow-modelling context, data gaps in the path of a flow are detrimental to the model as they would significantly affect the simulated flow path and could affect other modelled conditions such as the flow depth, velocity and the final extent of the flow. However, due to the importance of DEM resolution, using only a low-resolution dataset because a higher resolution dataset is incomplete should be avoided, where possible (Leitão et al., 2016b).

2.2 DEM merging

The production of a single topographic dataset that covers the entire area of study, with the highest available accuracy at any given location — utilising the beneficial aspects of both a complete but low-resolution dataset and an incomplete high-resolution dataset — could be facilitated through the process of merging multiple topographic datasets (Bourgine et al., 2004). In cases where an area’s topography is affected by large flood or landslide events, DEM merging would also allow for specific areas of existing datasets to be updated where more recent or accurate surveys are conducted (Ruiz et al., 2011). However, the process of combining topographic datasets with differing resolutions, sources, and methodologies, can be challenging and a source of errors and discontinuities along the boundary where datasets are merged.

Elevation datasets produced using differing acquisition and/or interpolation methods have differing characteristics, such as acquisition date, spatial resolution, vertical and horizontal accuracy, and coordinate system. This can lead to the a single physical location having numerous potential elevation values, depending on the dataset used (Leitão et al., 2016b). Although these inconsistencies in elevation between various datasets may be within an acceptable bounds for modelling with an individual dataset, they can result in unrepresentative and inconsistent terrain slope and aspect along the boundary of the DEM when using simple DEM merging methods (Luedeling et al., 2007). In the context of over-land flow modelling, these edge artefacts are manifested as artificial cliffs or steps, which result in unrealistic overland flow patterns and are detrimental to modelling results (Leitão et al., 2016b).
2.3 Existing DEM merging methods

Commercial GIS software packages such as ArcGIS Pro or QGIS provide basic functions for merging multiple raster datasets, with some assumptions that the datasets have the same spatial resolution and the same coordinate system. Generally, there are three categories of conventional DEM merging methods; ‘Cover’, ‘Average’ and ‘Blend’ (de Sousa & Leitão, 2019). The Cover merging method is the most basic, simply overlaying one DEM over another. Both the Average and Blend methods involve elevation adjustments within the overlapping area of the two input-DEMs.

The modified blend, or MBlend method was proposed by de Sousa & Leitão (2019) and aims to merge two overlapping topographic datasets by introducing a smooth transition from a lower resolution dataset (LR) to a higher resolution dataset (HR). This is achieved by modifying only the LR, producing a single DEM that covers an entire study site with the highest possible accuracy, while ensuring a smooth transition between datasets (de Sousa & Leitão, 2019). The primary advantages of the MBlend method are that a smooth transition between DEMs is achieved and elevation adjustments are only performed in the lower-resolution DEM (Leitão et al., 2016b). The methodologies behind these merging methods are discussed further in the technical report (Author, 2022b).

2.4 Lahar flow characteristics

Iverson et al. (1998, pp. 972) define lahar flows as 'debris flows that originate on volcanoes and surge toward adjacent lowlands'. Lahars, also referred to as volcanic debris flows, behave similarly to other debris flows but can vary greatly in size and origin. The magnitude of a lahar is commonly characterised by the volume of its deposit; small lahars, with volumes ranging from $10^3$ to $10^5$ m$^3$, occur most frequently. Large lahars, with volumes $>10^8$ m$^3$ occur rarely (Iverson et al., 1998). The relatively high concentration of water in many lahar flows allows them to flow over shallow gradients (<5°) and to inundate areas far from their source with recorded runouts of over 100km (Vallance, 2000). The mobility of a lahar can be determined by the friction coefficient along its flow-path; this is a measure of the resistance where the flow material contacts the underlying topography (Charbonnier et al., 2018).

Lahar flows can be categorised by their their sediment concentration; debris flows are typically >50% sediment, hyper concentrated flows 20-50%, and muddy stream flows <20% sediment (Charbonnier et al., 2018; Muñoz-Salinas et al., 2009). A lahar’s sediment concentration can vary as it flows as lahars acquire sediment from both the source area and as they flow, through the process of ‘flow bulking’. Lahar modelling is made more complex due to the range of rock sizes they carry and the varying flow behaviours these materials possess. As the flow of a lahar decreases, the coarse and fine-grained sediments can separate; coarse-grained sediments often lose momentum and are deposited earlier, while fine grained sediments and water can flow further downslope (Charbonnier et al., 2018).
Section 3 - Study Area

3.1 Panabaj

This project largely focuses on the October 2005 lahar, which flowed from the high slopes of Volcán Tolimán, westwards towards Panabaj; a village of around 3,000 indigenous Tz'utujil Maya, located on the South-Western shore of Lake Atitlán. The name Panabaj is derived from a Tz'utujil word meaning ‘head of mud’ due to the common occurrence of lahars in the area (Charbonnier et al., 2018). As figure 2 illustrates, Lake Atitlán is located in South-West Guatemala, within an extinct volcanic caldera, and fringed by three potentially active volcanos: Tolimán, Atitlán, and San Pedro. The caldera hosts numerous communities of indigenous Maya which have expanded in recent decades as a result of unregulated development (Charbonnier et al., 2018). Heavy seasonal rainfall and the steep-sided walls of the caldera mean that rainfall-induced landslides are common in the region, leaving community members and housing infrastructure highly vulnerable to landslide associated hazards (Charbonnier et al., 2018).

![Figure 2 Towns and volcanos around Lake Atitlán (Author 2022; data from NASA, 2022)](image)

3.2 October 2005 Lahar

In October 2005, Hurricane Stan passed over much of Central America, shown in figure 3, resulting in sustained heavy precipitation. Stan was a relatively weak hurricane, classified as Category 1 at its peak, however it caused widespread damage across Central America and caused hundreds of landslides, mudflows and debris flows throughout steep mountainous areas across the region (Charbonnier et al., 2018).
At approximately 04:00 on the 5th of October 2005, a large debris flow descended from the upper slopes of Volcán Tolimán. The flow then split into two, high on the volcano's flank, and both flows descended westwards down two channels towards Lake Atitlán. The two flows then reached Panabaj and spread across the relatively flat ground, inundating much of Panabaj; the Guatemalan government’s disaster reduction organisation CONRED estimate the lahar caused hundreds of deaths and displaced around 2,600 people (Sheridan et al., 2006). Panabaj suffered the largest number of casualties, estimated to be around 1,000 — though there is uncertainty due to a lack of an official census prior to the disaster (Sáenz and Girón, 2015), however other areas such as Santa Catarina Ixtahuacan were affected.

