Lahars and Lyrics:
Learning from Adjustments in Landscape and Culture Following prolonged Volcanic Disturbance on the Island of Montserrat

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Abstract

Explosive volcanic eruptions can profoundly disturb surrounding landscapes. Volcanic phenomena (e.g., pyroclastic density currents, tephra fallout) inundate the headwaters of proximal river systems with vast quantities of sediment. This perturbs the hydrology of these systems which then respond by increasing sediment and water flux to downstream reaches via *lahars*. These hazardous sediment-laden flows can induce dramatic, potentially destructive, and long-lived geomorphic changes within affected drainages. Most understanding of the readjustment of rivers following volcanic disturbances comes from studies following short-lived, transient eruptions. By contrast, limited research has considered responses to prolonged episodic eruptions, characterised by repeat phases of eruption and quiescence. This thesis addresses this research gap by exploring how the morphodynamics and lahar activity within the Belham Valley, Montserrat, have evolved in response to episodic disturbance by the eruption of Soufrière Hills Volcano, 1995 - present. Methods involved include novel longitudinal synthesis of a range of observational data, from ground-based photographic surveys to satellite-derived Digital Surface Models, as well as statistical analysis, and numerical modelling. I show: 1) episodic eruptions induce distinct fluvial responses, manifesting in aggradation-degradation cycles driven by evolving sediment availability, water supply, and vegetation cover; 2) lahar hazard is mediated by evolving catchment-scale conditions; 3) modelling the temporal evolution of lahar activity in such systems shows promise but remains a challenge. During a research assistantship alongside my PhD, I was heavily involved in the development of a co-created public engagement project on Montserrat, *Mountain Aglow*. This project sought to incorporate the lived experience of eruption in the form of arts – i.e., *lyrics* – into Disaster Risk Management (DRM) strategies. The final chapter of this thesis presents an evaluative study of this project. I demonstrate that incorporation of lived experience and co-creation of DRM practices is an effective and recommendable means of improving engagement with at-risk populations.

Cover photo: Mountain Aglow on the Montserrat Volcano Observatory helipad with Soufrière Hills Volcano in the background.

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Chapter 1: Introduction and Literature Review

The acute and instantaneous environmental and societal impacts of paroxysmal explosive volcanism are well known within both the scientific and public spheres. The dramatic imagery of turbulent eruption columns, 200 mile-an-hour pyroclastic density currents (PDCs) and burning buildings capture the imagination, inspire awe, and cater to a thirst for drama (Bahk and Neuwirth, 2000; Sigurdsson and Lopes, 2015). Primary volcanic phenomena are indeed among the most hazardous and lethal aspects of volcanic eruptions and thus warrant commensurately intense scientific focus (Siebert et al., 2015; Brown et al., 2017). However, attention paid to these sudden movements of volcanoes neglects the fact that, in many instances, eruptions themselves, as well as their impacts and the risk they pose, are far more protracted than their moments of paroxysm (e.g., Thouret et al., 2014; Calder et al., 2015; Siebert et al., 2015; Barclay et al., 2019; Major et al., 2019).

Volcanic eruptions may exert longer-term influence, i.e., spanning years to centuries, over both physical and human landscapes, particularly if the eruption is long-lived (e.g., Thouret et al., 2014; Wolpert et al., 2016; Barclay et al., 2019; Major et al., 2019). These lasting effects are important considerations for the management of risk around volcanoes. In the physical domain, eruptions may disturb river systems leading to the modification of sediment and water transport regimes which drive hazardous and protracted geomorphic changes within affected catchments (e.g. Gran et al., 2011; Jones et al., 2015). Within the social domain, volcanic eruptions can cause prolonged displacement and loss of livelihood, which have considerable socio-economic impacts (Barclay et al., 2019). An important difficulty faced by disaster risk managers when confronting longer-term volcanic risk is balancing the risks posed by volcanoes with the risks posed by the potential socio-economic impacts of evacuations (Woo, 2008; Lechner and Rouleau, 2019). A key challenge is maintaining vigilance and preparedness within at-risk populations during periods of quiescence between paroxysmal events when volcanic risk may be less evident (e.g. Fanta et al., 2019; Monteil et al., 2020).

As this introduction and literature review will demonstrate, challenges remain with regards to both 1) understanding the evolution of geomorphic impacts and lahar hazard, and 2) maintaining community preparedness, during periods of prolonged and episodic volcanic activity and risk. Most of this thesis explores the effects of volcanism on river systems as, originally, this was the sole focus of my PhD; literature relevant to this will be explored in sections 1.1 and 1.2 of this chapter. Early in my PhD I took on a role as Research Assistant on the Disasters Passed project, a volcanic risk communication initiative based in the Eastern Caribbean, with a primary focus on Montserrat, led by one of my supervisors (Prof Jenni Barclay). Three years later I found myself with an opportunity to perform an evaluative analysis of this initiative to assess its success. This was seen as a valuable chance to develop my inter-disciplinary research skills. Thus, a small part of this thesis presents this analysis. Section 1.3 of this introductory chapter reviews literature relevant to this component of my work. Section 1.4 will then provide details specific to the study area of this work: Montserrat.

1.1 Volcanic Landscape disturbance: fluvial response and recovery

Fluvial systems act as conveyors of water and sediment through the landscape; stable steady-state conditions permit hydro-geomorphic equilibrium within them (Burt and Allison, 2010; Fryirs and Brierley, 2012). Equilibrium is met when the boundary conditions, consisting of inputs (sediment and water) and any processes that mediate their transfer through the system (e.g., vegetation controls on rainfall runoff), maintain a quasi-stable balance within a typical range of variability. This manifests as a consistent and characteristic spectrum of flow behaviour, which maintains a stable range of morphology within the drainage network. Disturbances to these systems impact the boundary conditions by altering:

- Water supply (e.g., an extreme rainfall event, outburst floods),
- Sediment supply (e.g., via landslides or volcanic eruptions)
- Landscape processes that mediate water and sediment transfer (e.g., damage to vegetation by wildfires, hurricanes, volcanic eruptions, etc.).

Fluvial systems are self-regulating and respond by altering water and sediment fluxes to recover towards a new steady state (Fryirs and Brierley, 2012). Downstream this may manifest as a dramatic change in flow behaviour, which in turn may modify channel structure/morphology, both of which are potentially hazardous.

Explosive volcanic eruptions are among the most dramatic agents of landscape disturbance on Earth (e.g., Major et al., 2000, 2021; Gran and Mongomery 2005; Manville et al., 2009). Sudden deposition of pyroclastic sediment by primary volcanic phenomena, such as pyroclastic density currents (PDCs) and tephra fall from eruption columns, may leave behind deposits of pyroclastic sediment which fill proximal valleys and blanket the landscape, i.e., landscape modification or mantling (Manville et al., 2009). This constitutes a major deviation from pre-disturbance rates of sediment supply. The characteristics of these deposits depend on the process of genesis; however, they are often loose and poorly consolidated, and may be made up of a variety of particle sizes, which has important hydrological implications. In particular, the introduction of fine grained sediment particles can decrease infiltration rates by orders of magnitude soon after deposition (Teramoto et al., 2003; Major and Yamakoshi 2005; Jones et al., 2017); though this has not necessarily been observed to the same degree in all cases (e.g., Soufrière Hills Volcano, Barclay et al., 2007). This effect is particularly prominent on steep slopes (Barclay et al., 2007; Pierson and Major, 2014) or when deposited sediment is ash-grade because this very fine sediment may be hydro-repellent or form surface seals when wet (Ogawa et al., 2007; Capra et al., 2010; Pierson and Major, 2014; Jones et al., 2017). The loose nature of sediments also renders them particularly prone to erosion and remobilisation by any resultant surface flow.

In some cases, pyroclastic deposition may also lead to topographic changes, also known as 'landscape-forming' impacts (e.g., Manville et al., 2005; 2009). These can redefine watershed margins which may lead to 'stream piracy', whereby portions of watersheds are swapped from one to another (Pierson and Major 2014). This type of landscape modification was observed in the head waters of the Sacobia and the Pasig-Potrero rivers following the eruption of Mt Pinatubo, Philippines 1991 (Gran and Montgomery, 2005), and following the truncation of the head waters of the North Fork Toutle River following the eruption of Mt St Helens, USA, 1980 (e.g., Major et al., 2000). Alteration to watershed margins influences the amount of rainfall received by the catchment and has significant implications for potential discharge of resultant flow.

The presence of vegetation has four important effects on catchment hydrology (Swanson et al., 2013):

1) Water may be stored temporarily on the leaf surface or stems, slowing the rate of throughfall during and after a rainfall event,
2) Rainfall impact velocities are greatly reduced when intercepted by leaves, which reduces impact-driven erosion,
3) The presence of vegetation increases surface roughness and substrate stability, thereby impeding flow, substrate erosion and flow bulking, and
4) Soil surfaces may be interrupted by root systems, which encourages infiltration and limits potential runoff magnitudes.

Defoliation or complete removal of vegetation e.g., by burial, blowdown, burning, ash loading, gaseous corrosion, restricts these effects, resulting in increasing downstream water flux and downstream sediment flux (Antos and Zobel, 2005; Barclay et al., 2007; Ogawa et al., 2007; Alexander et al., 2010; Pierson and Major, 2014).

In combination, these changes exacerbate runoff during rainfall, resulting in altered water flow behaviour, typically with higher discharge and sediment transport capacity, a phenomenon known as a *lahar*. The term 'lahar' is an Indonesian word describing mixtures of water and pyroclastic sediment which travel downstream via watercourses (Vallance and Iverson 2015, and references therein). Lahars are the primary manifestation of increased sediment availability and modified water flux in volcanically-disturbed catchments; they are the dominant vectors of sediment transport from disturbed headwaters to downstream reaches (Lavigne, 2004; Pierson and Major, 2014). Section 1.2 explores lahars, their initiation, and impacts in more detail.

Transport of sediment by lahars and other post-eruptive stream flow leads to sedimentation in downstream reaches where flows lose their energy and deposit their sediment load. The subsequent geomorphic modifications typically evolve over timescales far exceeding paroxysm. A general conceptual model of post-disturbance fluvial recovery at volcanoes is presented by Gran and Montgomery (2005) (Figure 1.1). This landscape disturbance and recovery model is derived from long term (i.e., decadal) observations of the fluvial responses to short-lived, large-magnitude eruptions, with instantaneous sediment inputs to headwaters of around or exceeding 1 km^3. Figure 1.2 is a schematic representation of the disturbance recovery process.

1) Prior to eruption (Figure 1.2, Panel A), the river system is in a steady state equilibrium; water and sediment supply are quasi-stable and the river maintains a characteristic form.
2) In the first year(s) (Figure 1.2, Panel B): An eruption induces landscape disruption by suddenly inundating the catchment with large quantities of sediment and destroying vegetation, both of which alter runoff dynamics and sediment availability. The resulting runoff is higher magnitude compared with pre-disturbance and easily entrains the loose pyroclastic substrate, resulting in large lahars which transport sediment downstream.

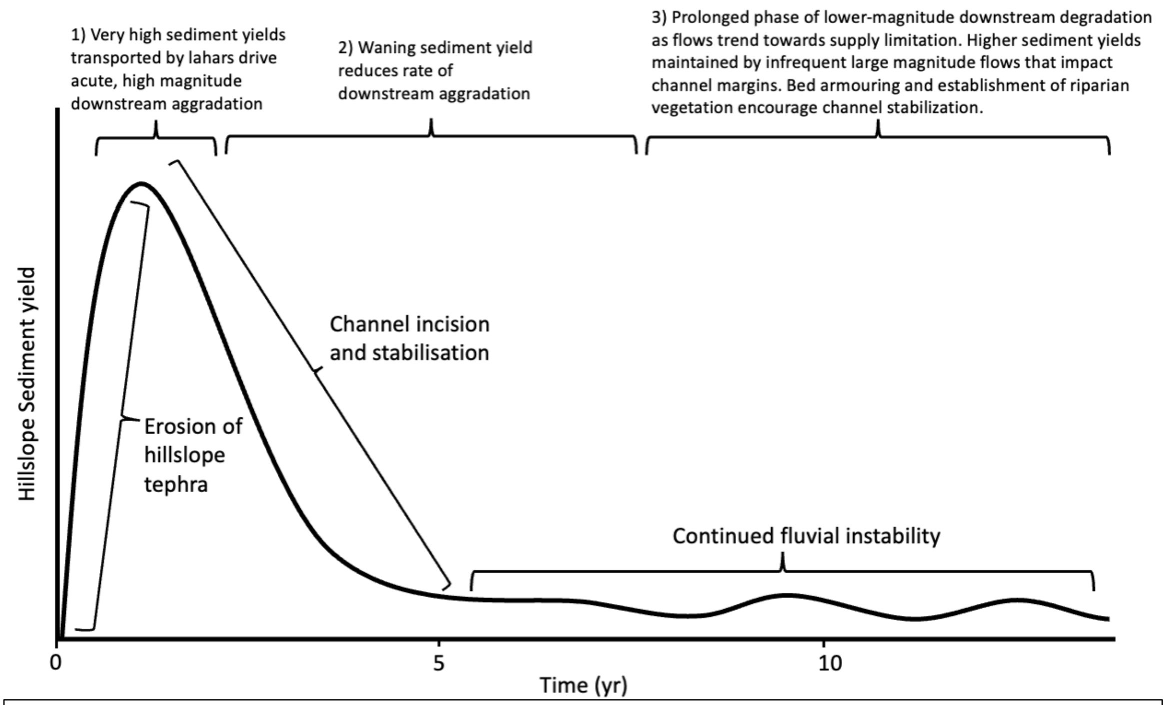


Figure 1.1: Conceptual schematic of post-disturbance sediment yield recovery presented by Gran and Montgommery (2005)/Gran et al. (2011) based on studies following the eruption of Mt Pinatubo, Philipines, 1991.

These substantial flows are likely to be hyper-concentrated flows (20 – 60% sediment by volume) or debris flows (>60% sediment by volume). Sediment yields from headwaters may be orders of magnitude above the pre-disturbance baseline. Deposition by lahars causes downstream aggradation and widening of channel bed. Channel forms are dominated by systems of braided sub-channels which rapidly migrate across the valley floor as they quickly avulse due to deposition.

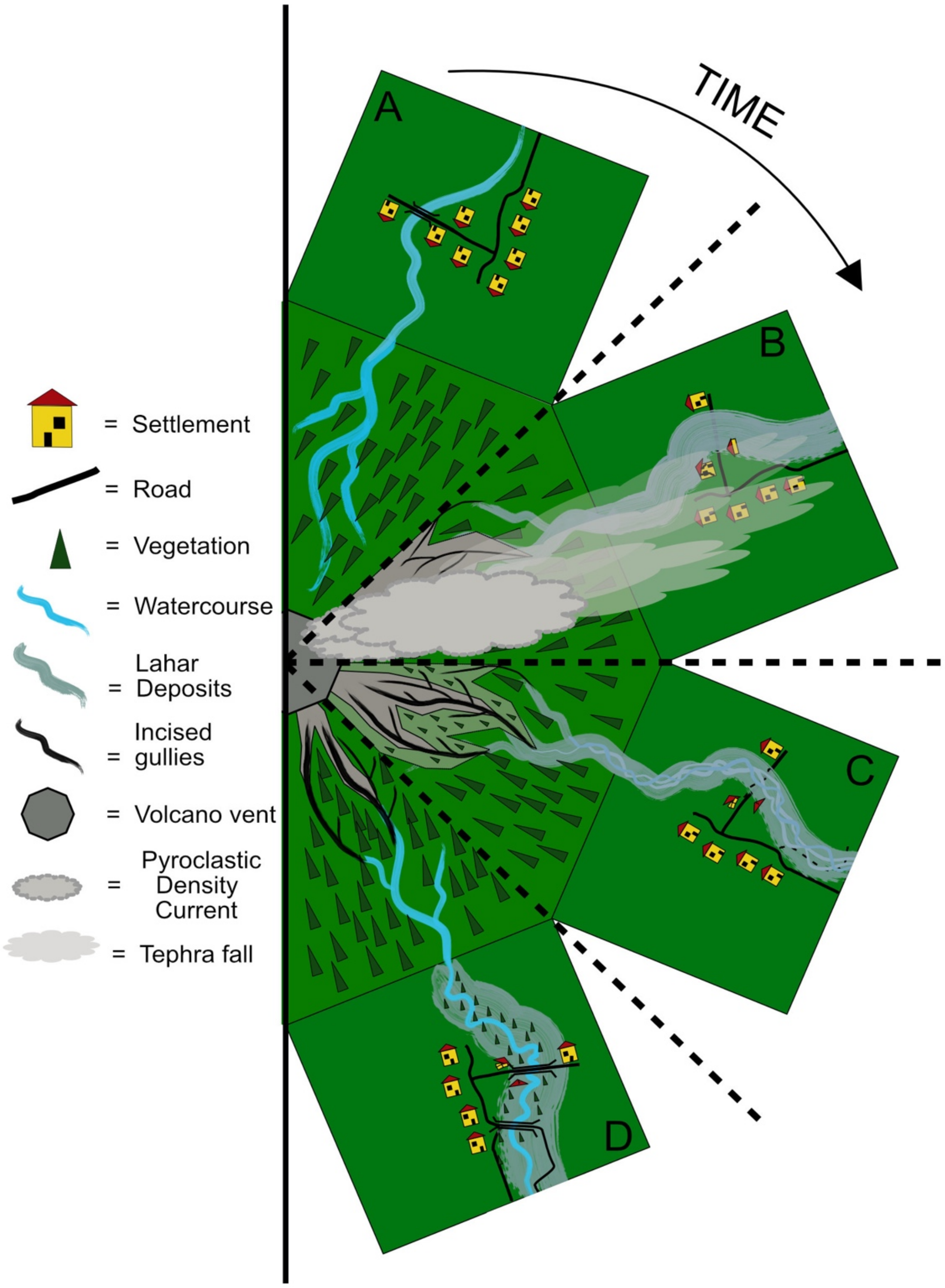


Figure 1.2: Generalised schematic of fluvial evolution in response to eruption based on the Gran and Montgommery (2005) model.

3) Up to 5 years after (Figure 1.2, Panel C): In combination, the removal of tephra, initiation-extension-stabilisation of rill and gully networks during Stage 1, stabilisation of hillslope sediments, and the gradual reestablishment of hillslope vegetation, all act to reduce availability of sediment for entrainment and dampen runoff responses. Subsequent flows are of lower magnitude and lower sediment concentration causing sediment yields from upper catchments to decline non-linearly. This results in a declining rate of aggradation in lower reaches of the affected fluvial system(s).
4) 5-10 years and onwards, potentially over many decades (Figure 1.2, Panel 4): most pyroclastic sediment may now be removed from headwaters or stabilised, and vegetation may be well established over much of the deposits. Major flows are now infrequent and likely to be supply limited when reaching lower reaches. In systems with permanent stream flow, background stream-flow is the dominant sediment transport mechanism, rather than lahars. Over time, declining sediment yield from upstream may initially encourage localised scour and may progress towards net degradation via the incision and stabilisation of primary channels. Seasonal variation in water supply may lead to subsequent seasonality in channel morphology and bed forms owing to unsteady rates of sediment transport. Channel margins may remain unstable and adjust laterally which maintains abnormally high sediment yields. The system may not fully recover to pre-eruption conditions but instead may establish a new equilibrium and steady state morphology owing to channel bed armouring or stabilisation of channel margins by vegetation. Recovery to new steady-state condition may take decades or up to a century. Ultimately the rate of adjustment following disturbance depends on the disturbance magnitude and the availability of water to flush excess sediment through the system.

Numerous studies have demonstrated the prolonged impacts of these extraordinarily high-magnitude and long-lived elevated sediment yields, and the associated dramatic and hazardous downstream geomorphic adjustments that such eruptions induce; e.g., Santa Maria, 1902 (Kuenzi et al., 1979); Mount St Helens, 1980 (Major et al., 2000, 2021); Mt Pinatubo, 1991 (Gran and Montgomery, 2005; Gran et al., 2011). However, globally, fluvial systems may be perturbed by a variety of other patterns of sediment input from volcanism which in turn may induce a spectrum of recovery pathways. For example, transient, small to moderate magnitude eruptions exert a lesser impact on the landscape as the sediment loading and the spatial footprint of impacted areas is reduced resulting in lower magnitude and shorter-lived pattern of elevated hillslope sediment yield and downstream channel response. In other cases, eruptions may be persistent or episodic, which causes the continuous or repeat introduction of relatively small quantities of sediment into headwaters inducing greater yields than large magnitude eruptions over the long term (Thouret et al., 2014).

The remainder of this section will describe some examples of the fluvial responses that have been observed following a range of explosive eruption types, including Transient (large- to small-magnitude), Persistent, and Episodic. Table 1.1 presents a summary. It should be noted that due to the spectrum of volcanic behaviour exhibited around the world (Siebert et al., 2015), it is difficult to classify some eruptions into clear sets. In the following, some of the examples could be considered as belonging to one, other, or two categories depending on how they are designated.

Eruption type	Characteristics	Impact and response	Examples
Transient, large	Short-lived (hours/ days) deposition of >1 km^3 of pyroclastic material, including ignimbrite forming events.	Acute elevation in sediment yields by 1 to 2 orders of magnitude within first 1-2 years due to rapid erosion of pyroclastic deposits. Very large lahars dominate sediment transport. Sediment transfer from upstream overwhelms downstream channels and drives rapid aggradation and valley floor widening; Protracted subsequent phase of declining aggradation rates and degradation; sediment transport typically dominated by background stream flow. Majority of geomorphic change occurs in first years; recovery may be protracted over several decades or exceed a century.	Taupo (Manville et al., 2005, 2009); Mount Saint Helens (Major et al., 2019, and references therein); Pinatubo (Gran and Montgommery, 2005; Gran et al., 2011); Santa Maria (Kuenzi et al., 1979)
Transient, small - moderate	Short-lived (typically hours/days) deposition of the order of up to 10^8 m^3 of pyroclastic material	Acute but relatively short-lived elevation in sediment yields, typically of lower magnitude than following large eruptions. Similar downstream response pattern as large-magnitude eruptions, but shorter-lived and typically of lower magnitude. Local geomorphology may lead to acute geomorphic modifications of similar or even larger magnitude than observed following large-magnitude eruptions.	Ontake (Kataoka et a., 2018); Merapi (Lavigne et al., 2005; de Belizal et al., 2013; Gob et al., 2016); Mount Hood (Pierson et al., 2011) Chaiten (Major et al. 2016)
Persistent	Long-term (years-decades) eruptions characterised by ~daily deposition of variable small-moderate (10^2 – 10^6 m^3) quantities of pyroclastic material. Total deposition over time may amount to as much as a large transient eruption.	Persistent supply of sediment from upstream allows for persistent sediment transport to lower reaches providing water supply is sufficient. Persistent lahar hazard. Channel morphology is determined by relative rate of upstream sediment supply. Typically induces long term aggradational trend or at least maintains aggradational channel forms. Periods of reduced sediment supply may induce localised degradation.	Semeru (Thouret et al., 2014); Tungurahua (Jones et al., 2015); Santiaguito (Lamb et al., 2006; Harris et al., 2019); Sakurajima (Levigne et al. 2004)
Episodic	Long-term (years-decades) eruptions characterised by episodes/phases of small-moderate eruption lasting months/years, punctuated by pauses of months/years.	Long-term research is limited but suggests episodic deposition leads to pulsatory sediment transport and aggradation-degradation cycles in downstream channel reaches.	Merapi (Wolpert et al., 2016); Soufrière Hills (Barclay et al., 2007; Susnik 2009; Froude 2015)

Table 1.1: Examples of eruption types, their characteristics, the typical fluvial response, and named examples with references.

1.1.1. Transient, large-magnitude eruptions

Such eruptions deposit very large quantities (>1 km^3) of sediment into fluvial headwaters over short periods of time. The magnitude and areal extent of deposition are profound; significant modifications to topography and watershed boundaries are not uncommon (e.g., Mt St Helens (MSH) and Mt Pinatubo), and devastating impacts to vegetation may be widespread. Numerous studies have demonstrated extraordinary increases in sediment yields that such eruptions induce, and the associated dramatic, hazardous and prolonged downstream geomorphic adjustment. Particularly detailed studies exist for the North Fork Toutle River (NFTR) following the 1980 eruption of MSH, USA, and the Sacobia and Pasig Potrero Rivers following the 1991 eruption of Mt Pinatubo, Philippines.

Mt St Helens, USA, 1980

The eruption of MSH unleashed a 2.8 km^3 debris avalanche and 0.19 km^3 of lateral blast tephra covering 550 km^2 (Major et al., 2000). This event truncated the head waters of the NFTR owing to the removal of the summit of MSH, inundated it with sediment and caused widespread vegetation blow down and ash damage. Sediment yields from the NFTR peaked within two years at around 500 times the pre-eruption rate, falling to about 10 times the background rate within 5 years. This period was associated with a complex pattern of fluvial network reestablishment in the headwaters and instigated major downstream channel adjustments in the NFTR. In this early period, the river channel aggraded by between 10-15 m and widened by 100s of metres. Since then, sediment yields have continued to decline, which has led to localised reincision of the NFTR. However, despite declining yields from the headwaters, sediment transport through the NFTR has remained abnormally high above the postulated pre-eruption rate; this is a result of ongoing complex geomorphic readjustment of the NFTR, particularly during large-magnitude geomorphically effective flood events (Major et al., 2018, 2019, 2021).

Pinatubo, Philippines, 1991

The Pasig-Potrero and Sacobia rivers of the Philippines were collectively disturbed by between 1.1 – 1.3 km^3 of pyroclastic deposition during the eruption of Pinatubo in 1991 (Gran et al., 2011). Half the deposits were removed by these rivers in the first two years, as a result of large cyclone-related lahars, elevating total sediment yields to around 3 x $10^6 m^3 km^{-2} yr^{-1}$; sediment yields remained above 1 x $10^6 m^3 km^{-2} yr^{-1}$ for a further three years (Janda et al., 1996, Gran et al., 2011). In 1997, aggradation rates on the alluvial fan head of the Pasig-Potrero River (15 km from the Pinatubo crater) were between 3 – 5 m yr^{-1}. Between 2002 and 2009, sediment yields had declined to approximately 3 $x10^4 m^3 km^{-2} yr^{-1}$ (a decline of two orders of magnitude in a decade) and average aggradation rates on the alluvial fan had declined to 0.7 m yr^{-1}.

Santa Maria, Guatemala, 1902

Dramatic fluvial aggradation and deltaic growth were observed following the Plinian eruption of Santa María, Guatemala, in 1902, though data relating to geomorphic changes is limited. This eruption produced an estimated 20 km^3 (8.5 km^3 Dense Rock Equivalent; DRE) of pyroclastic debris, with tephra fall impacting an area of 1.2 $x10^6$ km^2 (Williams and Self, 1983). Within a few years, the bed of the Samalá River had aggraded between 10-15m, blocking tributary rivers, leading to the formation of flanking lakes. By 1922, a coastal delta had formed with a volume of 4 km^3, extending 7 km out from the pre-eruption coastline. Waning sediment supply allowed marine erosion to transform this delta into a new arcuate coastline by 1947, though this has remained relatively stable owing to ongoing sediment supply from the present eruption of Santiaguito dome complex (Kuenzi et al., 1979; Lamb et al., 2019).

1.1.2 Transient, small-moderate magnitude eruptions

Transient small-moderate scale eruptions (i.e., those ejecting <1km^3 of pyroclastic debris) exert similar, albeit more limited, effects to large magnitude eruptions. As such, they are typically associated with both a rapid and short-lived increase and decrease in sediment yields as sediment supply is relatively limited. The downstream response is also typically relatively restricted, however, owing to local geomorphology or climatology, the magnitude of geomorphic changes may locally exceed those induced by large-magnitude eruptions.

Merapi, Indonesia, 2010

Gunung Merapi, Indonesia, is considered to be episodically active (Ogburn et al., 2015; Wolpert et al., 2016), and has undergone phases of eruption since the late 1700s (Voight et al., 2000). However, given its relative magnitude, the VEI 4 eruption of Gunnung Merapi, in October 2010, I argue it can be considered as a discrete moderate disturbance relative to the contemporarily recent activity and quiescence for five years (Jousset et al., 2012). It is a particularly well documented example of this rapid fluvial disturbance/recovery pattern caused by a moderate disturbance. ~130 $x10^6$ m^3 of tephra and PDC deposits were emplaced, primarily in the catchments of the Progo River and the Opak River. Lahars have been very common since 2010; approximately 70% of these have occurred within the Progo River and 30% in the Opak River catchment (de Bélizal et al., 2013; Syarifuddin et al., 2017). In the first rainy season, a total of 240 lahars (50 characterised as debris flows) were observed; by contrast, between 2011 and 2015, 180 occurred (de Bélizal et al., 2013; Gob et al., 2016).

Observations of the Progo River and its tributaries between 2010-2015 revealed an aggradation/degradation cycle in response this eruption (Ikhsan et al., 2020a). The 46 lahars that occurred in Kali Putih sub-catchment (impacted by 20 x10^6 m^3 pyroclastic deposition) in the first rainy season exceeded a total sediment volume of 5 x10^6 m^3 (de Bélizal et al., 2013; Hadmoko et al., 2018). In the following rainy season, only 18 lahars were observed, reflecting the depletion of sediment and recovery of the catchment upstream. Together, these two rainy seasons contributed to significant aggradation and channel widening. By 2015, upstream sediment supply had waned significantly, leading to channel narrowing and incision, with the flow state of the river returning to approximately pre-eruption conditions (Ikhsan et al., 2020a). The rapid and efficient transportation and subsequent recovery of this basin is attributed to particularly high rainfall (3000 mm yr^{-1}) and the steep and narrow valley morphology which encourages efficient and competent flash-flood behaviour.

The Opak River catchment was affected by ~50 x10^6 m^3 PDC and tephra fall deposition (Cronin et al., 2013; Gob et al., 2016). Observations of erosion to the Gendol River sub-catchment reveal PDC-driven aggradation of 30-50 m, followed by incision occurring at declining rates with time. Gully widening of 7 m yr^{-1} was observed between 2010-2012, which removed approximately 65% of the PDC deposits in this reach (Kassouk et al., 2014; Ville et al., 2015). This equates to a very high specific sediment yield of approximately 4 x10^6 $m^3km^{-2}yr^{-1}$ (Kassouk et al., 2014), exceeding those observed at Mt Pinatubo (Gran et al., 2011). Again, this very high yield is attributed to the high rainfall and narrow steep valleys that drain the volcano. A reduced rate of gully widening of 6.1 m yr^{-1} was observed between 2012-2014 (Ville et al., 2015a). This declining sediment yield from source deposits is further reflected by observations of only 9 debris flows between 2015-2018, i.e., ~2 per year, compared to ~15 during the 2010-2011 rainy season alone (Hapsari et al., 2020; Syarifuddin et al., 2017). Despite the ample sediment supply and high rate of incision, the expected sediment flux into the middle and lower reaches never materialised, owing to the presence of Sabo dams and rapid establishment of aggregate extraction, a common economic activity and human disturbance in volcanic catchments due to its use in concrete (Waqar et al., 2023). The relatively limited sediment flux into the middle and lower reaches encouraged supply-limited flows, which precluded aggradation and promoted the evacuation of sediment downstream of the Sabo dams, driving degradation, channel incision and bed armouring. Stable sediment bars were evident by October 2012 and by September 2014 these bars were densely vegetated, suggesting their detachment from the main channel due to incision (Gob et al., 2016).

Mt Hood, USA, 1781-93

Given its 12-year duration, the dome forming eruption of Mt Hood, USA, 1781-93, could be classed as a relatively short persistent eruption. However, given its age, insights into syn-eruptive geomorphic changes are limited, and more information is available with respect to catchment over the long-term following the eruption. Thus, here I consider it a transient disturbance. This dome-forming eruption progressively deposited 1 x 10^8 m^3 to the headwaters of the Sandy River over the 12-year period (Pierson et al., 2011). The influx of sediment resulted in a simultaneous and dramatic aggradational response in the confined lower reaches. Sediment yields are not known, but aggradation rates of 2 m yr^{-1} in the lower depositional reach (61-87 km from vent) meant peak aggradation of up to 23m was achieved within a decade; this was driven principally by one large lahar (debris flow) and cumulative sediment charged stream flow induced by winter storms. The termination of sediment production coincided with a switch from aggradation to degradation, which took at least half a century to complete, reaching the present-day bed elevation 3 m above the postulated pre-eruption profile. This river has now stabilised at a new post-eruption equilibrium (Pierson et al., 2011). Interestingly, the degree of aggradational response observed here is greater in magnitude than those observed following the large-magnitude explosive eruptions of Santa Maria, Mt St Helens and Mt Pinatubo which introduced an order of magnitude more sediment. This is understood to be due to the narrow, confining morphology of the Sandy River Valley.

Chaiten, Chile, 2008-09

Profound, hazardous and acute channel modifications were observed in the Chaitén River, Chile, following the Plinian eruption of Chaitén Volcano in 2008-2009. In response to sediment loading of the order of 10^8 m^3 and associated modifications to upland forest cover, the Chaitén river aggraded and its channel avulsed, subsequently inundating the town of Chaitén. The avulsed river proceeded to establish a new channel through the middle of the town to the sea (Major et al., 2016; Umazano et al., 2014a). Sediment yields are not accurately known due to extensive offshore deposition, but this disturbance of the Chaitén River drove the development of two new coastal fans within 2 years, with a total volume of ~12 x10^6 m^3, ~10 x10^6 m^3 of which was emplaced within the first year (Major et al., 2016). This case again demonstrates how the acute and rapid downstream response may quickly decline in magnitude within the first years of disturbance.

Ontake, Japan, 2014

There are few studies of small-magnitude disturbances, however, the 2014 phreatic eruption of Ontake Volcano produced in total an estimated ~1 x10^6 m^3 of volcanic ejecta (Maeno et al., 2016a). Two of the affected drainage basins exhibited lahar activity and heightened sediment discharge (Kataoka et al., 2018). The Akagawa River was the most affected during this eruption and exhibited a rapid increase in sediment transport via both lahars and bedload transport. Transport by lahars decreased steadily to the equivalent of pre-eruption background rates within two years, non-lahar/bed load transport remained markedly elevated by the end of the two-year study period. In contrast, the Shirakawa River, which was subject to a more limited impact, exhibited moderately raised sediment output via lahars, declining to fluctuate around the background rate within a few months (Kataoka et al., 2018). This example demonstrates how a reduced magnitude of a disturbance induces commensurately low-magnitude response and rapid recovery.

1.1.3 Persistent eruptions

In contrast to transient eruptions, some volcanoes may exhibit prolonged states of eruption and sediment production. ‘Persistently’ eruptions provide a continuous supply of sediment via frequent (~daily) small explosive events or rockfalls over a prolonged period (>decade). Occasionally this sediment supply may be augmented by larger scale explosive phenomena or dome collapses, which transiently increase sediment flux into head waters (Thouret et al., 2014). Examples of such volcanoes include: Santaguito, Guatemala, of the Santa-Maria-Santiaguito volcanic complex, which has been active since 1922 (Harris et al., 2006; Lamb et al., 2019); Semeru, Indonesia, active daily since 1884 (Thouret et al., 2014); Tungurahua, Ecuador, active since 1999 (Jones et al., 2015); Sakurajima, Japan, which has been persistently active since 1955, aside from a 9 month pause in 2016 – 2017 (Lavinge et al., 2004; Global Volcanism Programme, 2022). Annual sediment yields from catchments affected by this type of activity are lower than those following large eruptions, however, over the long term, the total yield may be equivalent or even greater. In these cases, downstream sediment and channel dynamics are determined by the *relative rate* of sediment and water supply to source areas. Relatively high rates of sediment supply may encourage more widespread aggradation (i.e., the transition to an aggradational regime may migrate upstream) or maintain aggradational landforms (e.g., the arcuate coastline formed following the 1902 eruption of Santa-Maria which has been in part maintained by persistent sediment supply from Santiaguito (Kuenzi et al., 1979)). Conversely, relatively reduced sediment supply will encourage lower rates of aggradation or instigate a minor degradational regime. Uniquely, owing to the persistent supply of sediment, these aggradation/degradation dynamics may occur over timescales of 10-15 years (Thouret et al., 2014).