3.3 Following the event

Efforts to rescue and evacuate survivors were hindered by the continued heavy rains and severe damage to roads, limiting access to Panabaj to only via the lake. Following the lahar event, survivors were relocated to a temporary relief camp in the nearby town of Tzanchaj (Sáenz and Girón, 2015). The initial rebuilding efforts by government officials focussed on constructing homes directly behind Tzanchaj, away from the shore of Lake Atitlán, on the slopes of Volcán Tolimán. This construction began despite locals’ demands for a risk assessment to be undertaken for the new site, as is may be vulnerable to a similar landslide hazard from Volcán Tolimán. In May 2006 a government land assessment designated the site as ‘high risk’, halting the construction and rendering the partially constructed houses a mere waste of funds. Following a general assembly hosted by ADECCAP (Asociación de Desarrollo Comunitario del Cantón Panabaj) to create a comprehensive resettlement plan, construction for the new development began in July 2006. Four settlements for survivors of the Panabaj disaster were created, named Chuk’muk I, II, III and IV, located North of Santiago Atitlán (Sáenz and Girón, 2015).
Section 4 - LaharFlow methodology

The first stage of the modelling process was to produce two flow simulations using complete SRTM 30m and AW3D 10m resolution datasets. Flow simulations were conducted using LaharFlow, a cloud-based tool for modelling the dynamics of lahars (LaharFlow, 2022). The aim of this stage is to reproduce, as accurately as possible, the inundation boundaries measured by Sheridan et al. (2006), shown in figure 4. The primary parameter used to measure the accuracy of the lahar simulations is the degree of similarity between the modelled and measured inundation areas — using the Jaccard coefficient. More detailed methodology for this section is in the technical report (Author, 2022b).

Figure 4 Lahar inundation extents in Panabaj (Author, 2022; data from Sheridan et al. 2006)

4.1 Data pre-processing I

The SRTM and AW3D datasets are delivered having already been pre-processed and accuracy assessed, however some additional processing was conducted. Based on the data acquisition techniques and accuracy specifications for each of the DEMs — outlined in the technical report, section 1 (Author, 2022b) — the AW3D data should more accurately represent the steep topography surrounding Lake Atitlán, and thus the SRTM raster was orthorectified to improve the alignment with the AW3D dataset in the areas where the lahar flow occurred. Additionally, The fill function within ArcGIS was used to remove any ‘wells’ that appear in the terrain model. This process is often used in flow-modelling, e.g. Köthe & Bock (2009), as artificial wells are a common occurrence in radar-derived DEMs (Woodhouse, 2015).
4.2 Source conditions

The location of the flow channels were obtained through the 'flow accumulation' tool in ArcGIS. This tool analyses the flow direction between adjacent cells and generates a raster of accumulated flow into each cell (ESRI, 2022a). Based on the flow channel locations and satellite imagery taken in January 2006 (Google Earth, 2022), the source location was set as a circular area centred at N: 14.614, E: -91.1915 with a radius of 50m, shown in figure 5; this location coincides with the release area estimated by Charbonnier et al. (2018). Through on-site flow measurements, Sheridan et al. (2006) estimated a release volume at the source of approximately 156,000m³. This figure was used to establish a source 'flux' of 650m³/s for the initial trial. While measurements of flow density and solid concentrations can be made from measurements downstream, the conditions at the source are difficult to estimate. Therefore, a numerous trial simulations were run with solids concentrations at the source ranging from 10% to 60%.

![Flow Source and Channels](image)

Figure 5 flow source and channels (Author, 2022)

Following simulations trialling varying flux and solids concentration values, the most satisfactory values for these parameters were found to be a flux of 650m³/s and a solid concentration of 10%. The flux value aligns with release volume estimates by Sheridan et al. (2006) and the low solids concentration at the source correlates with reports of the ground being saturated following days of heavy rainfall in the area, outlined in the technical report (Author, 2022b).

4.3 Flow parameters

Following these initial trials, the results still showed the lahar depositing material and depleting significantly before reaching Panabaj, particularly in the Northern channel. It appeared only a small percentage of the flow volume was entering the Northern channel, and that the flow quickly lost momentum upon reaching the flatter terrain closer to Panabaj. As discussed in the technical report (Author, 2022b) lahar material only entered the Northern channel once the capacity of the Southern
channel was exceeded. To offset these two factors, further models were run with altered values for both erosion and friction coefficients. Trial models showed that a lower minimum-friction coefficient (0.03 compared to a default 0.05) resulted in a longer runout of the lahar, reaching Panabaj, and a higher erosion coefficient (0.0015 compared to the default 0.0010) resulted in a greater proportion of the flow entering the Northern channel.

4.4 Results and discussion I

![Figure 6 Results of the calibrated LaharFlow model, using 10m AW3D data (Author 2022)](image)

The results shown in figure 6, show that this model successfully followed the two channels downslope from the source area. While some additional channels formed, the majority of the material stayed in the two channels followed by the 2005 lahar. Additionally, upon reaching the relatively flat area of the alluvial fan Panabaj sits upon, the model successfully represented how the material began to spread laterally and thin out. While some specific branches, such as the Northern and Western arms of the South/West inundation area, were not replicated, there is significant overlap in the inundation areas from both the North and South flows. The result of the Jaccard coefficient, figure 8a, shows a correlation of 49.2% between the measured and simulated inundation areas, indicating a moderate similarity. The average thickness is 1.5m in the S/W area and 2.3m in the N/E area; this is comparable to the 0.5-3.0m thickness measured by Sheridan et al. (2006). The 'solids concentration' output, figure 9, shows that in the lower elevation areas of the lahar, solids concentration was over 60%. This aligns with Sheridan et al. (2006) who estimated that the flow volume, by the time it had reached Panabaj, was up to 40% water.
Using the same LaharFlow parameters, a flow was simulated using 30m SRTM data; this model generally followed the same route, though the two main flow channels are less defined and appear to 'spill' in most areas of the flow, including a significant amount of material from the southern channel following a different route. The distance between the source and the flow terminus is greater in the SRTM simulation, more closely matching the measured distance in the S/W flow, compared to AW3D, but overshooting the N/E flow. Additionally, the inundation area is far greater in area than the AW3D model, and less closely follows the boundaries of the measured area. The result of the Jaccard coefficient, figure 8b, shows a correlation of 25.8% between the measured and the simulated inundation areas, indicating a poor similarity.
Figure 8 Intersection and Union of simulated and measured inundation areas (Author 2022; measurements from Sheridan et al., 2006)

Figure 9 Solids concentration through the AW3D modelled flow (Author, 2022)
Section 5 - DEM merging methodology

5.1 Data pre-processing II

To compare the effects of different DEM merging methods on modelled flows, further simulations were run, using the same parameters as in the previous section, using a range of merged DEMs. As previously discussed, the data capture technologies and methodologies used to generate high resolution datasets can result in gaps occurring; the AW3D dataset used in this dataset, however, does cover the entire Panabaj lahar area. In order to assess DEM merging methods, two artificial scenarios were devised where the high resolution AW3D dataset covers only the lower/Western half of the flow area, and the upper/Eastern half. These scenarios are named HR West and HR East, respectively. A similar approach was used by Leitão & de Sousa (2018) to assess their method for merging LiDAR derived elevation data with a satellite DEM.

Raster files have a single spatial resolution and, consequently, a DEM representing both 10m and 30m data would have a ‘stepping’ effect in the 30m sections, where a 30m pixel is actually nine 10m cells in a grid; this can have adverse effects on flow simulations. Therefore, the 30m SRTM data was resampled to a 10m resolution through cubic interpolation, discussed in the technical report (Author, 2022b).

Figure 10 East and West halves of DEM area (Author, 2022)

5.2 Existing methods

A outlined in Section 2.3, there are a number of basic raster merging functions available. Of these, the Cover method was used, achieved through the mosaic tool in ArcGIS Pro. Figures 13a and 14a show the result of merging DEMs through the Cover function.
The *modified blend* (MBlend) method, proposed by de Sousa & Leitão (2019) was performed using the r.mblend module within GRASS, specific requirements and parameters used are discussed in the technical report (Author, 2022b). Figures 13b and 14b show the outcome of the MBlend method.