1.1.4 Episodic eruptions

Alternatively, some volcanoes exhibit ‘episodic’ eruptions with periods of active sediment production punctuated by phases of quiescence that can last for months or years. Variants on this type of behaviour have been observed at numerous volcanoes worldwide including Merapi, Indonesia (Wolpert et al., 2016), Mayon, Philippines (Paguican et al., 2009) and Soufrière Hills Volcano (SHV), Montserrat (Wadge et al., 2015; Ogburn et al., 2015). Evidence suggests that fluvial responses to these eruptions are a hybrid between persistent and small-moderate transient eruptions in terms of their impact and the subsequent response (e.g., Froude, 2015). However, to date, there are comparatively few or limited studies that examine the fluvial response and recovery associated with the longer-duration, lower-magnitude, stop-start perturbations induced by episodic eruptions. There is therefore an opportunity to explore further the nature of fluvial adjustments in response to these types of disturbance.

1.2 Lahars: understanding and modelling their occurrence.

Lahars are a very prominent and significant hazard associated with many eruptions, particularly those involving fines-generating explosive phenomena (Gudmundsson 2015). The term 'lahar' is an Indonesian term used to describe a gravity-driven flowing mixture of water and pyroclastic sediment. The definition is non-specific and encompasses a range of pyroclastic sediment-laden flows, which may be split into three main categories (Mulder and Alexander 2001; Lavigne and Suwa 2004; Vallance and Iverson 2015).

1) Normal stream flows, i.e., dilute lahars, which contain up to 20% sediment concentration by volume, and for which water turbulence is the primary driver of sediment motion;
2) Hyperconcentrated flows containing 20%-60% sediment by volume, and for which particle-particle friction and collision dominate particle motion, sometimes leading to non-Newtonian rheology when sediment concentrations are sufficiently high;
3) Debris flows which are composed of more than 60% sediment by volume, often exhibiting non-Newtonian flow with limited internal mixing, i.e., a 'slug' of material that moves downslope.

Lahars are dynamic and complex; they can evolve while they flow, via bulking and debulking, e.g., by entraining more sediment or becoming diluted (Vallance and Iverson, 2015). For instance, a lahar that initiates as a normal stream flow in the upper reaches of a catchment, may soon erode and entrain underlying loose material, and evolve into a hyper concentrated flow or debris flow as it moves along the channel. This bulking may also occur due to direct input from tephra fallout as has been observed at Soufrière Hills Volcano (Carn et al., 2004; Barclay et al., 2007; Alexander et al., 2010). Similarly, as this flow descends and reaches parts of the channel of a lower gradient, it may begin to deposit material as it loses energy, which will decrease the sediment concentration (debulking), and thus, alter the behaviour of the flow. Alternatively, water supply via rainfall or by additional discharge from tributaries may dilute the flow. Similar modifications in flow behaviour may occur as a result of lahar pulses, which are commonly observed (e.g., Lavigne and Thouret, 2003; Alexander et al., 2010; Bosa et al., 2021). Pulsatory behaviour may be caused, for example, by internal instability of flows, fluctuations in water supply (e.g., variability of rainfall, snowmelt, crater lake discharge), temporary dams or breaks in slope, and non-synchronous arrival of discharge from tributaries (Lavigne and Thouret, 2003).

Owing to their high sediment content, lahars typically exhibit higher velocity and discharge compared to normal stream flow; velocities are often of the order of several ms^{-1}, and discharges of the order of hundreds to thousands of cubic m^3s^{-1}. High mobility in combination with high viscosity and elevated basal shear stress enhances the sediment transport capacity and the erosivity of flows compared to stream flows. The erosive force exerted on the bed may be as much as six times greater than that of normal stream flow (Selby, 1993), and, due to increased buoyancy force caused by high sand/silt/clay concentrations, large and heavy boulders (i.e., tens to hundreds of tons) may be carried many kilometres from their source (Alexander and Cooker, 2016). Lahars are a key vector of sediment transport around volcanoes, they remobilise material deposited upslope and efficiently transport it down slope in to lower fluvial reaches, onto depositional fans, or into the sea (Pierson and Major, 2014). Subaerial deposition of transported material will occur when the energy of flow subsides typically due to a reduction in slope gradient or valley widening which diminish the driving force (e.g., Pudasaini, 2011). The nature of deposition is highly dependent on the nature of the lahar when sedimentation begins. Debris flow-like lahars with limited internal mixing may freeze en masse or with mild evidence of progressive aggradation, leaving behind massive, compact, and very poorly sorted deposits which may also contain vesicles of air trapped by the high viscosity mixture (Vallance, 2015). Otherwise, sedimentation may occur progressively as the energy state of a flow evolves, leaving behind deposits that are intermediate between debris flow and alluvial deposits. For example, stratification is common, from weak to strong, and deposits tend to be thinner than debris flow deposits (Vallance, 2015)

Lahars can be triggered via a range of mechanisms and may occur both during (syn-eruptive and long after eruption (post-eruptive) (Gudmundsson,2015; Vallance, 2015). Some high altitude or high latitude volcanoes, such as those in the high Andes or in Iceland, may be capped with snow and ice which can quickly melt when it contacts lava or pyroclastic material. Melt water accumulates, mixing with pyroclastic material, and flows downslope, entraining more pyroclastic material as it does so. Extreme snow-and-ice-melt initiated lahars have been noted at Cotopaxi, Ecuador, where the Chillos Valley Lahar (~4500yr BP) flowed ~325 km to the Pacific, and at Mt Rainier, WA, USA, where the Osceola Flow (~5600yr BP) covered and filled ~200km^2 of Pudget Sound; both of these events had remarkable volumes of ~3.8 km^3 (Vallance and Scott 1997; Mothes et al., 1998; Mothes and Vallance, 2015). Other volcanoes, such as Mt Ruapehu, New Zealand, have summit crater lakes enclosed by unstable and fragile pyroclastic impoundments. Should these impoundments fail, the retained water is free to escape, often violently, in an outburst flood, and flow downhill, entraining volcaniclastic material as it does so. On Christmas Eve 1953, this type of outburst-flood lahar emanating from Mt Ruapehu destroyed a railway bridge as a passenger train was crossing, claiming 151 lives (Lecointre et al., 2004; Proctor et al., 2010).

Heavy rainfall is the third and most common mechanism for lahar initiation (Pierson and Major, 2014). Rates of precipitation be sufficient to exceed rates of infiltration into the land surface or induce saturation, both of which generate surface runoff, which in turn can remobilise, erode and entrain loose volcanic deposits to generate sediment-laden flow (e.g., Jones et al., 2017). Alternatively, saturation of pyroclastic deposits may lead to the exceedance of the shear strength of the substrate which may initiate shallow landsliding and subsequent evolution into a lahar as the sediment-water mixture channelises (Mead et al., 2016). Rain triggered lahars (RTLs) are a particularly common phenomenon on the flanks of tropical volcanoes, owing to the common occurrence of high intensity and/or long duration rainfall events, and have been documented at volcanoes all over the world, including: Agung, Indonesia (Zen and Hadikusumo 1964); Aso (Miyabuchi and Daimaru 2004), Izu Oshima (Miyabuchi et al., 2015), Ontake (Kataoka et al., 2018), and Yake-Dake (Suwa et al., 2011), Japan; Casita and San Cristóbal, Guatemala (Vallance et al., 2004); Kelud (Dibyosaputro et al., 2015), Merapi (Lavigne et al., 2000, 2004; de Belizal et al., 2013) and Semeru (Lavigne and Suwa 2004; Starheim et al., 2013; Thouret et al., 2014), Indonesia; Mayon (Orense and Ikeda 2007; Paguican et al., 2009; Scott 2010) and Pinatubo (Newhall and Punongbayan 1996; Gran et al., 2011) Philippines; Soufriere Hills, Montserrat (Barclay et al., 2007; Alexander et al., 2010; Froude, 2015; Jones et al., 2017); Volcán de Colima, Mexico (Zobin et al., 2009; Capra et al., 2010, 2018). As section 1.1 has demonstrated, the RTL response following disturbance may be prolonged, which may result in a great number of lahars over many years (e.g. Gran et al., 2011; Thouret et al., 2014; Jones et al., 2015). Furthermore, the probability and nature of lahars also subsequently evolves as the catchment recovers (van Westen and Daag, 2005; Jones et al., 2017).

Lahars expand both the temporal and spatial extent of hazard posed by volcanoes, as they may both outlive and outrun primary volcanic phenomena (e.g., Newhall et al., 2002; Lavigne and

Thouret 2003; Barclay et al., 2007; de Belizal et al., 2013; Froude, 2015). These sediment laden flows are a hazard to life and property owing to the high discharge and sediment content. Individuals caught up in flows may be swept away or submerged, and structures may be destroyed by high dynamic pressures exerted by direct impact from flow or buried by the deposition of sediment in waning stages of flow or progressive lahar occurrence (Janda et al., 1996; Paguican et al., 2009; Gudmundsson, 2015). A particularly striking example of the far-reaching effects of lahars is the case of Nevado del Ruiz, Colombia, in 1985, during which 23,000 people were killed in the town of Armero, 74 km from the volcano; another lahar from this eruption extended as far as 104 km (Lowe et al., 1986; Pierson et al., 1990). This is an extreme example, however the threat should not be underestimated, as even relatively small events may be able to inundate, bury, or destroy buildings and infrastructure, or lead to injury or fatality (e.g., Janda et al., 1996; Bosa et al., 2021). Indeed, globally since 1600 CE, lahars, both primary and secondary, account for 20% (~56,000) of all fatalities related to volcanic eruptions and, together with tsunamis and tephra fall, dominate volcano-related causes of death beyond 15 km from the volcano (Brown et al., 2017).

Given the hazard posed by lahars, understanding and anticipating how they initiate and then subsequently behave is essential for hazard management. However, the complexity demonstrated above renders comprehensive analysis and modelling of lahars very challenging. There is a wide field of research relating to the study and modelling of geophysical mass flows and how they initiate and propagate. Indeed, other types of mass-flows also threaten populations and infrastructure, but also landslides, debris flows, rock avalanches, snow avalanches, mine tailings failures, among others (e.g. Jakob et al., 2005; Glade et al., 2005; Kossoff et al., 2014; Statham et al., 2018).

With respect to initiation of mass-flows, most studies focus upon the trigger mechanism with the aim of establishing a means of providing advanced warning of flow events (e.g., Arattano and Marchi 2008); in many cases the triggering mechanism is rainfall (e.g., Bacchini and Zanonni 2003; Barclay et al., 2007; Abancó et al., 2016). Some studies seek to establish simple rainfall thresholds, the exceedance of which is associated with flow events; these are often considered in terms of rainfall intensity and duration (Rodolfo and Arguden 1991; Tuñgol and Regalado 1996; Lavigne et al., 2000; Lavigne and Suwa 2004; Paguican et al., 2009; Capra et al., 2010, 2018; Jones et al., 2017). By contrast, physically-based and spatially-distributed models might be adopted to account for rainfall magnitude and the nature of the substrate/deposit (e.g., accounting for slope, deposit thickness, layering, grain size distribution and pore pressure). These models simulate the behaviour of the mobilisable substrate under a range of rainfall conditions to assess the spatial footprint of source areas and the potential volume of resulting mass flows. Examples of such models applied to lahars include SHALSTAB (Baumann et al., 2018), TRIGRS (Baumann et al., 2018; 2019) and the lahar susceptibility model presented by Mead et al. (2016).

In terms of propagation and runout, numerical models aim to predict the potential runout of individual flows, either in isolation or probabilistically, indicating where in the surrounding landscape is likely to be exposed to the highest hazard. These models have been designed with a range of complexity. The simplest are based on empirical height:length equations, used to relate initiation height, flow volume and local topography to runout distances. An example of this type of model developed specifically for modelling lahars is LAHARZ (Iverson et al., 1998; Schilling 1998, 2014). An advantage of empirical models like LAHARZ is that they are computationally inexpensive and have minimal data requirements: digital topography and initiation volumes. As such, it has been used for lahar hazard mapping in a variety of settings, including: Popocatépetl, Mexico (Huggel et al., 2008; Muñoz-Salinas et al., 2009); Villarica and Calbuco, Chile (Castruccio and Clavero 2015); El Misti, Peru (Vargas-Franco et al., 2010); Soufrière Hills Volcano, Montserrat (Darnell et al., 2012, 2013); Merapi (Lee et al., 2015) and Agung (Andaru et al., 2022), Indonesia; Mt Pinatubo, Philippines (Carranza and Castro 2006). A disadvantage of this type of model is that it is based on a set range of debris flow-like lahars and thus may not be appropriate for use on more dilute lahars which have different rheology and flow behaviour.

More complex, single or multi-phase (i.e., sediment and water), physically-based models consider the dynamics of a flow as it passes over terrain (defined by digital elevation models) and moves through space, taking into account the volume, sediment:water ratio, and rheology to forecast runout potential. These models present an opportunity to account for more variability between and within flows but are more data intensive and computationally expensive. Titan2D (Pitman and Le, 2005) is one such model, and has been applied to lahars at numerous volcanoes, including Mt Ruapehu, New Zealand (Procter et al., 2004, 2010), Tungurahua, Ecuador (Williams et al., 2008) the Tacaná Volcanic Complex, Mexico-Guatemala (Cruz-Vázquez and Alatorre-Ibargüengoitia 2021), Kusatsu-Shirane Volcano, Japan (Kataoka et al., 2021), El Misti, Peru (Vargas-Franco et al., 2010). Other similar models include LaharFlow (Philips et al., 2023), r.avaflow (Mergilli et al., 2017), and RAMMS (Christen et al., 2010). Some more complex models are able to account for changes in these parameters due to bulking/debulking via interaction with underlying sediments/bedrock (e.g., RASH3D, Pirulli and Pastor 2012; RAMMS, Frank et al., 2015, 2017), or may be used to simulate complex flow behaviour at small scales to assess flow impacts on buildings and infrastructure, e.g., Smoothed Particle Hydrodynamics (SPH, Cleary and Prakash 2004; applied to lahars by Mead et al., 2017).

The advances noted above are considerable and pertinent for the study of mass flows and assessing their hazard. However, these models consider the occurrence of individual flows or an ensemble with a set range of initiation conditions and flow behaviours. Section 1.1 has demonstrated that a very limited amount of research has focussed on the decadal scale evolution of catchments disturbed by volcanoes exhibiting episodic activity. Equally, a relatively small quantity of research has sought understanding of how the activity of lahars is mediated by cycles of catchment disturbance and recovery. Both van Westen and Daag (2005) and Jones et al. (2017) present quantitative results that suggest that lahars become less likely as time elapses after a disturbance, positing that gully/channel stabilisation and hillslope recovery exert a control, but these are for short 2-5 year periods. Furthermore, to my knowledge, to date no studies have sought to examine or model this evolution and associated changes in sediment transport over the longer term. A possible exception is Meadows (2014). They use CAESAR-Lisflood (Coulthard et al., 2013; Lowry and Coulthard 2013) to forecast sediment yields from the North Fork Toutle River, which was disturbed by the eruption of Mt St Helens, 1980, with projections extending to 2100. However, their work examines trends in sediment yield by a river, not lahars specifically. The Gran and Montgomery (2005) conceptual model presented in Section 1.1 again loosely approaches this point, but it is not numerical. This therefore presents another opportunity for research.

1.3 Societal disturbance of eruptions and building resilience through sharing experience

Beyond their impact on the landscape, volcanic eruptions impact and shape human lives. Brown et al. (2017) identify that volcanic fatalities had been recorded in 18 of the 20 years up to 2017, and that, since 1500 AD, 635 eruptions have claimed a total of 278,378 lives. Fatalities, however, are just one metric of the impact of volcanism on people, which does not account for the number of, and the extent to which, human lives are impacted by eruptions.

Volcanic eruptions, and indeed any hazardous phenomenon, have the capacity to disrupt lives and livelihoods in a range of ways. Eruptions may cause death or injury and destruction of homes and infrastructure, particularly during paroxysmal episodes (Siebert et al., 2015; Brown et al., 2017). Indeed, potentially large swathes, or the entirety, of towns may be ruined, e.g., Saint Pierre, Martinique, 1902 (Fisher et al., 1980); Armero, Colombia, 1985 (Lowe et al., 1986); Plymouth, Montserrat, 1997 (Kokelaar et al., 2002); Goma, Democratic Republic of the Congo, 2002 (Komorowski 2002). However, some areas may not be directly impacted by the most hazardous phenomena but may be included in evacuation orders or exclusion zones, thereby displacing a greater number of people from their homelands (Winson et al., 2014). On a personal basis, experience of an eruption may thus cause physical injury (e.g., burns, ash induced asthema, etc.;

e.g., Horwell et al., 2015), psychological injury (trauma of directly experiencing the hazard event, any associated relocation, or losing/being separated from their home, friends and family, etc.; e.g., Ohta et al., 2003; Hlodversdottir et al., 2016; Dhilon and Sasidharan 2021), as well as a broad range of socio-economic damages/losses via the loss of community and livelihood (Doocy et al., 2013; Barclay et al., 2019). Importantly, volcanic eruptions may have more complex effects because many eruptions are not momentary events; eruptions come in variety of forms and achieve paroxysm and dormancy at different rates. Long-lived eruptions can cause protracted displacement and loss of livelihood, which have considerable socio-economic impacts (Barclay et al., 2019). With at least 800 million people living within 100 km of the Earth's suspected 1500 active volcanoes this is a critical challenge (Siebert et al., 2015; Brown et al., 2017).

To limit the impacts of natural hazards on society, communities and individuals, the practice of Disaster Risk Reduction (DRR) has been developed. DRR serves to prevent new and reduce existing disaster risk, and thereby improve resilience, via the implementation of risk-reducing policies, strategies and plans (i.e., Disaster Risk Management, 'DRM'; UNDRR 2015). The development and upkeep of Community preparedness is an essential component of effective Disaster Risk Reduction (DRR) and key for bolstering of community capacity and resilience in the face of disaster (Paton and Johnson 2001, Kitagawa 2016). The UNDRR defines 'capacity' as:

> *'The combination of all the strengths, attributes and resources available within an organization, community or society to manage and reduce disaster risks and strengthen resilience. This may include infrastructure, institutions, human knowledge and skills, and collective attributes such as social relationships, leadership and management.' – UNDRR, 2015*

'Resilience' is further defined as:

> '*The ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management'. – UNDRR, 2015*

Awareness is considered an essential prerequisite for improved preparedness (e.g., Paton and Johnston 2001; Eisenman et al., 2009; Shaw et al., 2009; Lindell and Perry 2012; UNDRR 2015).

Effectively engaging and educating the public to build their awareness of environmental hazards and how to respond to them (Disaster Risk Education; DRE) is thus a primary focus for DRM. A key principle of the United Nations Sendai Framework for Disaster Risk Reduction is to, *‘provide easily understandable information on disaster risks and protection options, to encourage and enable people to take action to reduce risks and build resilience’* (UNDRR,2015). Traditionally, a range of macro-level, top-down approaches may be adopted, whereby experts and authorities work together to assess the risk and provide advisories for the public to act upon (e.g., Glik 2007; Cadag and Gaillard, 2011). These advisories may manifest as the active creation of rules and decisions that keep decision-making in the hands of experts. For example, legally enforced lockdowns (e.g., COVID-19, White et al., 2022), evacuation orders (e.g., Bird et al., 2009; Lechner and Rouleau 2019; Connolly et al., 2020) and exclusion zones (e.g., Haynes et al., 2007; Winson et al., 2014); large scale drills (e.g., Chen et al., 2022). This is the set of actions most closely aligned with disaster risk management (DRM). They may also create and share knowledge designed to embed improved awareness, preparedness and implicitly decision-making into the lives of communities at risk, for example via educational curricula (e.g., UNESCO 2014); issuance of information and educational resources (e.g., hazard maps and information leaflets (Fearnley et al., 2017). Finally, they may also include more passive approaches, such as signage designed to encourage protective actions in the moment of an emergency, e.g., ‘duck, cover, hold’ (Matthews et al., 2014). However, despite this broad array of means to communicate disaster risk at their disposal, disaster managers are still regularly confronted by disasters brought about by preparatory or responsive action not being taken by affected individuals (Gaillard et al., 2013; Sufri et al., 2020; Dallo et al., 2022). Inaction may be a result of competing priorities (e.g., relating to wellbeing or actions to secure livelihoods), alternate beliefs (e.g., religious attitudes), and an incomplete understanding of hazard impacts and timescales given the inherently complex and uncertainty-laden nature of environmental risks (Barclay et al., 2019; Sufri et al., 2020; Bankoff 2021; Lejano et al., 2021; Dallo et al. 2022).

In many cases, there may also be an informalised and community-driven response to disaster risk based upon alternate knowledges, with local/contextual, experiential or traditional bases, which are not solely grounded in the timescales or causal sequencing associated with scientific analysis (Parker and Handmer 1998; Whitman et al., 2015; Kitagawa 2016; Lejano et al., 2021). Indeed, previous research based on volcanoes (e.g., Cronin et al., 2004; Armijos et al., 2017; Joseph et al., 2022), and within a wider risk context (e.g., Eisenman et al., 2009; Walshe and Nunn 2012, Uekusa et al., 2020 and references therein, Lejano et al., 2021), have demonstrated that community-level responses to, and understandings of, disaster risk are beneficial and improve community resilience. Engaging directly with communities offers great insights into ways in which communities make sense of these situations and understand their priorities in preparing for and more cost-effectively mitigate, or at least prepare and recover from disasters.

Community engagement can, firstly, improve understanding of the context in which communities live (Few et al., 2022), and the competing pressures they experience that may impact decision around preparedness and in the moment of emergency (Barclay et al., 2019). Secondly, it can bring a wide variety of knowledges and understandings of risk and hazards to the fore (Armijos et al., 2017). Thirdly, it can enhance community social capital (i.e., the social connections available to an individual or community, e.g., Aldrich and Meyer et al., 2014, and references therein), which contributes to the enhancement of a community's capacity to adapt or respond and maintain resilience in the face of disaster (Paton, 2006; Mimaki and Shaw, 2007; Shaw et al., 2009; Gil-Rivas and Kilmer 2016). The assimilation and understanding of communicated material, the hazard itself, and subsequent action-taking, are all highly individual and dependent on contextually-defined pre-existing knowledges, experiences and understandings (Paton and Johnston 2001; Kelman et al., 2012; Mercer et al., 2012; Gil-Rivas and Kilmer 2016; Bankoff 2021). Local-level, grass-roots responses can thus mediate and complement top-down communications of scientific information by appropriately framing them, increasing trust and understanding between communicating parties, and thus increasing the relevance of communicated information (Cronin et al., 2004; Haynes et al., 2008; Eisenman et al., 2009; Cadag and Gaillard 2012). When executed well, this complementary approach improves the outcomes of disaster risk reduction measures (Donovan et al., 2012; Gaillard and Mercer 2013).

An individual's direct experience of any type of hazardous event is one form of alternate knowledge (Shaw et al., 2009; Lejano et al., 2021). Numerous studies have demonstrated the influence of prior disaster experience and memory on disaster preparedness (Shaw et al., 2009; Onuma et al., 2017, Fanta et al., 2019, Walshe et al., 2020); in some cases they have been shown to be a predictor of the adoption of self-protective behaviours (Espina and Teng-Calleja 2015; Christie 2015 Bachelor's thesis; Onuma et al., 2017). However, demographic changes may occur between hazard events, as a result of prolonged or permanent evacuation, immigration, and natural deaths and births. Therefore, at-risk populations often consist of a mixture of disaster-experienced and inexperienced individuals (Fanta et al., 2019). For those without direct experience of a disaster, the physical hazard phenomena and their potential impacts are abstract concepts that are difficult to conceive, anticipate and thus prepare for (Fearnley et al., 2017). Additionally, with time, collective memory of disasters may fade, or be consigned to the past and subsequently rendered irrelevant to assist the process of 'moving on' and accelerate post-disaster recovery (Garde-Hanse et al., 2016, Monteil et al., 2020, Sutton et al., 2020, Walshe et al., 2020). This may result in a reduced perception of risk and/or discourage the adoption of preparatory and self-protective behaviours within these populations. Furthermore, in the specific case of volcanic eruptions, the intra-eruptive interval is often greater than a human lifetime, and volcanic eruptions span a range of behaviours so experience of one eruption may generate false expectations about the next. The above present a significant challenge for disaster management authorities, especially in circumstances of prolonged risk exposure (e.g., Barclay et al., 2020; Monteil et al., 2020), or prolonged repose between hazardous events (e.g., Barberi et al., 2008); responsibility falls to them to make these unfamiliar concepts more tangible and relevant to such populations (Lejano et al., 2018).

Previous studies and initiatives have demonstrated the positive influence of sharing disaster experiences on the communication of risk and disaster preparedness (Hansel et al., 2015; Hicks et al., 2017; Kato and Endo, 2020; Prawoto and Octavia, 2021). Experiential knowledge of hazards and risk is culturally mediated and individuals adopt alternate ways of knowing based upon contextually mediated preconceptions (Bankoff et al., 2015, Gibson et al., 2016). Thus, the exchange of experiences is notably more impactful on a community level than via media or educational efforts (Eisenman 2009). Indeed, the UNDRR Sendai Framework has endorsed building the '*knowledge of communities through sharing experiences and education on disaster risk reduction, including the use of existing education mechanisms and peer learning'*, advocating an '*all-of-society engagement and partnership with this effort'* (UNDRR 2015). Story-telling and artistic expression, from myths to music to the visual arts, are globally ubiquitous means of communication throughout human societies (albeit with considerable local variations) owing to a shared neurological evolution of humans (e.g., Killin, 2013; Zaidel, 2020; Paton, 2021, and references therein). Such artistic outputs act as a means of psychological processing, both in general terms and with specific respect to disaster-induced trauma and catharsis (Cashman and Cronin 2008). Within them may be valuable information, such as descriptions of experiences or phenomena which may be used to convey messages of risk associated with a particular event (Hicks et al., 2017; Prawoto and Octavia 2021, Paton et al., 2021). Indeed, for many, particularly in communities with a prevalent oral tradition, narratives and sensorial experiences are more effective means of synthesis, sense-making and learning, when compared with engagement with abstract concepts, e.g., scientific information (Cashman and Cronin 2008; Flemming et al., 2018; Yang and Hobbs, 2020; Barclay et al., in review).

Figure 1.3 presents a schematic of this process within the context of a hypothetical volcanic eruption. This schematic is inspired by events related eruptions of a range of volcanoes, (e.g., Soufrière Hills, Montserrat; La Soufrière, St Vincent and the Grenadines; Merapi, Indonesia; Pacaya, Guatemala; Mayon, Philippines) and does not represent a particular individual event (Donovan et al., 2011; Barclay et al,. 2019; Lechner and Rouleau, 2019; Martinez-Villegas et al., 2021; Joseph et al., 2022). In a similar fashion to Figure 1.2 (a schematic of the impacts to rivers), each wedge represents the same place, and time progresses clockwise around the figure. In Panel

A, there are communities living on the flanks and further away. In Panel B an explosive eruption has occurred. Upslope communities are evacuated to outside of an exclusion zone and take refuge in settlements downslope, or away from the area altogether. All people in the vicinity have experienced and have been affected by the eruption in some way, whether directly (e.g., displacement, loss of property/livelihood, being housed in shelters, impact from tephra fall) or indirectly (e.g., socio-economic stress caused by influx of evacuees). This is indicated by the blue ticks. As a means of processing these circumstances, people turn to creative outlets, such as song, indicated by musical notes in the figure. As time passes, represented by Panel C, the eruption subsides and the population has evolved as a result of natural change (births/deaths) and

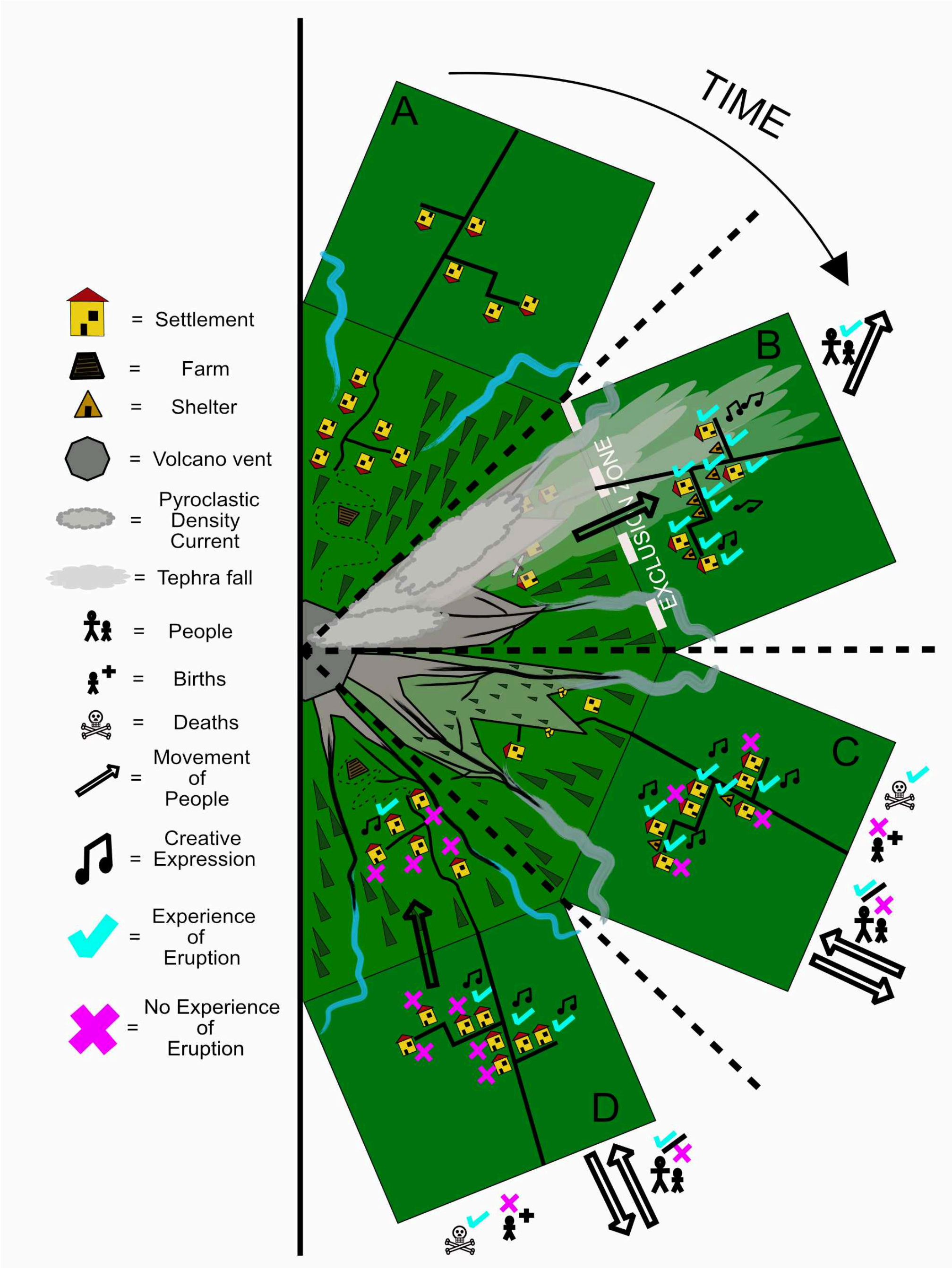


Figure 1.3: Schematic of societal impacts of eruptions, depicting population displacement, the evolution of population characteristics in terms of experience of eruption, and the use of creative expression in response to the eruption and its use after the event.

emigration/immigration. As a result, the population is now made up of a mixture of individuals with and without experience of the previous eruption. Experiences of the eruption are shared by those who lived through it via stories and other creative forms (again represented by musical notes on figure). In panel D, time has continued to pass, the population has continued to evolve, and the volcano has been quiescent for long enough for people to have returned to land on the volcano which may be vulnerable in the event of another eruption. Without the stories shared by those who lived through the previous eruption, or official information, inexperienced persons are unlikely to be aware of the risk.

The intertwining of scientific and alternate/experiential knowledges, though relatively novel as a concept, is thus increasingly viewed as beneficial for the development of locally and culturally appropriate Disaster Risk Reduction strategies (UNDRR 2015, Lejano et al., 2021, Sevilla et al., 2023). Co-production/co-creation frameworks, whereby different forms of knowledge and perspectives from a range of stakeholders (scientists, DRR practitioners, public bodies, communities and individuals) are given parity of respect, are encouraged in order to combine these knowledges (Lejano et al., 2021; Sevilla et al., 2023). On one hand, the inclusion of culturally-relevant information/knowledge increases the potential relevance of communicated material; on the other, co-creation frameworks provide an opportunity for co-learning, a means to improve our understanding, as scientists, of the local and cultural context into which we are communicating (Shiroshita 2018). Thus, co-creation not only enables the incorporation and dissemination of numerous knowledges, but also helps scientists to situate their scientific knowledge within the local cultural context and reframe their communications to better suit and complement the needs and knowledge of the communities they work with.

The recent (2020-21) eruption of La Soufrière, St Vincent and the Grenadines, is a particularly salient example of how top-down scientific communications and community-based initiatives can work effectively in tandem to successfully mitigate volcanic disaster. The success of combined efforts to monitor and anticipate evolution in volcanic activity, and effectively communicate these changes to at-risk populations, meant that evacuations were timely and complete, so that no lives were lost during this eruption (Joseph et al, 2022; Mani et al., 2023). In part, this success can be attributed to the preceding community-level awareness and adaptive capacity building programme, the Volcano Ready Community Project (VRCP; https://uwiseismic.com/projects-research/projects/vrcp/), which began in June 2018 and ran until the explosive eruption ensued in April 2021. The VRCP was a risk communication and awareness campaign led by the University of the West Indies Seismic Research Centre (UWI SRC) and the St Vincent National Emergency Management Organisation (NEMO). It was aimed towards increasing resilience of the 12 northern most communities on the island, within the Orange and Red zones of the volcanic hazard map (Joseph et al., 2022). Activities included community mapping exercises, community workshops, and the distribution of information about the volcano and its hazards. In addition, there were annual Volcano Awareness Weeks, which included other features, such as ‘Soufrière Blow’, an exhibit co-created with the community, funded by the Arts and Humanities Research Council (AHRC, UK) based on poetry and stories written about experiences of the 1902 and 1979 eruptions. Soufrière Blow’s success led to it being followed-up by another project in 2019, ‘Disasters Passed’, which also produced a co-created exhibit to communicate volcanic risk on Montserrat: ‘Mountain Aglow’ (https://www.mountainaglow.com). Given their novelty, there is an opportunity to explore and evaluate how effective these types of co-created initiatives are for enhancing DRR practices in a volcanic risk context.

1.4 Study area: Montserrat, Eastern Caribbean

1.4.1 Regional Tectonics and Climate

Montserrat is a small volcanic island on the Lesser Antilles arc of the Eastern Caribbean (Figures 1.3 and 1.4; see Macdonald et al., 2000 for a review of magmatism on the arc). This island arc has formed as a result of volcanism arising from the subduction of the North American tectonic plate beneath the Caribbean plate at a present day rate of 20 mm yr^{1}. This subduction is oblique, and the lateral motion is accommodated by transtensional response, via normal faulting and a component of left lateral strike-slip motion (Figure 1.4 and 1.5). On the north and south margins of the Caribbean Plate, lateral motion with respect to the North and South American plates is accommodated by left and right-lateral strike-slip faulting, through Hispañola-Puerto Rico and Venezuela, respectively. The volcanic history of the eastern Caribbean is complex and has evolved dramatically over the Cenozoic owing to arc migration driven variation in the subducting angle of the North American plate. Analysis by Allen et al. (2019) suggests that subduction dynamics and the resulting foci of volcanism have shifted twice since the termination of the Cretaceous. Cretaceous-Paleocene subduction was shallower than the present day and was associated with melt generation and volcanism located along the Aves Ridge arc, some 200 km to the west of the present-day Lesser Antilles arc. Evidence of volcanism from this time is also found in the Leeward and Greater Antilles to the south and north of the Venezuela basin, respectively. Roll-back of the subducting slab of the North American plate, i.e., the steepening of subduction, during the early Eocene (~40 Ma) caused the abandonment of the Aves Ridge and an eastward migration of melt generation and volcanism. The only existing evidence of volcanism from this time comes from the limestone Caribees (e.g., Antigua, eastern Guadeloupe) and, by the mid-late Miocene/early Pliocene (~5.3 Ma), slab shallowing had caused the abandonment of these volcanic centres to form the younger islands of the modern-day volcanic arc (e.g., St Kitts, Nevis, Montserrat, western Guadeloupe). One theory (McCann and Sykes 1984) suggests that subduction of a buoyant feature (e.g., ocean ridge) under the northern arc caused this Pliocene shallowing in the north and that volcanism along the southern Lesser Antilles has remained in this location since the Eocene. However, others (e.g., Allen et al., 2019) proffer that the Limestone Caribbees may form part of a larger arc to the east which surrounds the Tobago Basin (Figure 1.4).