### 5.3 Proposed method

The *dual blend* (DBlend) method is proposed in this dissertation and is based on the fundamental processes of the MBlend method, however it alters both DEM datasets, rather than just the LR dataset. While this could be seen as ‘destructive’ to the HR dataset, it provides scope for a smoother transition between datasets, especially where there is a significant elevation difference at the boundary between DEMs; in this scenario MBlend can produce an artificially steep or shallow section at the boundary. As there is no existing module to perform the DBlend, the process was performed manually, method outlined in figure 11; this is discussed further in the technical report (Author, 2022b). Figures 13c and 14c show the outcome of the DBlend method.

**Figure 11 Flow chart of the DBlend methodology (Author, 2022)**
Figure 12 Comparison of channels in AW3D and resampled SRTM datasets (Author, 2022)

Figure 13 Comparison of flow channels in the West HR merging scenarios (Author, 2022)
5.4 Results and discussion II

The resulting blended DEMs in figures 13 and 14, show the effects each merging method has had at the 'seam' between datasets. The cover method results in predictably abrupt elevation changes, particularly at the channels only present in the AW3D data. MBlend and DBlend produced similar results, though the impact of DBlend smoothing data both sides of the 'seam' appears to have reduced the presence of subtle wells that can be seen in the channels in figure 14b, and the change in elevation at the channels in figure 13, appear more gradual following DBlend.

The Jaccard coefficient was used to compare the flow-inundation areas of each blended-DEM model against the complete AW3D control model. The Jaccard coefficient is a measure of similarity between two datasets, using the ratio of Intersection over Union (Chung et al., 2019). The 'inundation area' was defined as the area of the flow extent West of -91°13’40 longitude, as this is the area measured by Sheridan et al. (2006).
Figure 15 Intersection (orange) and Union of AW3D-based (purple) and blended DEM-based (blue) inundation areas (Author, 2022)
Table 1 Total area of union and intersection between the inundation area simulated using complete AW3D data and the area simulated using blended DEMs (Author, 2022)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Intersect (m²)</th>
<th>Union (m²)</th>
<th>Jaccard coef.</th>
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<td>HR-West - Cover</td>
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<td>HR-East - MBlend</td>
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<td>509046.69</td>
<td>41.27%</td>
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<tr>
<td>HR-East - DBlend</td>
<td>210097.59</td>
<td>509046.68</td>
<td>41.27%</td>
</tr>
</tbody>
</table>

The similarity of Jaccard scores among the three West HR results (<1.5% variance) and the East HR results (0.15% variance) may indicate that in scenarios where flows are channelised and follow steep topographies for much of the length of the flow, such as near Panabaj, the method for merging may have little impact on the outcome of the model. Due to the channelised nature of the flow, there is little room for the flow to 'pool' where there is a step up in elevation (seen in East HR) and the flow is quickly 'funnelled' into channels where there is a drop down in elevation (seen in West HR).

However, there is a greater difference in similarity when comparing the West-HR and East-HR scenarios; West-HR shows an average Jaccard score of 45.58%, whereas East-HR shows 41.32%. This represents a 4.26% greater accuracy in the West-HR models, on average. This may indicate that modelled flows are more sensitive to their underlying topography in shallower areas where the flow is slower — consequently, it may be more important to have high resolution elevation data in prospective hazard inundation zones, such as Panabaj, than in areas closer to the flow source.

These results, therefore, indicate the potential benefits of using mixed-resolution DEMs for flow modelling, where high resolution data is available for potential inundation areas. However, in some scenarios, the specific method for blending DEMs may have little impact on the model outcome. If modelled flows are more sensitive to topographic changes in shallower areas, the mode of DEM blending may have a greater impact if the data 'seam' occurs in shallow areas.
Section 6 - Creating more accessible maps

Spatial mapping can facilitate the inclusion of various stakeholders and users, with little literacy or experience, in participatory activities; however, traditional visual outputs for modelling can be complex, inaccessible, and subsequently incompatible community engagement (Bou Nassar et al., 2020). This can consequently reinforce external, academic-orientated opinions which can lack local-contextual knowledge and experience (Cooke and Kothari, 2001). The use of accessible spatial mapping can make information more comprehensible, enabling stakeholder participation, and leading to model development with greater situated knowledge (Bou Nassar et al., 2020).

Following this project, depictions of the flow models may be used by a range of stakeholders, from external academics or scientists working in Panabaj, to the local residents affected by the 2005 lahar. To fulfil the aim of making outputs accessible to users with limited experience in using spatial data, outcomes of past participatory mapping projects were to be used to inform the design and creation of 3D rendered map outputs.

6.1 Participatory mapping

Through discussions with local stakeholders in Guatemala, Langmuir-Sánchez (2022) found that locals responded positively to maps where they could easily identify the place they worked or lived, and responded negatively where landmarks were omitted, misspelled, or if their town was not the focus of the map. Figure 16 shows examples of existing depictions of hazards in Panabaj and other nearby villages. These depictions often favour a 3D perspective, placing the town at centre frame and the hazard above, emulating the perspective of a resident of the town. This perspective also often maintains the familiar silhouette of the surrounding volcanic landscape.

Figure 16 Depictions of volcanic or lahar hazards in Guatemala
During participatory mapping exercises, locals were asked to create maps showing volcanic hazards and evacuation routes in their town, with the freedom to choose any mode of representation, with no predetermined scale or extent (Langmuir-Sánchez, 2022). The maps produced, shown in figure 17, also often favoured a similar 3D perspective to existing hazard depictions, suggesting this is a common, familiar perspective.

Figure 17 Hazard maps produced through participatory mapping exercises (Langmuir-Sánchez 2022)
6.2 Use of Blender software

Producing a hazard visualisation that satisfied as many positive criteria as possible, was achieved using the free, open-source 3D modelling software, Blender. This software allows topographic data to be adapted into a 3D relief model with realistic lighting and rendering, as shown in Figure 18.

Figure 18 Shaded relief map of the Atitlán area using AW3D elevation data (Author 2022)

Upon this, further spatial data can, such as aerial imagery and flow model outputs, can be projected onto the surface of the 3D model, expanding the ways that hazard information can be portrayed. High-resolution RGB satellite imagery (ESRI, 2022c) was used, as its resolution allows individual buildings and roads to be seen within the image. However, the January 2021 capture date of the imagery means subsequent developments will not be reflected in the visualisation. Additionally, the perspective of the map can be altered; by adjusting the virtual camera, Panabaj and Volcán de Tomilán can be framed in a similar perspective to many community maps, with their town at the centre/bottom, and the volcano hazard above.

Figure 19 shows a potential mapping output, fulfilling mapping criteria set out by locals in participatory mapping exercises, and utilising high-resolution topographic data and aerial imagery to portray flow simulation outputs in Panabaj. The map succeeds in making individual buildings and landmarks in Panabaj visible and portrays the ‘scene’ in a perspective familiar with residents, while maintaining geographical scale and accuracy.
Figure 19 Blender Map depicting AW3D-based flow model over Panabaj (Author, 2022)
Section 7 - Future work

Due to the specific course the lahar flow took in Panabaj — for example, its steep and channelised nature — there are limitations to assessing the wider application of these DEM merging techniques. Repeating the methodology outlined in this project in other lahar scenarios, particularly where the data 'seam' is in an area of shallower topography, may better highlight the different impacts the merging techniques have on flow simulations.