The Lesser Antilles region is prone to a range of hazardous geophysical and meteorological phenomena owing to its location in the tropics and being positioned above an active subduction zone. Tropical storms and cyclones impact the region on a near annual basis (see below; Klotzbach, 2011; NOAA, 2022); the region has medium-high seismic hazard - ~60 earthquakes of

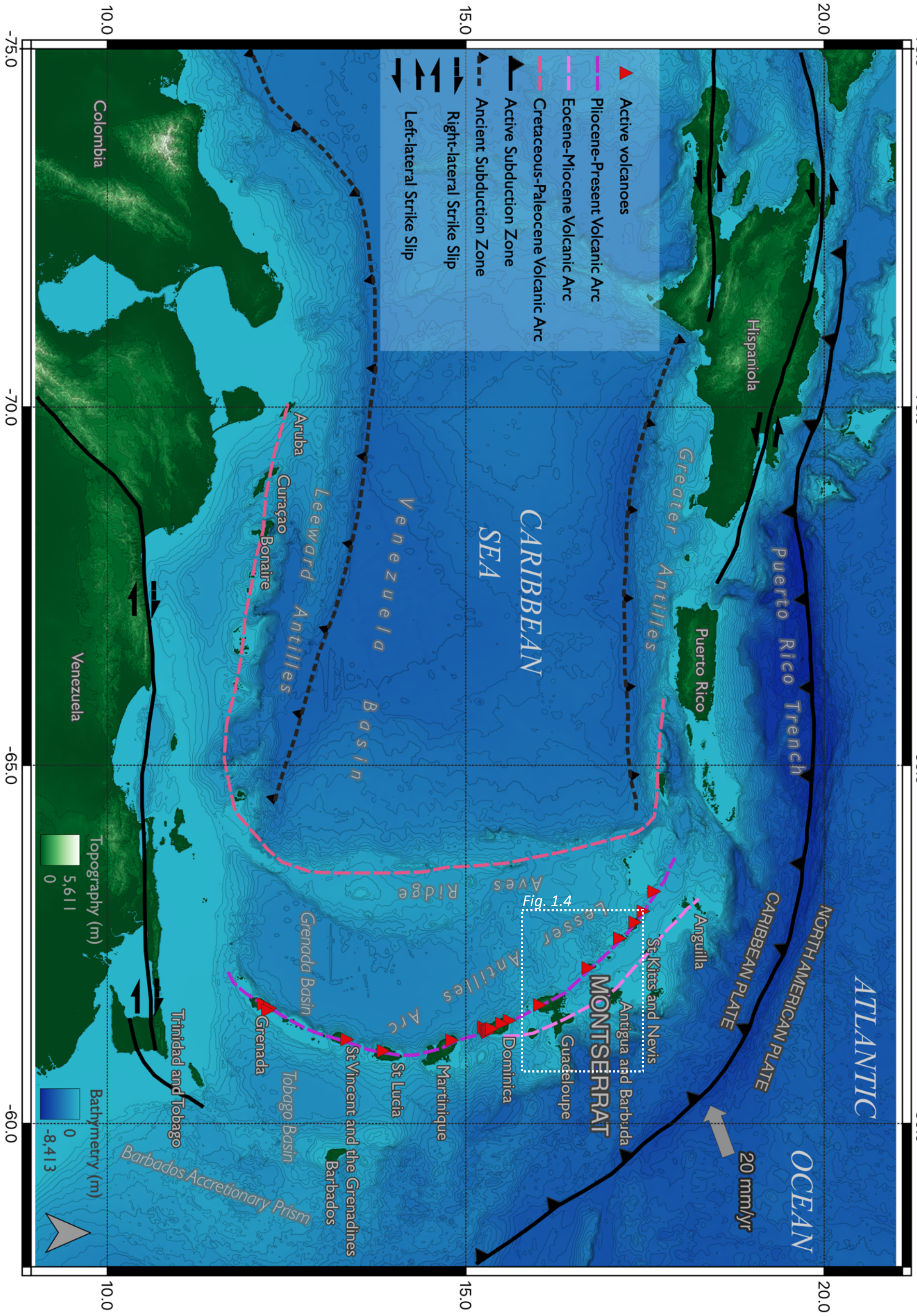


Figure 1.4: Map of the Eastern Caribbean region and its main tectonic features. 'Active volcanoes' denotes those inferred to have been active in the last 10,000 years. Topography and bathymetry data courtesy of GEBCO (2022). Sources: Feuillet et al. (2010,, 2011); Hippolyte and Mann (2011); ten Brink and López-Vanegas (2012); Allen et al. (2019); Garrocq et al. (2021).

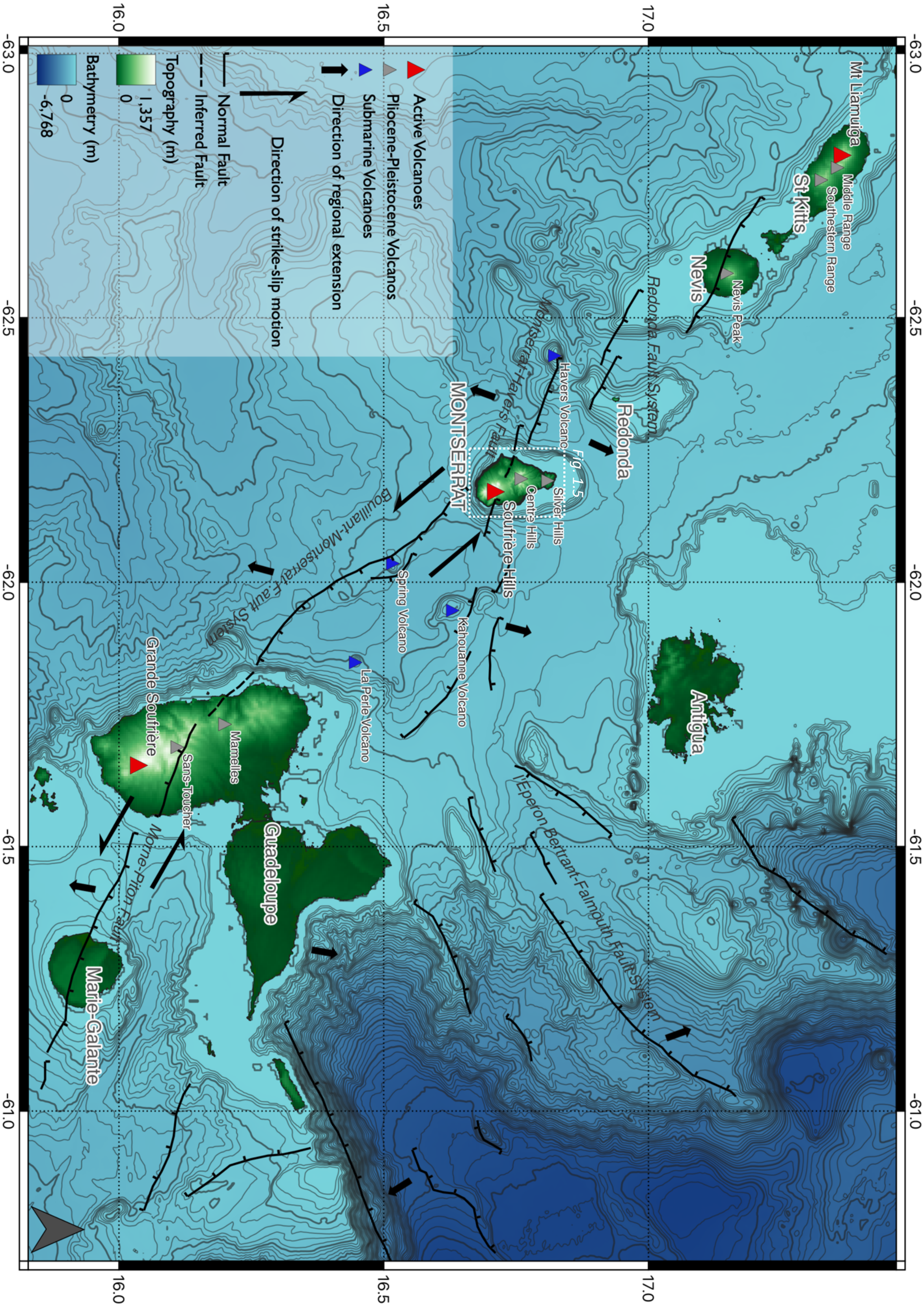


Figure 1.5: Map of Montserrat and the neighbouring islands in the Lesser Antilles chain. Also shown are the main tectonic features in the area, active volcanoes, as well as Pliocene-Pleistocene and submarine volcanos. Topography and Bathymetry courtesy of GEBCO (2022). Sources: Feuillet et al. (2010, 2011); Roberston (2017); Modlin and Allen (2017).

magnitude 5.0 or greater have occurred along the arc in the last 30 years (Bozzoni et al., 2011, USGS 2022); and since the dawn of the 20th century, five eruptions (Martinique 1902; St Vincent 1902, 1972, 1979, 2021) and one phreatic episode (Guadeloupe 1976) have collectively caused in excess of 30,000 fatalities and the evacuation of ~75,000 people (Kokelaar et al., 2002; Chenet et al, 2014; Joseph et al., 2022). The island of Montserrat itself has a history of disasters wrought by natural phenomena. Since the establishment of the first European colonial settlement in the early 1600s, Montserrat has been impacted by at least 30 hurricanes - 5 of which are recorded as being destructive, most notably, Hurricane Hugo made landfall in Montserrat on 17th September 1989 and destroyed approximately 90% of the structures on the island (Nelson 2017) - and numerous earthquakes including an Mw 8.5 megathrust earthquake in 1843 described as having destroyed all masonry on the island (Feuillet et al., 2011; Hough 2013; USGS 2022). Some of this earthquake activity was associated with periods of volcanic unrest (i.e., volcano-seismic crises) in 1897-8 (accompanied by changes to Soufrière activity), 1933-1937, 1966-67, and 1992-5 (MacGregor 1938; Shepherd et al., 1971; Kokelaar et al., 2002). The volcanoseismic crisis of 1992-1995 eventually culminated in the initiation of the present eruption (Kokelaar et al., 2002).

In common with 45% of the world's actively volcanic regions (Matthews et al., 2002), Montserrat has an equatorial, fully-humid climate (Kottek *et al.,* 2006), which renders it prone to high intensity precipitation (Matthews et al., 2002; Barclay et al., 2007; Froude, 2015). More than 200 mm of rainfall may fall in a single event at intensities of up 50 mm hr^{-1} during both mesoscale convective storms and less frequent large-scale synoptic weather systems (Matthews *et al.,* 2002). Estimates of mean annual rainfall range from 1000 - 1500 mm yr^{-1} owing to highly heterogenous rainfall across the island; mountain tops are estimated to receive ~60% more rainfall than lower lying areas (Barclay et al., 2006; Hemmings et al., 2015). Rainfall patterns are highly seasonal, with a wet (April – November) and dry (December – March) season. The wet season is bimodal, owing to the migration of the Inter Tropical Convergence Zone (ITCZ); there is an initial peak in rainfall in May, and a second larger peak centred around September (Barclay et al., 2006). Regional weather patterns are strongly affected by the El Niño Southern Oscillation (ENSO). Tropical cyclone activity is enhanced during La Niña phases owing to weaker vertical wind shear, weaker trade winds and reduced atmospheric stability; opposing conditions prevail during El Niño years (Klotzbach 2011; Schmitt et al., 2020). Up to 2010, the 10 strongest La Niña years were associated with 29 tropical cyclones tracking through the Caribbean basin, conversely, the 10 strongest El Niño years were associated with 2 (Klotzbach 2011). Between 1990 and 2020, Montserrat was within 50 miles of the tracks of 22 tropical storms/hurricanes (NOAA 2022).

1.4.2 Volcanic activity on Montserrat

Montserrat (Figure 1.6) consists of three basaltic – andesitic volcanic centres which have been active at different but overlapping times throughout the Pleistocene (Harford et al., 2002; Hatter et al., 2017). The oldest, and northern most is the Silver Hills, which was active between 2.17 and 1.03 Ma. This edifice is now the smallest owing to significant fluvial and marine erosion over the intervening 1 Ma (Hatter et al., 2017); the Silver Hills is surrounded by a large coastal shelf which extends offshore by approximately 5 km (this shelf is evident in Figure 1.4), which is inferred to be the remnant of the previous full extent of the massif. The middle of the island comprises the forested and now extinct Centre Hills volcanic massif, which was active between 1.14 and 0.38 Ma. Findings by Coussens et al. (2018) indicate that the Centre Hills produced the largest known eruptions on Montserrat, with Volcanic Explosivity Index (VEI) magnitudes of 5. The Soufrière Hills and south-Soufrière Hills complex is the southern-most and youngest of the three volcanic centres that make up the island. Activity began at SHV around 450 Ma and has continued to the present day; the largest magnitude eruptions of SHV are inferred to have occurred around 170 ka, with evidence of Plinian activity emanating from SHV being limited to around this time (Coussens et al., 2018). The South Soufrière Hills portion of the complex developed as a result of the eruption of basalt – basaltic andesite which, despite its spatial proximity, is inferred to originate from an alternate magma source to SHV. This activity was relatively short-lived, lasting from between approximately 145 ka and 120 ka (Harford et al., 2002). This southward migration of volcanism is related to the mid-Miocene shift in subduction in the northern portion of the Lesser Antilles arc. A similar north-to south migration of volcanism with similar timing is identified on Basse-Terre, Guadeloupe, where the active Grande Soufrière is located (Hatter et al., 2017; Coussens et al., 2018).

The Soufrière Hills Volcano itself is a complex stratovolcano made up of a central complex of relict lava domes and surrounding volcanic and volcaniclastic debris fans. Prior to the present eruption, there were five peaks: Chance's Peak (<200 ka), Gage's Mountain (151 ± 8 ka), Galway's Mountain (112 ± 18 ka), Perches Mountain (24 ± 4 ka) and Castle Peak (1.6 ka), which was contained within English's Crater, a remnant collapse scar which formed the head wall of the Tar River Valley (Harford et al., 2002, Hatter et al., 2017). The present eruption of Soufrière Hills commenced in July 1995 within English's Crater, initially with phreatic explosions followed by extrusion of juvenile lava in November the same year. Over the ensuing 2 years, the first phase of the eruption dramatically altered the physical and social landscape of the island (Kokelaar et al., 2002). The volcano has since undergone a further 4 phases of eruption characterized by successive episodes of andesite dome building, collapse, and explosion (Druitt et al., 2002; Loughlin et al., 2002, 2010; Cole et al., 2002, 2014; Carn et al., 2004; Herd et al., 2005; Stinton et al., 2014), as well as one

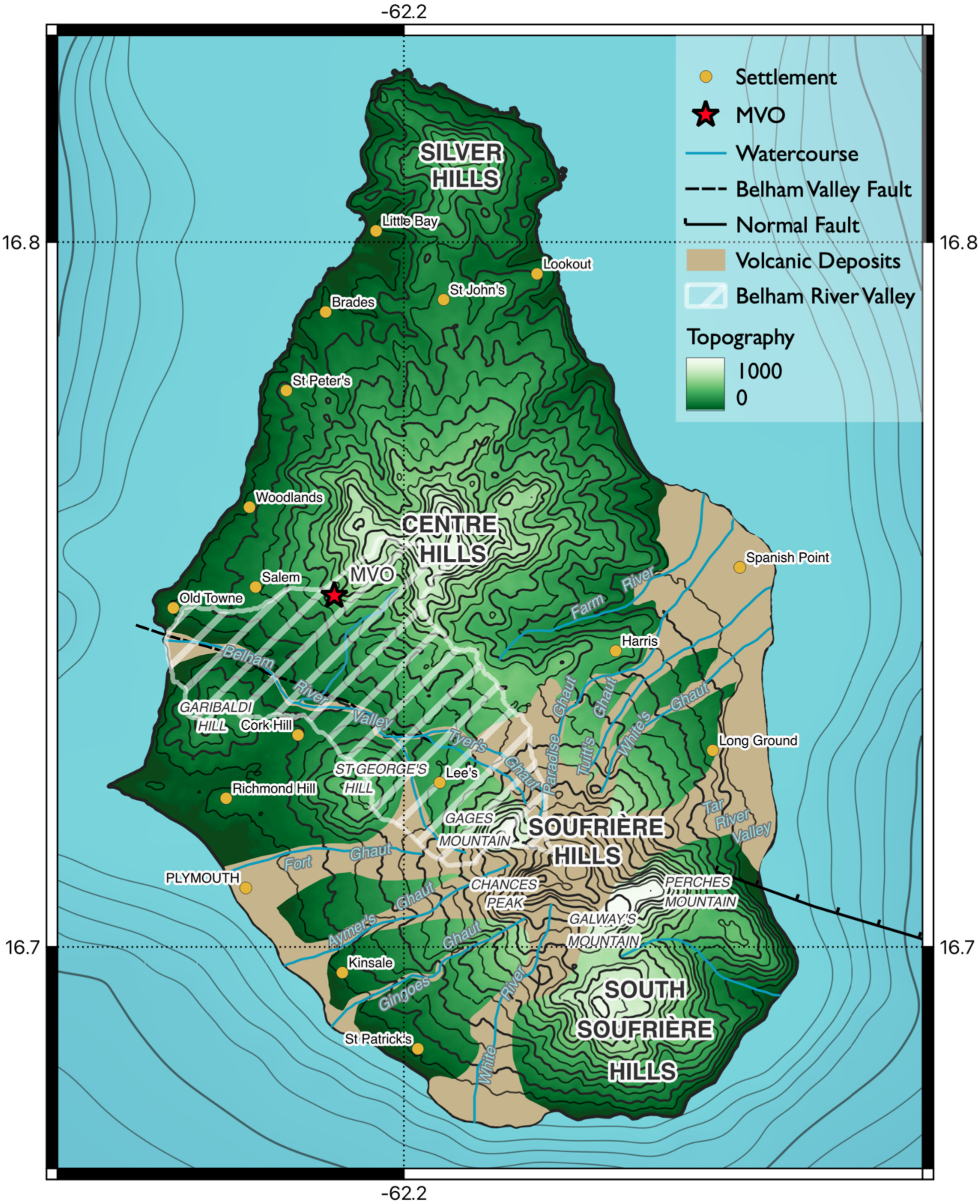


Figure 1.6: Map of Montserrat detailing locations of the volcanic centres on the island, faults, main drainages, the Belham River Valley watershed, approximate extent of volcanic deposits, and settlements. 50 m contours shown. Fault information from Hemmings et al. (2015). Topography courtesy of NASA: 2013 ASTER Global Digital Elevation Model (GDEM) V003, acquired October 2022; bathymetry courtesy of GEBCO (2022). Sources: Wadge et al. (2014).

southwest-directed lateral blast event in December 1997 which annihilated the village of St Patrick's (Figure 1.5, Voight et al., 2002). The most recent fifth phase of lava extrusion terminated in February 2010, however at the time of writing, the volcano remains in an active state of unrest (Wadge et al., 2014; SAC 2021). Variation in the direction of dome growth throughout eruption phases has meant that deposition has varied both spatially and temporally. This activity has been associated with significant deposition (up to a total ~230 m thickness; Arnold et al., 2016; Stinton et al., 2014) of pyroclastic sediments in the ghauts (local name for valley) and onto surrounding hillslopes. In all, approximately 1 km^3 of lava has been erupted, much of which has been deposited at sea (Le Friant et al., 2010; Karstens et al., 2013). As a result of direct marine deposition by PDCs and subsequent offshore deposition by lahars, the estimated volume of remaining on-land deposits (including the lava dome) is 300-350 $x10^6 m^3$ DRE (Arnold et al., 2016a). Soufrière Hills Volcano has and continues to be one of the most intensely monitored volcanoes in the world; a rich and detailed record of its activity exists.

1.4.3 Geomorphic impacts of recent eruption

The hydrogeomorphic consequences of this eruption have been severe. Following extensive deposition of pyroclastic material in radial ghauts, subsequent destructive lahars have been a common and hazardous feature in all catchments draining the volcano (Barclay et al., 2007; Alexander et al., 2010). Most notably, the former capital town of Plymouth has been progressively buried by lahars flowing west via Fort Ghaut since September 1997. The Belham River Valley (Figures 1.5 and 1.6) is one of several ephemeral radial catchments (i.e., streamflow typically only occurs during and for short periods after rainfall) that have been impacted by the eruption of SHV (Barclay et al., 2007, Alexander et al., 2010). Since 1995, more than 200 lahars of varying magnitudes and character, from dilute stream flows to the occasional debris flow-like activity, have buried buildings and infrastructure in the BRV (Barclay et al., 2007l Alexander et al., 2010; Froude, 2015).

The BRV drains the north-western flank of SHV, as shown in Figure 1.6. Its primary head waters originate in the extinct Centre Hills volcanic centre to the north, principally via the Sappit River sub-catchment, and the active Soufrière Hills to the southeast. Two sub-catchments drain from SHV into the Belham River Valley: the Tyer's Ghaut/Farrell's plain sub-catchment drains to the north from SHV and converges distally to form a short reach known as Dyer's River; the North Gage's fan drains west from SHV and deflects to the north through a narrow, incised channel (Lee's Channel). For simplicity, these areas (i.e., those draining the volcano) will henceforth be collectively referred to as the Upper Catchment unless specificity is required. The Belham River

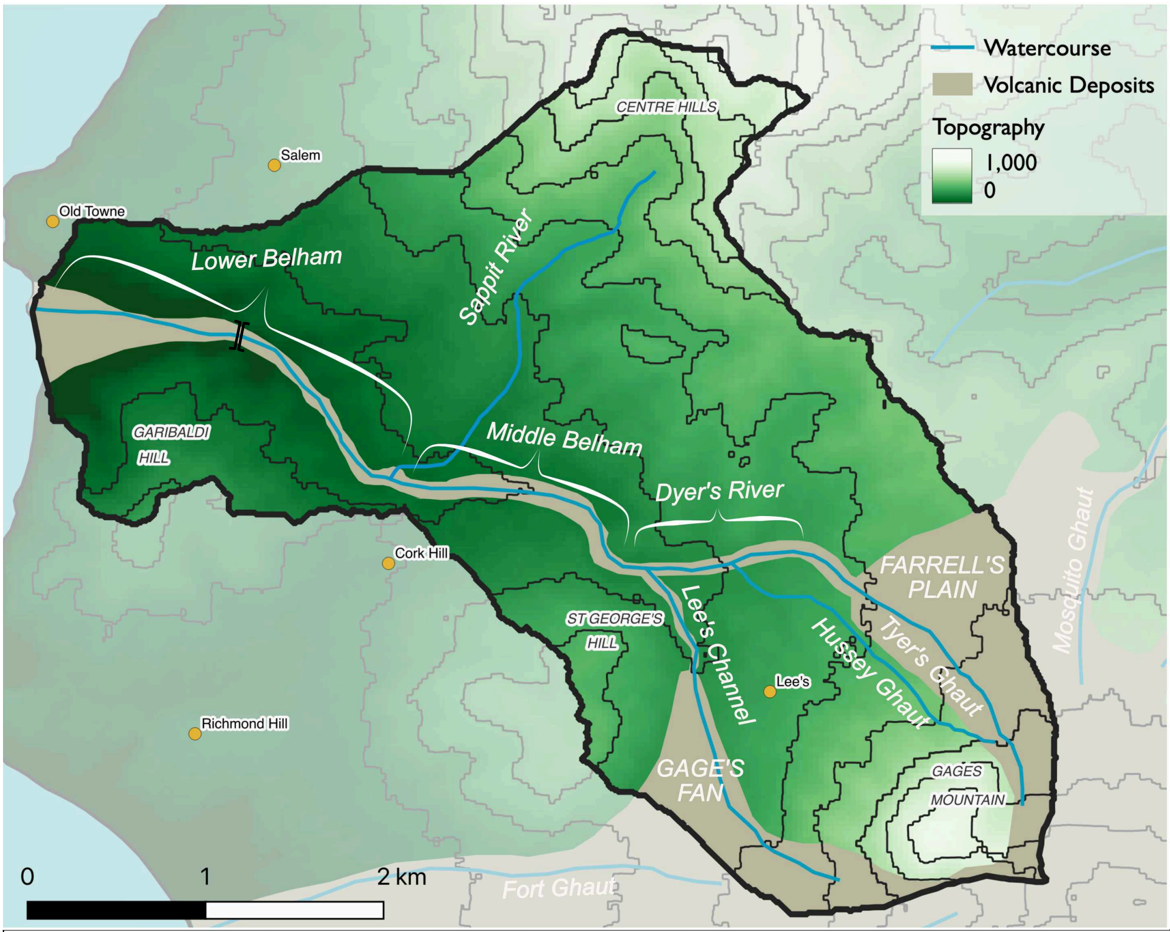


Figure 1.7: Map of the Belham River Valley detailing locations of the main features discussed in this thesis, approximate extent of volcanic deposits, and settlements. 100 m contours shown. Topographic data source: NASA (2022).

forms at the confluence of Dyer's River and Lee's Channel. From here, it follows a double S-bend towards the north-west for c.5 km where it reaches the sea. I delineate three key areas of interest along the Belham River, also shown in Figure 1.7: 1) the Middle Belham, which has been impacted directly by long-runout PDCs and remained predominantly untouched by human activity throughout the study period; 2) the Lower Belham, into which the Sappit River drains much of the Centre Hills-derived runoff, which has been mined for the export of volcanic aggregate since 2002, extensively since 2012 (Barclay et al., 2007; Froude, 2015a); and 3) the coastal fan which has been developed and modified by both lahar and marine activity (Froude, 2015).

Prior to the onset of eruption, the Belham Catchment had an area of 12.6 km^3 and was densely vegetated; dry forest covered much of the lower catchment, mesic forest predominated over much of the middle and upper catchment, and wet forest was found at the highest altitudes on the Centre Hills and the Soufrière Hills (Barclay et al., 2007). In the middle reach the Belham River was a narrow (2-3 m) ephemeral channel residing within a steep-sided valley, with an average gradient of 0.02 (1.15°) which widened with increasing distance downstream. In the lower reach, the river was crossed by the Belham Bridge (now buried, shown in Figure 1.7), formerly an important component of Montserrat's infrastructure. Here, the valley floor was ~6m below the bridge with a width of ~18m. The channel then continued westwards and to the south, dissected the Belham Valley golf course before reaching the sea via a 4-5 m wide channel incised into the south end of a broad sandy beach. A small harbour with a depth of ~10 m was positioned at the north end of the beach and enclosed by a jetty. Anecdotal evidence indicates that the Belham River flooded and overtopped its banks approximately on an annual basis, producing over-bank deposits of limited volume and lateral extent, suggesting a low suspended sediment load (Barclay et al., 2007; Froude, 2015a). The lower reach of the Belham River is now the only part of any drainage of SHV that remains inhabited. It is also the only area where volcanic aggregate extraction is permitted on the island; this has become an important economic activity since ~2012. Consequently, it is the most intensely studied reach on Montserrat as lahars remain hazardous to these communities (Barclay et al., 2006, 2007; Susnik 2008; Alexander et al., 2010; Darnell et al., 2012, 2013; Froude, 2015; Jones 2017a). Thus, in combination with the detailed record of volcanic activity, there is a wealth of relevant available data which makes this valley an ideal case study.

1.4.4 Societal context of the eruption and its impacts and

Montserrat is an internally self-governing British Overseas Territory (Loft, 2022). British Overseas Territories (OSTs) are territories that constitute the last remnants of the British Empire; their title of OST came about following The British Overseas Territories Act 2002, before which they were known as colonies. The UK and OSTs therefore form a continuous realm which enables the British Crown and Parliament to legislate in OSTs. The head of state is, at the time of writing, King Charles III, who is represented locally by a Governor, who presides over the government. However, the affairs of Montserrat are predominantly devolved which limits the influence of the Governor in terms of legislature and external relations. Montserrat is internally self-governing which means that the Government of Montserrat is locally elected, chaired by a Premier, and is responsible for the constitution and most domestic legislation in Montserrat. Nonetheless, the Governor can reject proposed legislation and retains responsibility for defence, internal security (i.e., police), and financial affairs. The latter applies due to Montserrat’s operational budget being provided by the UK Government and about 50% of Montserrat’s Gross Domestic Product is generated via UK overseas aid budget. The Office of the Governor hosts members of staff from the Foreign and Commonwealth Development Office (FCDO) who administer these finances.

Montserrat became self-governing in 1961 and its economy grew steadily through the 1970s - 80s; operational budgetary aid from the UK was revoked in 1981 and by 1989 GDP per capita had reached US$4,000. The island was a popular holiday destination, had a flourishing offshore banking sector, and famously hosted a vibrant artistic scene, particularly musically. Montserrat was the birthplace of internationally renowned Soca artist, Alphonsus 'Arrow' Cassell, and the base of George Marin's AIR Studios, where a range of international music superstars, such as The Police, would work and record (Cherry et al., 2013). The year of 1989 wrought disaster for Montserrat when it was struck first by a banking scandal (90% of offshore banking licences were revoked), and then by Hurricane Hugo, which destroyed >90% of the buildings and infrastructure on the island, both of which had major economic repercussions (Clay, 1999; Nelson, 2017). Despite these setbacks, by 1994 GDP per capita had rebounded to US$5,000 and the economy was in budgetary surplus. *'The prospects for this relatively prosperous small island with a vibrant economy and society seemed favourable.'* (Clay et al., 1999, pp. 15).

However, the rebounding prosperity of Montserrat was curtailed by the onset of eruption of the Soufrière Hills Volcano on 18th July 1995, details of which have been provided in previous sections. The societal consequences of the eruption have been profound. Prior to eruption, most of the population lived and made their livelihoods in the south of the island, particularly in the former capital town, Plymouth. Most industry, healthcare, education, and administrative facilities also resided within Plymouth. As the volcanic emergency developed in the early years, decisions were made to begin evacuations and draw up exclusion zones (Kokelaar et al., 2002; Haynes et al., 2007; Donovan et al., 2012). Table 1.2 provides a summary of key evacuation events and Figure 1.8 presents the timing of evacuations of the early years. A full review can be found in Kokelaar (2002). Figure 1.9 shows the present-day extents of exclusion zones. This was a complex and protracted process owing to a combination of evolution of the developing/growing crisis, scientific uncertainty, and competing priorities (e.g., maintenance of livelihoods vs risk management; Loughlin et al., 2002). On the most part, these evacuations maintained the safety of Montserratians, however, on 25th June 1997, 19 people were killed by pyroclastic flows tending to homes or farmland to the north of the volcano (Loughlin et al. 2002).

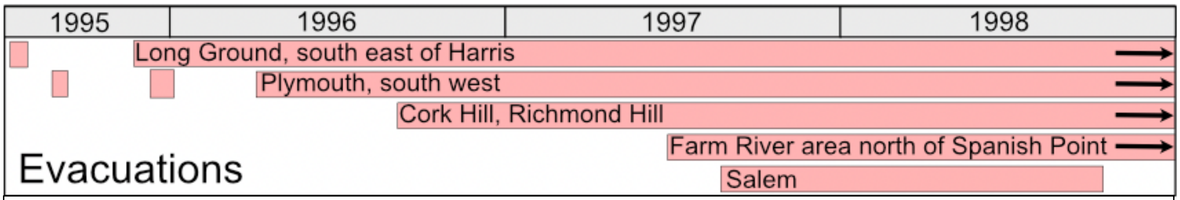


Figure 1.8: Timeline of the evacuation of areas around the volcano. Modified from Clay et al. (1999)

Date	Event
18th July 1995	Eruption begins
28th July 1995	Long Ground temporarily evacuated
21-22 August 1995	6000 people evacuated from southern and eastern areas for 2 weeks
Late November 1995	Long Ground evacuated
1-2 December 1995	6000 people evacuated from southern and eastern areas for second time, for one month
January 1996	Civilian contingency 'Operation Exodus' begins; people begin leaving the island
3-4 April 1996	Plymouth and southern areas fully evacuated; >1300 people housed in temporary shelters
May 1996	First risk maps introduced
October 1996	Risk map revised
December 1996	Risk map revised
February 1996	Risk map revised, 6000 people remain on the island
June 1997	Risk map revised, 19 people killed (25th June), Cork Hill evacuated
July 1997	Risk map revised, exclusion zone introduced.
August 1997	Areas just north of Belham River (Old Town, Salem) evacuated, 1600 housed in temporary shelters
September 1997	Risk map revised, Salem and Old Town included in exclusion zone
Early 1998	3000 people remain on island
September 1998	Risk map revised
October 1998	Phased reoccupation of areas north of Belham River including Salem

Table 1.2: List of key evacuation events in the first three years of the eruption (Kokelaar 2002).

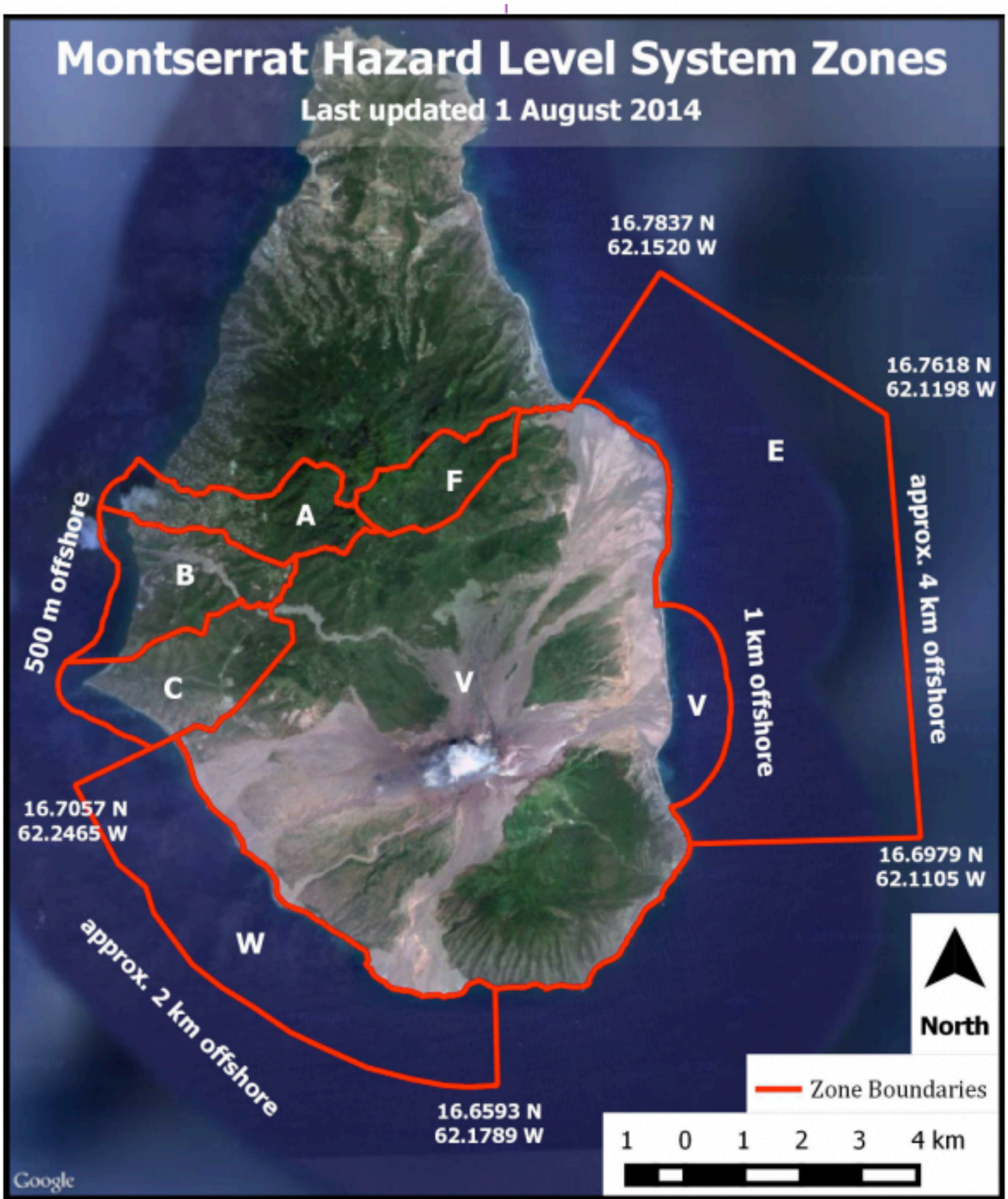


Figure 1.9: Hazard Level System map of Montserrat showing extent of exclusion zones. Full information on the Hazard Level System can be found at http://www.mvo.ms/pub/Hazard_Level_System/HLS-20140801.pdf

Economically, the eruption was catastrophic, as captured by the following section from a report from the Department for International Development (DFID).