Additionally, due to time constraints, simulations were run at a lower resolution than the 5m resolution the AW3D data was delivered at; following the assumption that greater resolution data can result in more accurate flow modelling, repeating this methodology at the highest resolution available may yield more substantial results. The more significant difference between 30m and 5m data would likely result in the DEM merging method having a greater impact on the modelled flow.

Section 8 - Conclusions

Of the key aims set out for this project, all three were met; The LaharFlow model was used to reproduce the October 2005 lahar event, informed by on-site measurements. Three DEM merging methods were used to produce six mixed-resolution DEMs, including an original method. These were then used to assess the impact these different methods have on overland flow modelling. In addition, in an effort to improve accessibility, findings from participatory mapping exercises were used to inform the design and production of alternate visualisations of flow models, using Blender.

Results from the comparative analysis of the inundation areas resulting from models on different merged DEMs showed that the location of the high-resolution data had an impact on the accuracy of the model. Models using high-resolution in the area containing Panabaj, showed an average of around 5% greater similarity to the control model, than where the high-resolution data was at the source. These results indicate that using higher-resolution data in potential inundation areas can improve the accuracy of modelled inundation areas, and by extension, the benefit of using blending DEMs, where high-resolution data is available in these areas.

While, in this case, the merging method made little difference to the modelled flow, there is potential that in cases where the DEM 'seam' is in an area of flatter topography, the difference may be more impactful.
References


Part II: Technical Report
Contents

Contents .................................................................................................................. i

List of figures .......................................................................................................... ii

List of tables ........................................................................................................... ii

List of appendices ................................................................................................... iii

1. DEM Data ........................................................................................................... 1

   1.1 SRTM ........................................................................................................... 1

   1.2 AW3D ......................................................................................................... 1

   1.3 Comparing datasets ....................................................................................... 2

2. Software ............................................................................................................ 3

   2.1 GRASS and r.mblend .................................................................................. 3

   2.2 QGIS ........................................................................................................... 3

   2.3 LaharFlow .................................................................................................... 3

   2.4 Blender ........................................................................................................ 4

3. Literature review ............................................................................................... 5

   3.1 Conditions contributing to the 2005 lahar ................................................... 5

   3.2 Sheridan et al. (2006) fieldwork survey ......................................................... 6

   3.3 Accuracy and availability of topographic data ............................................. 7

   3.4 DEM merging ............................................................................................... 7

   3.5 Details of basic merging methods .................................................................. 8

4. Methodology I: LaharFlow testing ..................................................................... 9

   4.1 Measured inundation area .......................................................................... 9

   4.2 Data management ......................................................................................... 9

   4.3 Calibrating LaharFlow parameters ............................................................ 10

5. Methodology II: DEM merging ......................................................................... 11

   5.1 MBlend method ........................................................................................ 12

   5.2 Proposed DBlend method .......................................................................... 14

   5.3 Comparison of inundation areas ............................................................... 15
6. Methodology III: Utilising Blender ......................................................... 16
  6.1 Setting Up .......................................................................................... 16
  6.2 Producing the 3D model ..................................................................... 16
  6.3 Logistical challenges with Blender ..................................................... 18

References .................................................................................................. iv

Appendices .................................................................................................. vii

List of figures

Figure 1  Elevation difference between AW3D and SRTM datasets .............. 2
Figure 2  Comparison of (a) hill-shaded render and (b) ray traced render ....... 4
Figure 3  Accumulated rainfall from 2nd to 6th of October ............................. 5
Figure 4  Approximation of the flow channels and inundation areas ............ 6
Figure 5  Georeferenced inundation areas from Sheridan et al. (2006) .......... 9
Figure 6  SRTM resampled using a) nearest neighbour and b) cubic interpolation 11
Figure 7  West HR merged DEM generated by r.mblend ............................... 13
Figure 8  Profile diagram of DBlend between two elevation datasets .......... 14
Figure 9  Stages of producing a Blender relief map ..................................... 17

List of tables

Table 1  Parameters available within the r.mblend GRASS module ............... 14
List of appendices

Appendix I  Merged DEMs  .................................................................  vii
Appendix II  Modelled flows  ............................................................  xii
Section 1 - DEM data

1.1 SRTM

The SRTM (Shuttle Radar Topography Mission) mission was flown aboard the Endeavour shuttle from 11\textsuperscript{th} - 22\textsuperscript{nd} of February 2000; Over the course of the mission, Endeavour orbited the earth 176 times and collected radar data for over 80% of the Earth’s land surface between 60° North and 56° South. The data was collected using single-pass interferometry from C-band radar signals (5.6cm wavelength), spaced at intervals of 1 arc-second (approximately 30m resolution) (USGS, 2018). The radar data was collected from two sensors, one on board the satellite and the other at the end of a 60m antenna, resulting in an azimuth resolution of 30m. This elevation data has a horizontal accuracy ranging from 12.6m in North America to 7.2m in Australia, its absolute vertical accuracy is between 9m in North America and 5.6m in Africa (USGS, 2005).

Originally, SRTM data was available globally at a 90m resolution and at a 30m resolution for the United States, however since 2015 30m NASA have made the global dataset available at a 30m resolution (Su et al., 2015). This data is one of the most commonly used DEM products and is commonly used in flow modelling due to its moderate resolution and free global availability; for example in Fanghui et al. (2019), where various DTMs were combined to model lava flows.

1.2 AW3D

AW3D elevation data was captured by the PRISM (Panchromatic Remote-sensing Instrument for Stereo Mapping) instrument aboard JAXA’s ALOS (Advanced Land Observing Satellite), also referred to as DAICHI. PRISM uses 3D stereoscopic observation to collect data in three directions: forward, backward and nadir; theoretically allowing PRISM to have no blind angle, even in regions of steep topography, such as the area surrounding Lake Atitlán. PRISM can record spatial information at a ground resolution up to 0.5m, with a horizontal and vertical accuracy of <5m (without ground control points) (NTT, 2017). Data from AW3D is delivered having been through several stages of pre-processing; these are satellite referencing and ground-truthing, 3D elevation analysis, map stitching and removal of defects, and finally a quality assurance stage (NTT, 2017).

This data has roughly a 36 times higher effective spatial resolution compared to SRTM (5m vs 30m). This increased resolution should more accurately reflect the topography of the areas surrounding Panabaj, including small valleys on the hill-slope, and facilitate a greater degree of accuracy in the LaharModel.

While 5m AW3D data was made available for this dissertation, the potentially lengthy calculation times required to perform overland flow models in LaharFlow, as well as the need to run multiple simulations during the calibration phase, the decision was made to run simulations using AW3D data at a 10 metre resolution. This is still within the 5-10m resolution range recommended by Capra et al. (2010) for flow modelling in areas with steep topographies, as outlined in the Research Paper, and would enable simulations to be run roughly four times faster.
1.3 Comparing datasets

Both datasets (30m and 10m) were imported into ArcGIS Pro, ensuring the same vertical and horizontal projection system was used for both. Visual assessment was made to ensure DEMs were aligned. Both datasets were then clipped to the relevant study site, spanning from Panabaj in the West to the flow source in the East. Before any calculations were done, the 30m dataset was resampled to a 10 resolution, meaning each 30m pixel was split into 9 10m pixels (in a 3x3 grid). This was done so that the raster calculator function would perform any calculations at a 10m resolution, as opposed to a 30m resolution. The Raster calculator function was then used, subtracting the height values of the supersampled 30m dataset from the 10m dataset. The result is shown in figure 1. This revealed that many of the channels, such as those the 2005 lahar followed, were especially pronounced when the datasets were compared. This shows that the 30m dataset loses a significant amount of information for smaller topographic features, such as small gulleys or channels.

![Elevation difference between AW3D and SRTM datasets](image)

**Figure 1 Elevation difference between AW3D and SRTM datasets (Author, 2022)**
Section 2 - Software

2.1 GRASS and r.mblend

*Geographical Resources Analysis Support System* (GRASS) is a free and open-source GIS package developed by the US Army Corps of Engineers with an emphasis on managing and analysing spatial data (Neteler *et al.*, 2012). The software is ‘characterised by a deep dataset management and archiving structure’ and an extensive list of analysis modules. GRASS can manage a range of dataset types including raster, vector and voxel (de Sousa & Leitão, 2019).

GRASS has a fully modular structure and has incorporated a system to host additional modules or ‘add-ons’ where third party developers can add their code to the GRASS repository; making these modules freely available to all GRASS users. The inbuilt `g.extension` module automatically connects to the GRASS add-on repository, downloads and installs the required code for a desired module (Neteler *et al.*, 2012). The module that executes the MBlend DEM merging method, named `r.mblend`, is an example of these third party modules and is managed at GitHub and released under the EU Public Liscence (de Sousa & Leitão, 2019).

2.3 LaharFlow

‘LaharFlow is a tool for modelling the dynamics of lahars on topography’. Its mathematical model is based on the fluid and granular dynamics, as well as erosion and depositional morpho-dynamics of shallow flows (LaharFlow, 2022). The LaharFlow program was developed at the University of Bristol by Mark Woodhouse, Andrew Hogg and Jeremy Phillips.

By default, LaharFlow uses SRTM 30m topographic data for its simulations, but allows for some users to use import their own DEM data, e.g. AW3D 10m. LaharFlow provides numerous tools and parameters to define the source conditions of a flow. Sources can be set in two ways: Flux sources, where the material is released over time, or Cap sources, where the material is released all at once (LaharFlow, 2022).

A flux source allows the user to define, first the radius of the source area and then to define a time series for the flux source and concentration. Three times must be outlined, in seconds: start time, peak flow, and end time. Next, three values for flux must be outlined (in cubic metres per second), corresponding to these times. Finally, the solids concentration of the flow at the three times must be defined, between 0% and 60%.

If setting a cap source, LaharFlow allows the user to define the source area as a cylinder where two of the radius (m), height (m) and volume (m$^3$) are defined by the user and the third is calculated automatically.
2.4 Blender

Blender is a free and open-source 3D modelling and rendering software package used for a range of products including 3D-Printed models, visual effects and animated films. Blender can also be used to render complex 3D models and lighting.

One key feature of Blender, for this project, is the capability to simulate ray-traced lighting; Ray-tracing is a rendering technique that works by simulating actual light rays, tracing the path that a beam of light would take in the physical world. This models the way light reflects and scatters in an environment, producing a realistic and natural appearance. In a topographic mapping context, this means that light from one mountain would reflect onto nearby mountain faces, peaks will cast shadows and shadowed areas, such as valleys, will be softly lit by scattered light from nearby mountain faces.

Figure 2 Comparison of (a) hill-shaded and (b) ray traced render of the Panabaj area (Author, 2022)

A hill-shade algorithm, as is commonly applied in most GIS packages, assigns pixels a brightness value solely on the direction of the slope. The ray-traced approach results in not only a more realistic and attractive appearance than a standard hill-shade relief, but the result is also more intelligible. Figure 2 shows the same scene of the landscape surrounding Panabaj (a) displayed as a standard hill-shade, common in GIS packages, and (b) produced in Blender using a ray-traced lighting simulation. Comparing the two approaches, the shape of the volcanos and slopes appear more intelligible in the ray-traced render (b) than the hill-shade (a).
Section 3 - Literature review

3.1 Conditions contributing to the 2005 lahar

Of the volcanos surrounding Lake Atitlán, Tolimán has historically seen the most frequent occurrence of lahars, as evidenced by the presence of fluvial palaeochannels crossing old alluvial fans (Giron and Matias, 2006). This may be the result of the steep (>50°) slopes on high up Tolimán's flanks, near its crater (Charbonnier et al., 2018). Recorded lahar events around Lake Atitlán have most commonly occurred around October to early November, during the latter parts of the rainy season, following intense rainfall from storms and hurricanes. Three relatively recent severe debris-flows in Panabaj have been identified through stratigraphic evidence; these occurred in 1910-1920, 1949 and 2005 (Giron and Garavito, 2006). The long intervals between these events may have contributed to a false sense of security as the perception of a threat diminishes over time (Charbonnier et al., 2018).

Hurricane Stan passed over Central America from the 1st to the 10th of October 2005 bringing intense rainfall. The mean monthly October precipitation for the period 1970-2004 was 139.8mm; for the period of 2nd - 9th of October 2005, the Santiago Atitlán meteorological station measured 562.3mm. The 4th of October (the day before the Panabaj lahar) was the single day with the greatest accumulation, measuring 297.5mm, over double the monthly average (INSIVUMEH 2005), shown in figure 3.

![Figure 3 Accumulated rainfall from 2nd to 6th of October (INSIVUMEH 2005)](image)

At approximately 04:00 on the 5th of October 2005, a large debris flow descended from the upper slopes of Volcán Tolimán. The timing of the hurricane likely contributed to the triggering the lahar; the sudden increase in rainfall happened 5 months into the rainy season, meaning the soil in the region was already saturated and subsequently, only little additional rain was required to trigger a lahar (Charbonnier et al., 2018; Capra et al., 2010).
3.2 Sheridan et al. (2006) fieldwork survey

Shortly following the Panabaj lahar event, Sheridan et al. (2006) conducted a fieldwork survey to assess various features of the flow; using differential GPS, they attempted to outline the debris flow boundaries, plot flow directions, estimate flow thickness and determine flow volumes. Additionally, flow vectors were plotted using cross-stride accumulations against physical obstacles such as trees or rocks, and flow velocities were determined by superelevation on flow curves.

Sheridan et al. (2006) estimate that the 2005 Panabaj lahar flow was a moderate size debris flow, with an estimated 360,000m$^3$ of sediment and water. Roughly 65% of the flow volume descended the Southern channel, eventually forming the Southern/Western deposit. The Southern flow resulted in a greater lahar deposit with a planimetric inundated area of 180,000m$^2$, compared to 77,000m$^2$ from the Northern flow, shown in figure 4.

![Figure 4 Approximation of the flow channels and inundation areas (Author, 2022; inundation area data from Sheridan et al. 2006)](image-url)

The higher areas of the channel have a steep topography with a slope of 11.5° around 1km above the alluvial fan Panabaj sits upon. This slope gradually decreases as it moves downwards with a slope of around 5.3° just above the fan. Additionally, The Northern channel is not a regular drainage channel on the volcano; the lahar flow only entered this channel as the capacity of the Southern channel was exceeded. Charbonnier et al. (2018) note that the Northern channel appears to be the less mature of the two due to the its slope profile showing steep grades and varying steepness, compared to the Southern channel's more gradual change in slope. Similar to the Southern channel, the Northern channel is steeper higher up, with an average slope up to 16.7°. However, this channel
dramatically steepens to 12.8° just before reaching the alluvial fan; this slope resulted in an increased flow velocity just before reaching the populated fan area.