> *'The volcanic crisis has had a devastating economic impact. Most of the island's administrative, commercial, and industrial facilities as well as much of its infrastructure (including tourism) and prime agricultural land have been destroyed or are inaccessible in the short to medium term. The Sustainable Development Plan (SDP) estimates total damage to buildings alone at around £40m. The GoM's work to determine the scale of total losses is incomplete: unofficial insurance industry sources put it as high as £1bn. Many firms have been forced to close and the real estate market has collapsed. Reflecting these impacts, real GDP fell by 44% between 1994 and 1997. Problems have been exacerbated by the impact of the crisis on the financial sector. Most of the insurance industry withdrew cover at the height of the crisis in August 1997, leaving homeowners and businesses to bear a considerable share of losses. There were major implications too for the availability of new lending and the viability of financial institutions themselves. The Montserrat Building Society (MBS), which had accounted for approximately 90% of mortgages on the island and a high proportion of savings, collapsed. This in turn undermined people's capacity to cope without public support – both housing and other needs - and has had multiplier impacts throughout the economy. There is a pervasive problem of negative equity… The distribution of impacts has been very unequal. No formal assessment has been made of relative impacts but, on balance, the poorer segments of society appear to have fared particularly badly. The economy will not be viable in either the short or medium term without large-scale subventions.'* (Clay et al., 1999, pp. 17).

New infrastructure has been established in the previously sparsely populated north of the island. The Government now resides in Brades, there is a new airport, a new harbour and socio-cultural zone have been established in Little Bay, and new housing developments have been built in Lookout and Davy Hill. However, economic recovery and opportunity remains limited; the most recent estimate suggests a trade deficit of ~US$70 million (Montserrat Statistics Department, 2023). Annually, about US$1.6 million, or 14%, of the exports from Montserrat is of volcanic aggregate mined from limited areas of volcanic deposits in the Belham River Valley (OEC, 2021). Plans to build a new port facility and expanded town centre in or around Little Bay have been delayed with little advancement between 2013 – 2023 (personal observation). The island's prospects for economic growth are hindered by its complex circumstances, including but not limited to limited access to land (60% of the island remains within an exclusion zone), ongoing volcanic unrest, the fact that the airport is only large enough for small 8-seat planes, and the ferry service is unreliable (the latter is a personal observation consistent with numerous reports from Montserrat residents).

The demographic consequences of the eruption, the ensuing evacuations, and economic catastrophe have also been drastic. Table 1.3 shows key population and demographics statistics from census data and other available sources. At the last census before the eruption in 1991, the total population was estimated to be 10,639 (SDM, 1991). At this time, the population was largely homogenous with an estimated 81% of persons identifying as native Montserratian; the male:female ratio was even. Evacuations caused the internal displacement of approximately 80% of the population who were forced to live with friends and relatives, in temporary shelters (either repurposed community buildings or purpose-built temporary shelters), or on neighbouring islands. In January 1996 the UK Government initiated a contingency plan called 'Operation Exodus' and by April 1996 established a Voluntary Evacuation scheme which provided financial support to evacuees and leave to remain in the UK for two years (Clay et al., 1999). At this time living and economic conditions were harsh, and people began to leave the island. The population of the island reduced from ~10,500 at the start of the eruption, to minimum of between 2,400 – 3,000 in early 1998 (Kokelaar et al., 2002; Monteil and Simmons, 2017). Population levels rebounded to 4,500 by 1999 and have remained around this level since that time (Kokelaar, 2002; SDM, 2001, 2011, 2018, 2022).

'*Losses at individual level have caused considerable psychological distress and related health problems'* (Clay et al., 1999, pp 17). The destruction of Plymouth and other settlements, the evacuations and relocations, the familial separation and fragmentation of social networks, the loss of livelihood - in all, the loss of home - were psycho-socially catastrophic for many Montserratians (Cashman and Cronin, 2008). In common with the wider Caribbean region, Montserrat has a deeply rooted oral tradition based around storytelling, stemming from African

	Population		Demographics (Natives/Male/Female)		
Date	Census	Other source	Census	Other Source	Source
1991	10,639	-	N: 81%; M:49.7% ; F: 50.3%	-	Montserrat Census 1991
03/1996	-	~9000	-	-	Kokelaar (2002)
08/1996	-	~7500	-	-	Kokelaar (2002)
02/1997	-	~6000	-	-	Kokelaar (2002)
11/1997	-	3338	-	-	Kokelaar (2002)
1998	-	2,400 – 3,000	-	-	Kokelaar (2002), Monteil et al. (2020)
06/1999	-	~4,500	-	-	Kokelaar (2002)
2001	4,492	-	N: 82%; M: 53.8%; F: 46.2%	N: ~50%	Montserrat Census 2001, Monteil et al (2020)
2011	4,922	-	N: 73%; M: 51.7%; F: 48.3%	-	Montserrat Census 2011
2018	4,649		N: 56.2%; M: 49.2%; F: 50.8%	-	Montserrat Census 2018
2022	-	4,433	-	-	Montserrat Statistics Division

Table 1.3: Demographic statistics of Montserrat detailing key changes in population, including total population from censuses or other sources, and the proportion of native Montserratians (N), males (M), and females (F).

heritage and the period of colonial occupation and enslavement (Spanos, 2016; Cabey, 2022). The island also has a rich literary and artistic history (e.g., Donovan et al., 2011). In response to the upheaval caused by the eruption, there has been a wealth of artistic responses, in the form of poetry, literature, Calypso and song. These creative outputs have manifested as a means of processing and accepting the impacts and losses wrought by the eruption for those remaining on Montserrat and the wider diaspora (e.g., Fergus, 1995, 2000, 2010; Edwards, 1996; Shotte, 1996; Weekes, 2006; Donovan et al., 2011; Skinner, 2011; Gough, 2012).

The proportion of native Montserratians in the population has been altered by subsequent immigration from other Caribbean islands and elsewhere. Census data from 2001 indicates that the proportion of the population who were native remained robust, at 82%, compared with 81% in 1991, however other estimates suggest that this was closer to 50% (Monteil et al. 2020). In any case, census data shows that there has been a progressive reduction in the proportion of native Montserratians. According to the most recent estimates (SDM, 2018) Montserrat now has a population of 4,649 with a median age of 40 years; 56.2% of residents of Montserrat are native Montserratians, the remainder were born in other Caribbean nations (28.8%), the United Kingdom (3.6%), the United States (1.8%), or elsewhere (6.4%). A small proportion of the population are permanent or temporary ex-patriots primarily from the UK, Canada and USA, most of whom live around the Old Towne/Isles Bay/Garibaldi Hill areas to the south (SDM, 2011). The majority of Montserrat residents are English-speaking, though a small minority of post-eruption immigrants are primarily Spanish speaking. This demographic shift has compounded the sense of loss for some native Montserratians (Monteil et al., 2020). No recent data is available on the age distribution of the population, however, given the time elapsed since the last major activity in Februray 2010 and the demographic trends outlined here, there is likely to be a significant portion of immigrants and young people within the population who have no experience of surface activity from the volcano. This has important implications for the level of awareness and preparedness within the population.

1.5 The scope of this thesis

This literature review has demonstrated that in both the physical and social domains, volcanic eruptions leave behind legacies, manifesting, for example, as lahars and lyrics. These legacies contain valuable insights from which we can learn about the longer-term hazard posed by eruptions, and how it can be better managed and lived with. This thesis seeks to contribute towards the academic literature relating to longer-term adjustments to volcanic eruptions by using the island of Montserrat, Eastern Caribbean, as a case study.

The first three chapters will address research gaps related to fluvial responses to volcanic perturbation and related lahar hazard. Section 1.1 of this chapter demonstrated that research focussed upon decadal patterns of lahar activity and geomorphic change in response to episodic eruptions is limited. This provides an opportunity for novel research and as such my first research question is:

1) *How do episodic eruptions influence lahar hazard and geomorphic evolution in rivers, and what are the main catchment-wide controls that mediate this response?*

To address this question, Chapter 2 of this thesis considers how and what controls larger-scale dynamic changes in such systems. My case study is the Belham River Valley, Montserrat. As section 1.4 explains, the headwaters of this catchment have been perturbed by episodic dome collapse/explosion-derived PDCs and tephra fall associated with 5 phases of andesitic lava dome growth at SHV between 1995-2010 (Wadge et al., 2014). By synthesising datasets and findings presented by previous authors (Barclay et al., 2007; Susnik 2008; Alexander et al., 2010; Darnell et al., 2011, 2012; Froude, 2015; Jones et al., 2017), with new analysis of rainfall, geomorphic change, and vegetation cover variation, I have created an unprecedented 25-year dataset documenting the evolution of the Belham River Valley in response to eruption. I use this to explore how the complex interconnectivity of sediment supply, water supply, and mediating hillslope conditions exert control over the subsequent downstream lahar hazard and geomorphic change, and to develop a novel conceptual model of the response and recovery of catchments perturbed by episodic disturbances.

Section 1.2 went on to identify gaps in research from the literature with respect to lahar initiation and modelling. Specifically, very limited research has either examined the effect of evolving catchment conditions on lahar initiation conditions or attempted to simulate this behaviour computationally. This then poses the next two research questions for this thesis:

2) *How is the probability of rain-triggered lahars mediated by evolving antecedent catchment conditions during episodic eruptions?*

3) *To what extent can the longitudinal, decadal-scale fluvial responses to episodic eruptions be simulated by a numerical model?*

To address question 2 above, based on the dataset developed in Chapter 2, Chapter 3 of this thesis explores in more detail the conditions that are associated with lahar activity in the Belham River Valley. This analysis considers the mediating effect that incident rainfall, antecedent rainfall, sediment availability and vegetation cover have on the probability of lahar incidence. Specifically, I will explore:

1) Variation in the likelihood of lahars under different incident rainfall magnitudes, and
2) The relationship between lahar occurrence with respect to:
    a) Antecedent rainfall,
    b) Sediment availability, and
    c) Vegetation cover.

To address question 3, the Belham River Valley can be conceptualised as a sediment cascade, whereby energy and material is transferred from source to sink (Burt and Allison 2010). First, sediment is supplied by volcanic activity to the hillslopes/debris fans. Here it is deposited into either long-term storage, contributing to edifice building, or short-term storage in active channels - these storage areas can be considered as sediment 'reservoirs' (Bennett et al., 2014). Second, overland flow erodes and transports this sediment downslope from short-term storage into the lower reaches, which can be considered the next sediment reservoir(s). In effect, sediment transport can be conceptualised as sediment cascading through reservoirs within the landscape (Bennett et al., 2014). 'SedCas' is a simple, probabilistic sediment cascade model designed by Bennett et al. (2014) and since built upon by Hirschberg et al. (2021). This model is spatially lumped and one-dimensional, and conceptualises compartments of the landscape (e.g., hillslopes, channels) as discrete reservoirs. It was designed to reproduce the first order (magnitude/frequency) patterns of debris flow activity in a Swiss alpine torrent, the Illgraben, based upon stochastic sediment supply and observed rainfall. In this model landslides supply sediment to active channels where they are temporarily stored. Debris flows are then generated by exceedance of a critical discharge which is produced by rainfall or snow melt. If sediment is unavailable or insufficient, SedCas generates flows with more limited sediment contents.

Chapter 4 of this thesis presents SedCas_Volcano, an adapted version of SedCas, which I have modified to fit a volcanic context account for the evolution of prevailing catchment characteristics (e.g., changes to vegetation cover). I have done this to assess how well lahar behaviour and sediment yields observed within the BRV can be reproduced with this type of simple modelling approach. SedCas_Volcano produces an output of modelled lahar volume and sediment yield through time. The ultimate purpose of this exercise is to make steps towards providing a means of longer-term lahar hazard assessment by enabling the forecast of lahar activity under changing catchment conditions.

I will then turn my attention to Disaster Risk Reduction. Section 1.3 has introduced the importance of story and experience sharing for awareness raising and resilience building in at-risk populations. It has also demonstrated the novelty of co-created arts- and science-based risk communication initiatives to enhance Disaster Risk Management practices. As stated in the opening section of this chapter, I was involved in the Mountain Aglow project as a research assistant in 2019, and later had an opportunity to perform an evaluative study of this initiative as part of my PhD work. I therefore have a fourth research question for this thesis, which is:

4) *In what ways has the Mountain Aglow initiative contributed to the Disaster Risk Reduction activities on Montserrat?*

Chapter 5 first presents 'Mountain Aglow', which is an innovative co-created multi-media DRR initiative for communicating volcanic risk on Montserrat. I then approach the above question by presenting results derived from interviews and focus groups with project stakeholders and beneficiaries, as well as feedback forms. I use these results to identify and discuss the outcomes (i.e., short-term effects) and impacts (i.e., longer-term effects) of the initiative on DRR practices on the island.

Owing to the varied nature of the topics covered by each chapter, and the range of methods required to approach each research question (e.g., Chapter 2 uses a range of satellite imagery, whereas Chapter 5 has relied upon feedback forms/interviews/focus groups), this thesis does not include a dedicated methods chapter. Instead, the methods applied for each piece of work will be described in a methods section within the chapter.

Chapter 2: Multi-decadal catchment evolution and lahar hazard driven by episodic volcanic disturbance: the Belham River Valley, Montserrat, 1995-2020.

2.1 Introduction:

Explosive volcanic eruptions are among the most dramatic agents of landscape disturbance on Earth (Pierson and Major, 2014). Sudden deposition of large quantities of pyroclastic sediment can induce major deviations from pre-disturbance rates of sediment supply, modifications to topography and drainage network structure, alteration of hillslope surface grain size distribution, and damage and destruction of vegetation (Major et al., 2000; Gran and Montgomery 2005; Pierson and Major 2014; Major et al., 2016). Stable pre-disturbance conditions permit states of hydro-geomorphic equilibrium within fluvial systems; inputs (sediment and water) and any processes that mediate their transfer through the system (e.g., vegetation controls on rainfall runoff) maintain a quasi-stable balance within typical variability. This manifests as a consistent and characteristic range of flow behaviour and morphology within the drainage network. Systems disturbed by volcanic eruptions are knocked out of equilibrium; they exhibit modified rainfall-runoff responses and typically respond by 1) increasing downstream water flux and 2) increasing downstream sediment flux (Gran and Montgomery, 2005; Alexander et al., 2010; Pierson and Major, 2014). This leads to altered flow behaviour (e.g., higher discharge, flash floods, debris flows) and consequent adjustment of downstream channel forms (e.g., aggradation/degradation, cross section change). Both the altered flow and the morphological response pose a potential hazard to proximal, or occasionally distal (e.g., Nevado del Ruiz, 1985; Lowe et al., 1986) communities and are thus pertinent foci of research (Newhall and Punongbayan 1996; Barclay et al., 2007; Major et al., 2016).

Lahars, rapidly flowing mixtures of water and pyroclastic sediment (Vallance and Iverson, 2015, and references therein), are the primary manifestation of increased sediment availability and modified water flux in volcanically-disturbed catchments. Rainfall-triggered lahars, the focus of this study, are initiated either by coalescence of sheet-flow or by shallow land-sliding; they may occur both during (syn-eruptive) or after (post-eruptive) volcanic disturbance. They are the principal drivers of sediment transport and related downstream geomorphic modifications, particularly in catchments with intermittent/ephemeral stream flow (Barclay et al., 2007; Alexander et al., 2010; Capra et al., 2010). Lahars and their related impacts often reach further downstream than preceding primary volcanic phenomena (e.g., PDCs), thereby expanding both the spatial and temporal extent of hazard posed by volcanic eruptions. Consequently, they are a major hazard, capable widespread infrastructure damage and livelihood disruption, and responsible for a significant proportion (20%) of eruption-related fatalities worldwide (Brown et al., 2017).

Downstream channel modifications induced by lahars and post-eruptive streamflow vary spatially and temporally depending on the magnitude and nature of the disturbance, variations in hillslope condition (e.g., vegetation cover), climatic conditions, and local variations in valley geomorphology (Gran et al., 2011; Major et al., 2020). Geomorphic modifications typically evolve over timescales far exceeding the eruption owing to incremental sediment transport (Swanson et al., 2013; Major et al., 2020). A general conceptual model of post-disturbance fluvial recovery at volcanoes is presented by Gran and Montgomery (2005) and discussed in Chapter 1 of this thesis (Figure 1.2). This model is derived from long term observations of short-lived, large-magnitude eruptions, with instantaneous sediment inputs of around or exceeding 1 $x10^9 m^3$. Numerous studies have demonstrated the importance of characterising these extraordinarily high-magnitude and long-lived elevated sediment yields, and the associated dramatic and hazardous downstream geomorphic adjustments that such eruptions induce (e.g., Kuenzi et al., 1979; Gran et al., 2011; Major et al., 2019). However, globally, fluvial systems may be perturbed by a range of other patterns of sediment input from volcanism that may in turn induce a variety of recovery pathways. Short-lived, small to moderate magnitude eruptions exert a lesser impact on the landscape as the sediment loading and the spatial footprint of impacted areas is reduced (see Section 1.1 for examples, e.g., Table 1.1). Fluvial response in systems disturbed in this way is typically characterised by a similar but lower magnitude and shorter-lived pattern of elevated hillslope sediment yield and downstream channel response (Thouret et al., 2014).

By contrast, some volcanoes may exhibit prolonged states of eruption and sediment production. ‘Persistently’ active volcanoes provide a continuous supply of sediment via frequent (~daily) small explosive events or rockfalls (e.g., Tungurahua, Jones et al., 2015; Semeru, Thouret et al., 2014; Santiaguito, Lamb et al., 2019). Alternatively, some volcanoes exhibit ‘episodic’ eruptions with periods of active sediment production punctuated by phases of quiescence that can last for months or a couple of years; variants on this type of behaviour have been observed at numerous volcanoes worldwide (Ogburn et al., 2015). Importantly, although annual sediment yields from these catchments are lower, total yield may be equivalent or greater over the longer term than the larger-magnitude transient events (Thouret et al., 2014). Downstream sediment and channel dynamics are determined by the relative rate of sediment and water supply from source areas. Thus, it is important to understand how these differing patterns of sediment supply influence the magnitude of fluvial response and recovery and the timescales over which they occur until a new post-disturbance equilibrium is met (Gran et al., 2011; Pierson et al., 2013; Major et al., 2020).