Sheridan et al. (2006) estimated flow velocities in channelised sections of the lahar flow by measuring superelevation at two bends for each of the two channels — Superelevation is a phenomenon that can be observed in curves along flow channels where the flow height is higher in the outer edge than the inner edge as a result of centrifugal acceleration (Scheidl et al., 2014). In cross sectional areas measuring between 144 and 160m², the calculated velocities ranged from 8.3-10.6m/s, resulting in fluxes of 1280 and 1680m³/s; Sheridan et al. (2006) highlight that both channels had surprisingly similar fluxes. Upon reaching the relatively flat alluvial fan where Panabaj is located, the debris flows thinned to approximately 0.5-3.0m and spread laterally as a broad sheet flow, bounded by flow fronts ranging from 0.3-0.6m in height. At this point, the flows still had sufficient force to overwhelm and destroy most of the concrete houses inundated. High water marks observed on surviving buildings suggest that up to 40% of the flow's volume consisted of water and fine sediments that had later drained from the deposits.

3.3 Accuracy and availability of topographic data

In recent years there has been a growing interest in developing new technologies and exploring new methodologies for generating high-resolution topographic data in flood-prone areas, that is both cost-effective and sufficiently flexible to enable frequent surveys. Two examples of these technologies are the growing use of ground-based LiDAR and UAVs (Andaru et al., 2021; Küng et al., 2011).

UAV surveys suffer some limitations however; finite battery capacity restricts the duration and maximum altitude of a flight, and therefore limits the overall coverage. Topographic datasets derived from UAV imagery may consequently only cover specific areas of a catchment or slope (Leitão & de Sousa, 2018). Data collection methods associated with light aircrafts and UAVs, such as LiDAR and photogrammetry — the process of producing 3-D point clouds based on overlapping images (Leitão et al., 2016a) — are capable of gathering high-resolution topographic data. However, unlike radar, these remote sensing methods are limited by factors such as cloud cover, particularly in high-altitude and tropical regions such as Atitlán. These factors combined can result in a UAV derived topographic dataset that either does not cover the full extent of a study site, or includes gaps within the dataset where cloud cover is present.

3.4 DEM merging

The production of a single topographic dataset that covers the entire area of study, with the highest available accuracy at any given location — utilising the beneficial aspects of both a complete but low-resolution dataset and an incomplete high-resolution dataset — could be facilitated through the process of merging multiple topographic datasets (Bourgine et al., 2004). In cases where an area's topography is affected by large flood or landslide events, DEM merging would also allow for areas of existing datasets to be refined where more up-to-date or accurate surveys are conducted (Ruiz et
al., 2011). However, the process of combining topographic data from different sources, generated using different methods, can be challenging and a source of errors and artefacts along the boundaries where different datasets end or overlap.

Elevation datasets produced using differing acquisition and/or interpolation methods will likely have differing characteristics, such as acquisition date, spatial resolution, vertical and horizontal accuracy, and coordinate system. This can lead to a single physical location having numerous potential elevation values, depending on the dataset used (Leitão et al., 2016b). Although these inconsistencies in elevation between various datasets may be within an acceptable bounds for modelling with an individual dataset, they can result in unrepresentative and inconsistent terrain slope and aspect along the boundary of the DEM when using simple DEM merging methods (Luedeling et al., 2007). In the context of over-land flow modelling, these edge artefacts are manifested as artificial cliffs or steps, which result in unrealistic overland flow patterns and are detrimental to modelling results (Leitão et al., 2016b).

3.5 Details of basic merging methods

The Cover merging method is the most basic, simply overlaying one DEM over another. The resulting DEM then has the cell values of the original ‘top’ DEM in the areas this DEM covers, and the cells in the remaining area are equal to the cell values of the ‘bottom’ DEM. Cover merging methods are not ideal for overland flow modelling as the resulting DEM can have significant elevation discontinuities/cliffs along the boundary where the DEMs meet and subsequently inaccurate aspect and slope values in these areas (Hickey, 2000).

Both the Average and Blend methods involve elevation adjustments within the overlapping area of the two input-DEMs. Average merging methods assign the average elevation value with the overlapping region of the two datasets, attempting to mitigate the elevation discontinuities along edges as can be generated by cover merging methods. However, as elevation values from the high-resolution dataset are adjusted within the overlapping areas, the Average merging process ultimately loses the high-accuracy of these elevation values (Leitão et al., 2016b).

Blend merging methods use a weighted function within the overlapping regions of the input DEMs; outside this area, elevation values are unaffected. Blend functions offer more flexibility in their implementation; the function curve can be linear, smoothed or discontinuous. However, as with Average merging methods, Blend methods result in altered elevation values within overlapping areas, and subsequently, increased uncertainty in the elevation, slope and aspect of the resulting DEM (Leitão et al., 2016b).

Additionally, as these methods assume the input DEMs are all of the same spatial resolution, prior to performing the merging operation one or both of the input DEMs must be resampled so that they have the same spatial resolution. If the resampled resolution is not a factor of the original resolution (i.e. a 30m to 10m resample would simply produce a 3x3 grid of pixels for every pixel in the original DEM), interpolation artefacts can be introduced and accuracy of the original DEM is compromised.
Section 4 - Methodology I: LaharFlow testing

4.1 Measured inundation area

As outlined in the Research paper (Author, 2022a), the results of modelled flows were to be compared with the inundation area as measured by Sheridan et al. (2006) in the field, following the 2005 lahar event. As the data for these inundation areas were not available online, the published outline was digitised using the georeferencing plugin within QGIS. The coordinate grid was used to place control points. Following georeferencing a visual check was performed in ArcGIS by comparing visible features in the inundation area map (roads in the Southern area) with satellite imagery. The inundation areas within the plot were then traced manually to produce shape-files. While there could be an element of error introduced here, the relatively coarse resolution of the modelled flows means any error introduced through tracing would be insignificant. Figure 5 shows the diagram produced by Sheridan et al. (2006) following georeferencing, overlaid on satellite imagery, as well as the traced inundation areas in green and purple.

![Figure 5 Georeferenced inundation areas from Sheridan et al. (2006) (Author, 2022)](image)

4.2 Data management

Simulating over-land flows takes a significant amount of processing power and, more importantly, time; at a 5m resolution, a single simulation could take upwards of a week. Taking this into consideration, the decision was made to run initial calibration tests of the model at a 20m...
resolution, and the final comparative models at a 10m resolution. The 10m resolution used for the final simulations is still within the range recommended by Capra et al. (2010) in Section I (Author, 2022a), and allowed for a significantly greater number of trial simulations to be run, allowing for a better informed flow model.

The AW3D data was delivered at a 5m resolution but was resampled to 10m. Additionally, in order for LaharFlow to correctly read the data, the DEM (all elevation datasets that were subsequently used in LaharFlow) was converted to floating point type.

4.3 Calibrating LaharFlow parameters

Measurements and estimations from Sheridan et al. (2006) were used as a starting point for the flow model. As outlined in Section I of this paper, Sheridan et al (2006) estimate a time of 6m 10s for the lahar flow to reach Panabaj, based on their field observations following event. This time can be used as a measure of the accuracy of the flow models. Additionally, based on the measurements of the inundation area and flow velocity, Sheridan et al. (2006) estimate a release volume of 156,000m$^3$.

These figures were used to inform initial simulations of the lahar in LaharFlow. To accommodate the estimated inundation time, a simulation time of 8 minutes (480 seconds) was chosen for the simulation. When calibrating a ‘flux source’ in LaharFlow, the release volume cannot be directly assigned; instead, the ‘flux’ in m$^3$/s must first be calculated, then a time series is created where the flux increases linearly from zero to the flux value, then back down to zero.

The flux in m$^3$/s is calculated using the following equation:

$$Fv = \frac{2Rv}{T}$$

Where:

$Rv$ = Release volume (m$^3$)
$T$ = Time (seconds)
$Fv$ = Flux volume (m$^3$/s)

Using a simulation time (T) of 480 and a mass (M) of 156,000, the equation gives a flux value of 650m$^3$/s.
Section 5: Methodology II: DEM merging

In order to create produce DEMs, the high resolution and low resolution DEMs must first be established. The SRTM and AW3D datasets were clipped to a ‘study area’, then split in half into East and West halves in order to produce the artificial split.

When combining DEMs of differing resolutions, the output merged DEM must be stored at a resolution equal to the resolution of the high resolution input DEM. However, this can introduce a ‘stepping’ effect to the low-resolution portion of the DEM, which can significantly affect overland-flow simulations. In order to prevent this, the 30m SRTM dataset was upscaled to a 10m resolution, to match the AW3D data, through a cubic interpolation algorithm. Cubic interpolation determines the value of a cell by fitting a smooth curve through the nearest 16 cell centres; this method produces less geometric distortion than other interpolation methods such as nearest-neighbour or bilinear (ESRI, 2022). This process does not improve the accuracy of the DEM, it simply smooths the surface to reduce the stepping effect in a flow-simulation. Figure 9 shows a comparison of the SRTM DEM upscaled to 10m using a) nearest-neighbour and b) cubic interpolation.

Figure 6 SRTM resampled using a) nearest neighbour and b) cubic interpolation (Author, 2022)
5.1 MBlend method

The MBlend method consists of several steps, described de Sousa & Leitão (2019):

- The area covered by only the LR dataset is calculated by vectorising the extent of both DEMs and performing an intersect function.

- The value of the difference in elevation between the two DEMs is calculated by subtracting LR from HR.

- Assign the near edge: The difference raster is vectorised into points and points that lay on the boundary between LR and HR are selected as the near edge.

- Assign the far edge: the LR is vectorised into points and points along the border are selected as the far edge. Points along the far edge area assigned a value of zero.

- A new raster is created by interpolation using the near edge and far edge data points. The resulting transition surface (diff) represents a smooth transition from the difference in the LR and HR values along the near edge, towards zero at the far edge.

- The values of the diff is added to the LR, the result is then patched with the values of the HR, forming a single DEM of the entire extent.

Within GRASS, MBlend can be executed using the r.mblend module. Table 1 shows the arguments the r.mblend module takes.

Table 1 Parameters available within the r.mblend GRASS module (de Sousa & Leitão, 2019)

<table>
<thead>
<tr>
<th>Argument</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>high</td>
<td>name of the high resolution DEM</td>
</tr>
<tr>
<td>low</td>
<td>name of the low resolution DEM</td>
</tr>
<tr>
<td>output</td>
<td>name of the resulting blended DEM</td>
</tr>
<tr>
<td>far_edge</td>
<td>percentage of the maximum distance to the high resolution DEM used to determine the far edge</td>
</tr>
<tr>
<td>inter_points</td>
<td>number of points (from both edges) to use in interpolation</td>
</tr>
<tr>
<td>-a</td>
<td>optional flag that indicates to assign the average difference between the two input rasters to the far edge (instead of zero)</td>
</tr>
</tbody>
</table>

Values for the far_edge argument are bounded from 0 - 100, with a default value of 95. Values closer to 100 translate to a lower number of points generated for the far edge, impacting the generation of the diff raster. The number of points along the near edge used to generate the diff raster can be up to one per cell; generally, the more points used for interpolation, the more accurate
and detailed the results (Leitão et al., 2016b). The \textit{diff} surface is interpolated using the Inverse Distance Weighting (IDW) method, calculated using the following equation:

\[
Z_i = \frac{\sum z_j d_{ij}^n}{\sum 1/d_{ij}^n}
\]

Where:

\begin{itemize}
  \item \(z_i\) = the interpolated value at point \(i\) \((x_i, y_i)\) in the \textit{diff} surface,
  \item \(z_j\) = the value of the \(j\) points used for interpolation \((x\) and \(0\) points),
  \item \(d_{ij}\) = Euclidian distance between points \(i\) and \(j\), and
  \item \(n\) = a factor that works as a weight of the distance (usually \(n = 2\)).
\end{itemize}

For this project, the \texttt{far\_edge} value was left at the default 95, and the \texttt{inter\_points} value was set to a 1-to1 ratio of the DEM cells, to generate a smoother surface. The \texttt{-a} argument was left/ignored, instructing the module to assign a value of 0 for points along the \texttt{far\_edge}.

The resulting MBlend DEM is shown in figure 7. The resultant DEM shows a smoothed boundary between the 10m AW3D data and the resampled 30m SRTM data.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure7.png}
\caption{West HR merged DEM generated by r.mblend (author, 2022)}
\end{figure}
5.2 Proposed DBlend method

This proposed *Dual Blend* (DBlend) method is based on the same fundamental processes of MBlend, however DBlend applies an interpolated *diff* surface to both DEM datasets, rather than just the LR dataset. The method could be described as applying two half-Mblend merges, mirroring each other. Where MBlend produces an interpolated *diff* surface within the LR area, and then adds these *diff* values to the LR dataset, DBlend involves creating a *diff* surface for both the LR and HR datasets, halving the *diff* values, then adding the LR *diff* to the LR dataset, and subtracting the HR *diff* from the HR dataset, causing the elevation profiles of the altered HR and LR datasets to ‘meet in the middle’ at the DEM boundary, shown in figure 8.

![Figure 8 Profile diagram of DBlend between two elevation datasets](image)

As there is no existing module to perform the DBlend, the process was performed manually, following similar steps to those outlined by de Sousa & Leitão (2019) to execute the MBlend method.

The distance between the *near* and *far edge* was chosen to balance the effects of the smoothing. Too small a distance and the interpolated surface could produce too steep a transition. Too far and the smoothing may begin to affect the shape and direction of any channels where they are not perpendicular to the edge.

The *raster calculator* tool was used to generate the difference between the AW3D and SRTM datasets by subtracting the SRTM data values from the AW3D data values. This raster was then clipped to the East and West blend areas. These rasters were then converted to point data using the *raster to point* tool. Next the points not on either edge of the rectangle area were removed. The points along the DEM ‘seam’ acted as the *near edge* and the points far from to the DEM ‘seam’ were assigned a value of 0 to act as the *far edge*.

Next the IDW Interpolation tool was used to generate a *diff* surface between these two rows of points. The raster calculator tool was then used to subtract half the value of this surface from the SRTM portion of the study area, and add half the value to the AW3D portion. This results in the elevation values to gradually come to a meeting, closer to the the DEM 'seam'.

Page 14
5.3 Comparison of inundation areas

Data outputs from LaharFlow depicting maximum flow heights throughout the simulated flow are provided in KML (Keyhole Markup Language) format. This data was converted to polygon data within ArcGIS Pro using the KML to Layer tool, then was converted to raster using the Polygon to Raster tool. Flow area rasters were then clipped to the ‘inundation area’ — As Sheridan et al. (2006) only provided measurements in the area of the flow West of -91°13'40 longitude, this is the area used as the inundation area to be compared. Clipped rasters were multiplied by 0 using the Raster Calculator to create a single-value raster. Following this, the rasters were then converted back to a shape-file, but as a single polygon. From here, intersect and union functions were run to generate the intersect and union for each blended-DEM based inundation area with the complete AW3D-based inundation area.

Using the area values for each of these areas, the Jaccard coefficient could be calculated. The Jaccard coefficient is calculated by dividing the intersection of two areas by the union of the two areas. The results from this function are provided and discussed in the Research Paper (Author, 2022a)
Section 6: Methodology III: Utilising Blender

6.1 Setting up

In addition to Blender’s diverse capabilities in the fields listed above, there is also a great deal of versatility when it comes to producing various map outputs. While Blender itself is not primarily a GIS, its modelling and rendering abilities allow typical GIS outputs to be taken a step further in their presentation. For this dissertation, Blender was used to produce shaded relief maps of various GIS outputs, using different map perspectives, lighting and colouring, with the aim of improving accessibility. Setting up Blender to produce an elevation map is akin to setting up a virtual photography studio; the three primary components are a camera, a light source and an object.

The aim of using Blender for this project was to be able to produce maps in both a top-down, and a more three-dimensional perspective. Within Blender, the camera can be set to various positions relative to the map surface, depending on the desired perspective of the map. For the purpose of producing figure 9, the camera was tilted down 30° from horizontal and set at a 45° angle, laterally, to the map object. In order to produce a typical top-down map, the camera should be pointed directly down. Additionally, the scene can be rendered with an orthographic view, where every point on the map surface is seen directly top-down much like an orthophoto; this option was used for all top-down Blender outputs in this project.

Blender’s lighting capabilities -- primarily the ability to render ray-traced lighting -- are what set Blender GIS outputs apart from more traditional GIS outputs. Within Blender, the light is used to illuminate the map surface and can be used to control the angle and intensity of the shadows cast across its surface. For the purpose for a shaded relief map, a ‘sun’ light was used — this is where the light contacts any point on the surface of a flat plane at a consistent angle, more accurately reflecting the way the Sun interacts with the Earth’s surface at a regional scale.

Regarding the light angle, setting the light angle directly down at the surface would not produce any shadows. Therefore the angle was set to fall across the surface at a relatively low angle. Setting the angle closer to perpendicular creates shorter shadows, setting the angle closer to parallel with the surface creates longer shadows, i.e. sunset/sunrise.

6.2 Producing the 3D model

Huffman (2017) describes a process of producing a 3D model from topographic data within Blender; this process was used as a starting point for producing Blender outputs in this project. The starting point when creating a shaded relief map Blender is with a blank plane (figure 9a), effectively a 2d sheet. This is then deformed according to the DEM data. Producing elevation maps in Blender was predominantly conducted through the use of the ‘shader editor’ workspace, which allows the user to utilise various modules to modify the surface of a chosen object.

Within this workspace, the Image Texture module allows an imported raster file, in this case the DEM, to affect properties of the material. In a standard 3D modelling context, this could be used to
apply an image texture to the surface, e.g. wood or brick. Applying the DEM output — through the *image texture* module — to the colour input of the plane changes the colour of the plane to reflect the DEM, as though it were printed on the plane’s surface (figure 9b). In order for the DEM data to be correctly scaled, the plane and DEM raster should have matching proportions e.g. if the DEM has 2000 x 3000 cells, the plane must have a 2:3 size ratio.

To make a 3D surface from the DEM data, the DEM data must be connected to the *displacement* property of the plane’s surface — Much like a GIS interprets the colour values of a DEM tif as height values, the *displacement* module pushes the plane’s surface out according to the DEM data, producing a 3D relief representation of the elevation data (figure 9c). The colour of the surface can be set to a colour scale representing the elevation data by additionally passing the DEM through a *colour ramp* and into the plane’s colour input (figure 9d).

To produce a more photorealistic model, satellite or aerial imagery can be applied to the surface of the map. Using a second *image texture* module, ESRI satellite imagery was assigned to the plane’s
surface colour (figure 9e). It should be noted, that to prevent the artificial Blender shadows and the ESRI scene’s real in-image shadows from clashing, the angle of the light in Blender should be set to align with the sun in the imagery. In order to add the flood model outputs to the render, a second plane with matching topographic displacement was created. Instead of the ESRI imagery acting as the texture, the flood model raster was applied. Any areas that were not part of the flood model were set to be transparent (figure 9f).

Initial tests using Landsat 8 data showed that at a small scale, the 30m resolution satellite imagery was sufficient. However, at a larger scale, where the lahar fills the frame, the resolution was too coarse with Panabaj appearing as a faint blur. Instead, satellite imagery from ESRI (2022) was imported from the Blender GIS module. This imagery is significantly higher resolution (<1m) and clearly shows roads, buildings, farms, trees etc.

2.3 Logistical challenges with Blender

Using Blender to produce ray-traced relief maps takes time. The primary GPU (Graphics Processing Unit) used throughout this project was an GeForce RTX 2070, currently retailing at around £650. This is not only expensive, especially for those in developing countries such as Guatemala, but also impractical to transport and use in the field — while laptops with high-powered GPUs exist, these are even more expensive.

If a familiarity with the ray-traced style of elevation maps is established and becomes part of the consistent communication of hazards, the render time could be a significant bottleneck in the communication process, especially in cases where information needs to be delivered quickly.

For example, a 4k render takes around 15-20 minutes, depending on the complexity of the terrain rendered, using an RTX 2070 GPU. Using less powerful hardware, which may be all that is available in the field, would take significantly longer (multiple hours). Animations in Blender also take significantly longer; a 10 second animation may contain 300 1080p frames, this can take multiple hours, even on powerful hardware.

Given these constraints, using Blender and ray-traced map outputs may only be appropriate in scenarios where there is little urgency in the communication of hazards, i.e. retrospective research such as this dissertation.
References


Appendix I - List of DEMs

Figure 1 SRTM 30m DEM

Figure 2 10m Resampled SRTM 30m DEM
Figure 3 AW3D 10m DEM
Figure 4 Blended DEM: Cover HR-West

Figure 5 Blended DEM: Cover HR-East
Figure 6 Blended DEM: MBlend HR-West

Figure 7 Blended DEM: MBlend HR-East
Figure 8 Blended DEM: DBlend HR-West

Figure 9 Blended DEM: DBlend HR-East
Appendix II - Modelled Flows

Figure 1 Flow modelled on 10m AW3D data

Figure 2 Flow modelled on 30m SRTM data
Figure 3 Flow modelled on the Cover - HR-West dataset

Figure 4 Flow modelled on the Cover - HR-East dataset
Figure 5 Flow modelled on the MBlend - HR-West dataset

Figure 6 Flow modelled on the MBlend - HR-East dataset
Figure 7 Flow modelled on the DBlend - HR-West dataset

Figure 8 Flow modelled on the DBlend - HR-East dataset