To date, there are comparatively few or limited studies that examine the fluvial response and recovery associated long-duration, episodic perturbations. This chapter seeks to address this and to consider how and what controls larger-scale dynamic changes in such systems. My case study is the Belham River Valley, Montserrat. The headwaters of this catchment have been perturbed by episodic dome collapse/explosion-derived PDCs and tephra fall associated with 5 phases of andesitic lava dome growth at the Soufrière Hills Volcano (SHV) between 1995-2010 (Sections 1.5.2 and 1.5.3; Wadge et al., 2014). By synthesising datasets and findings presented by previous authors (Barclay et al., 2007; Susnik 2008; Alexander et al., 2010; Darnell et al., 2011, 2012; Froude, 2015; Jones et al., 2017), with new analysis of rainfall, geomorphic change, and vegetation cover variation, I have created an unprecedented 25-year dataset documenting the broad trends in the evolution of the Belham River Valley in response to the eruption. As is typical of these types of system, monitoring is not continuous, rather, observations tend to be sporadic, instantaneous (i.e., snap-shot), and short term. Thus, this also serves as a case study means to integrate such non-systematic and discrete observations with continuous systematic data series (e.g., volcano monitoring data/observation logs, remotely sensed rainfall) to understand long-term evolution. I use this to explore how the complex interconnectivity of sediment supply, water supply, and mediating hillslope conditions exert control on the subsequent downstream lahar hazard and geomorphic change, and to develop a conceptual model for volcano-perturbed catchments that includes a broader spectrum of sediment supply events than is typically considered.

2.2 Methodology:

An important challenge was the development of several continuous timeseries of parameters that are known to impact sediment transport from a wide variety of data sources. Here, I do not seek to understand the impact of any one individual transport event, rather, I seek to examine long term catchment-scale influences on channel dynamics. Figure 2.1 details the process of analysis and the parameters under investigation; the data used are summarised in Table 2.1 below. Figure 2.2 shows the Belham River Valley, outlining key valley cross sections referred to through this analysis. Please refer back to Figure 1.7 for details of the names of key locations. Below I describe in more detail the methods used to derive new data and the limitations of the means I employed to synthesise or calculate data/parameters.

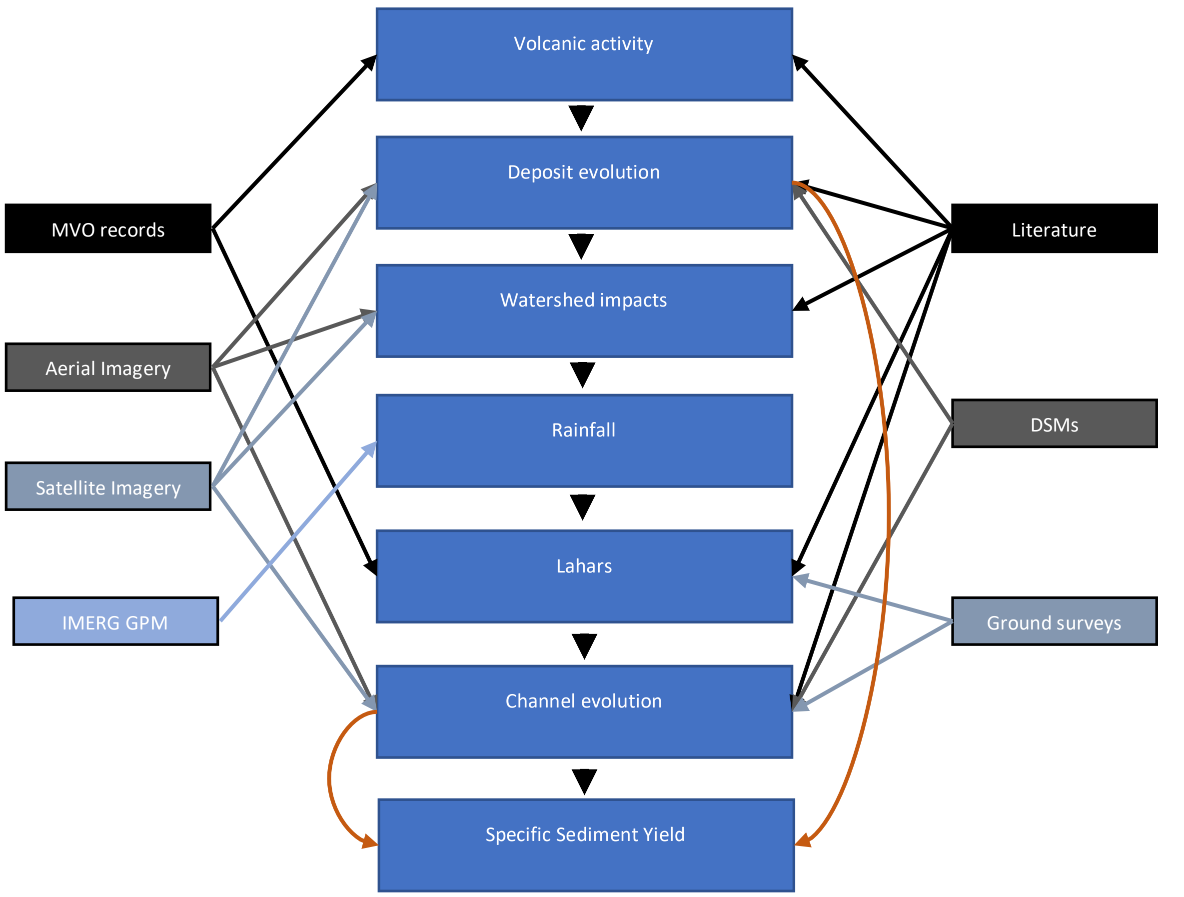


Figure 2.1: Schematic of key factors of this analysis and their respective data sources.

Parameter	Description	Data Source(s)	Date range	Observation frequency
Sediment input	Monthly estimates of sediment input from volcanic activity.	MVO activity records and literature sources (compiled by Froude, 2015); Analysis of aerial photography (compiled by Froude, 2015); DSM differencing.	Jul 1995 – Nov 2019	Daily
Deposit volume change	Estimated volume of pyroclastic deposits through time.	Estimates from Froude (2015); Digital Surface Model (DSM)/Digital Elevation Model (DEM) analysis;	1995 - 2019	Approximately every 2-3 years
Vegetation Cover	Estimate of vegetation cover over the study area.	Edmonds et al., (2006); Alexander et al., (2010); aerial photographs; Normalised Difference Vegetation Index (Advanced Spaceborne Thermal Emission and Reflection Radiometer [ASTER], Landsat, RapidEye and PlanetScope [PlanetLabs])	1995 - 2020	Approximately annual
Rainfall	Estimates of rainfall rate.	Intergrated Multi-satellitE Retrievals for GPM (IMERG; GPM = Global Precipitation Measurement)	Jan 2001 – Sep 2019	30 minutes
Lahar Frequency and Magnitude	Dates of known/validated lahar events and their estimated magnitude.	MVO records; seismic data	1995- 2019	Daily
Channel Elevation and condition	Measured channel elevation and observed state along the valley	DSM analysis; photographic surveys; literature sources.	1995-2019	Approximately every 2-3 years
Specific Sediment Yield	Estimated sediment yield	Deposit volume change in both upper catchment and middle/lower reaches.	1995-2019	Approximately every 2-3 years

Table 2.1 List of parameters analysed in this study, sources of data and frequency of observation.

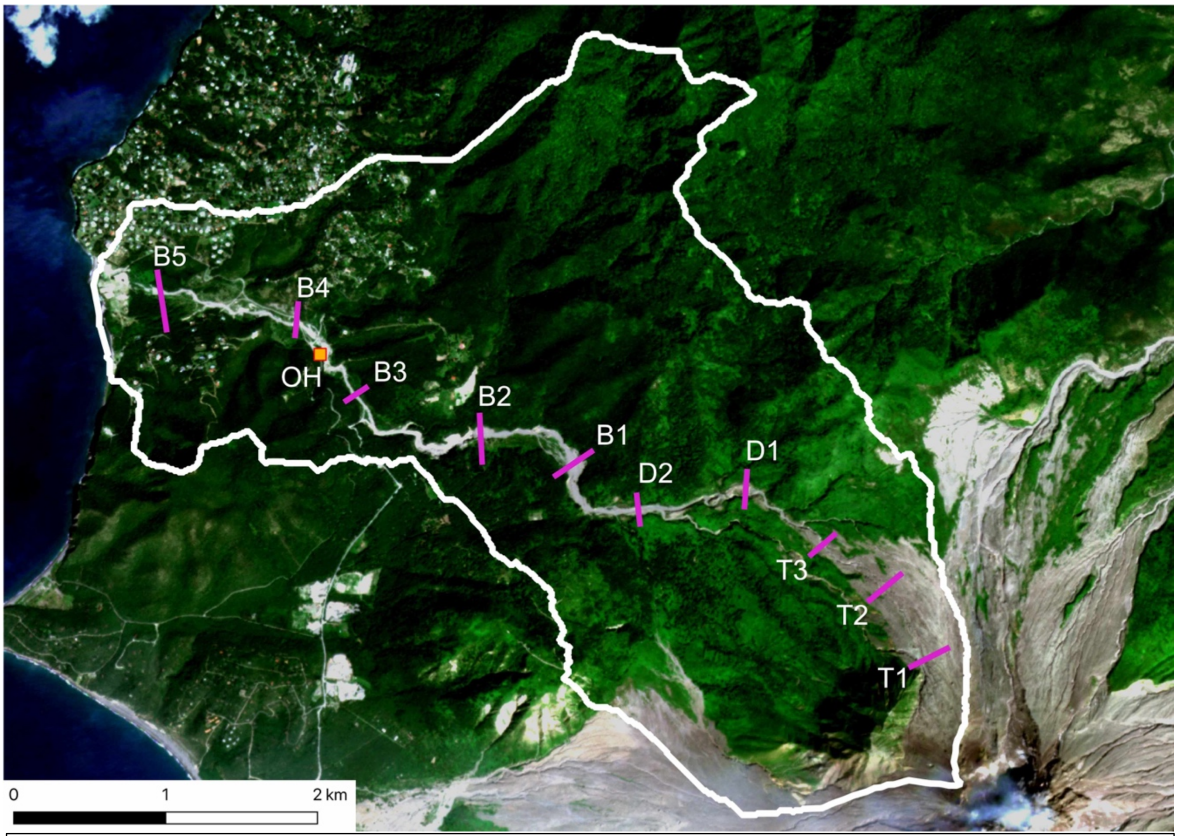


Figure 2.2: Map of the Belham River Valley cross sections used/referred to in this chapter. Image credit: PlanetLabs.

2.2.1 Characterisation of catchment-scale boundary conditions

In this sub-section I detail how I defined the catchment boundary conditions. In this case, I use the term 'boundary conditions' to refer to the conditions that apply to the whole catchment and affect/control sediment and water transport through the system. These include sediment supply, water supply and vegetation cover.

2.2.1.1 Volcanic activity, and the accumulation and erosion of pyroclastic deposits

My first objective was to produce a timeseries of the spatio-temporal distribution and estimated volume of volcanic sediment input, net volumetric change of the main deposits in the upper catchment, and a record of morphological changes occurring upon these deposits. Most of the compilation of recorded volcanic activity and valley fill analysis was completed by Froude (2015) via consultation of MVO records, published literature (e.g., Cole et al., 1998, 2002; Calder et al., 1999; Sparks et al., 2002, Herd et al., 2005, Alexander et al., 2010, de Angelis et al., 2010, Cole et al., 2014, Stinton et al., 2014a, b) and analysis of aerial photography (estimates of valley fill were made by comparing deposit widths with pre-eruption topography via use of cross-sections, see

Froude (2015) for details on this methodology). I have complemented this record by estimating the quantity of sediment within relevant sub-catchments via a combination of 1) Digital Surface Model (DSM) and Digital Elevation Model (DEM) difference analysis, for which I created a new volcano-wide DSM (see following section), and 2) aerial and satellite photography to estimate the volume of channel/valley fill where not completed by Froude (2015). For the latter, widths of valley-fill deposits and channels were estimated at a series of cross sections and compared using DSMs as reference (see following sections). Table 2.2 lists the DSMs/DEMs used in this chapter.

Date	**Source**	**Spatial resolution**	**Vertical error**	**Extent**
Pre eruption	Digitised contour map	10m	5m	DSM: Whole island (Wadge and Isaacs 1988, MVO)
Feb 1999	Aerial Photogrammetry	10m	5m	DSM: Whole island (Wadge 2000, MVO)
Jan 2002	GPS survey (Leica AT302)	10m	0.01-0.02m	DEM: Channel-limted from 1.4km upstream of coast, extending 610m (MVO/NERC)
May 2003	GPS survey (Leica AT302)	10m	0.01-0.02m	DEM: Channel-limted from 1.4km upstream of coast, extending 930m (MVO/NERC)
May 2005	GPS survey (Leica AT302)	10m	0.01-0.02m	DEM: Channel-limted coast to Sappit River (Susnik 2008)
Nov 2006	GPS survey (Leica AT302)	10m	0.01-0.02m	DEM: Channel-limted coast to Lee's Channel (Darnell 2010)
Nov 2007	GPS survey (Leica AT302)	10m	0.01-0.02m	DEM: Channel-limted coast to Lee's Channel (Darnell 2010)
Jun 2010	LiDAR DSM	1m	0.15m	DSM: Volcano-wide (MVO)
Mar 2011	GPS survey (Leica AT302)	10m	0.01-0.02m	DEM: Channel-limted coast to Lee's Channel (Froude, 2015)
Mar 2012	GPS survey (Viva GNSS GS15)	10m	0.035m	DEM: Channel-limted coast to Lee's Channel (Froude, 2015)
Mar 2013	GPS survey (Viva GNSS GS15)	10m	0.035m	DEM: Channel-limted coast to Lee's Channel (Froude, 2015)
Mar 2019	Tri-stereo Satellite Photogrammetry	0.5m	2.3m	DSM: Majority of Belham catchment, excludes coast.

Table 2.2: List of digital surface models used in the analysis of this chapter. All data can be found in Appendix 1.1.

It is important to acknowledge a key difference between DEMs and DSMs: DSMs are a model of the land surface, including any overlying vegetation or features; by contrast, DEMs are a model of the land surface without any overlying features. The difference is usually due to the method of generation. For example, models derived from optical imagery include vegetation and buildings. Conversely, LiDAR/radar techniques and use of GPS may penetrate vegetation cover and more accurately capture the land surface.

Construction of new DSM

I generated a new volcano-wide photogrammetry-derived DSM by processing very high resolution tri-stereo satellite imagery; to my knowledge this is the first of its kind for SHV. This imagery was acquired as part of the Committee of Earth Observing Satellites (CEOS) landslide hazard data access pilot scheme. Photogrammetry is a means of generating 3-dimensional renderings of physical objects with a series of overlapping 2-dimensional optical images. Photogrammetry has a range of applications from the biomedical sciences (e.g., Struck et al., 2019), video game design (Statham, 2020) through to environmental sciences (e.g., Westoby et al., 2012; Mancini and Salvini, 2019). Satellite photogrammetry requires pairs, on is this case, triplets, of overlapping images acquired at different along-orbit positions (Figure 2.3). It is dependent on the known location of the acquisition sensor in 3-D space (a.k.a. ephemeris), determined by GPS, and its attitude, i.e., its orientation (pitch/roll/yaw), with respect to the Earth's surface (e.g., Stumpf et al., 2017; Hodúl et al., 2018). These characteristics are then used to define a Rational Function Model (RFM) which makes use of a series of Rational Polynomial Coefficients. The RFM can triangulate features by identifying lines/samples common to overlapping sets of images, measuring spatial differences between them, and converting to object space, i.e. XYZ coordinates, thereby generating a 3-D model. Errors in the measurement of ephemeris and attitude can lead to subsequent synoptic horizontal and vertical errors in resulting DSMs. These errors are typically translational and consistent across a scene and may be corrected via georeferencing and/or co-registration techniques (e.g., Akca et al., 2007; Stumpf et al., 2017; Hodúl et al., 2018). Crucially, this method returns a Digital Surface Model, not a Digital Elevation Model, as optical imagery includes vegetation and other features which obscure the land surface.

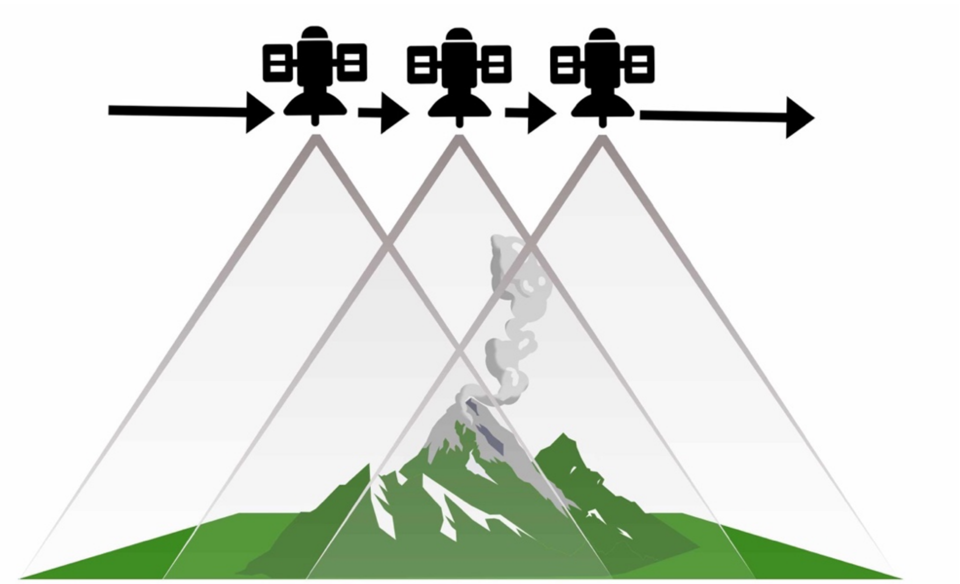


Figure 2.3: Schematic of tri-stereo image acquisition. As the satellite passes over the area of interest, it takes three overlapping images along its orbital track.

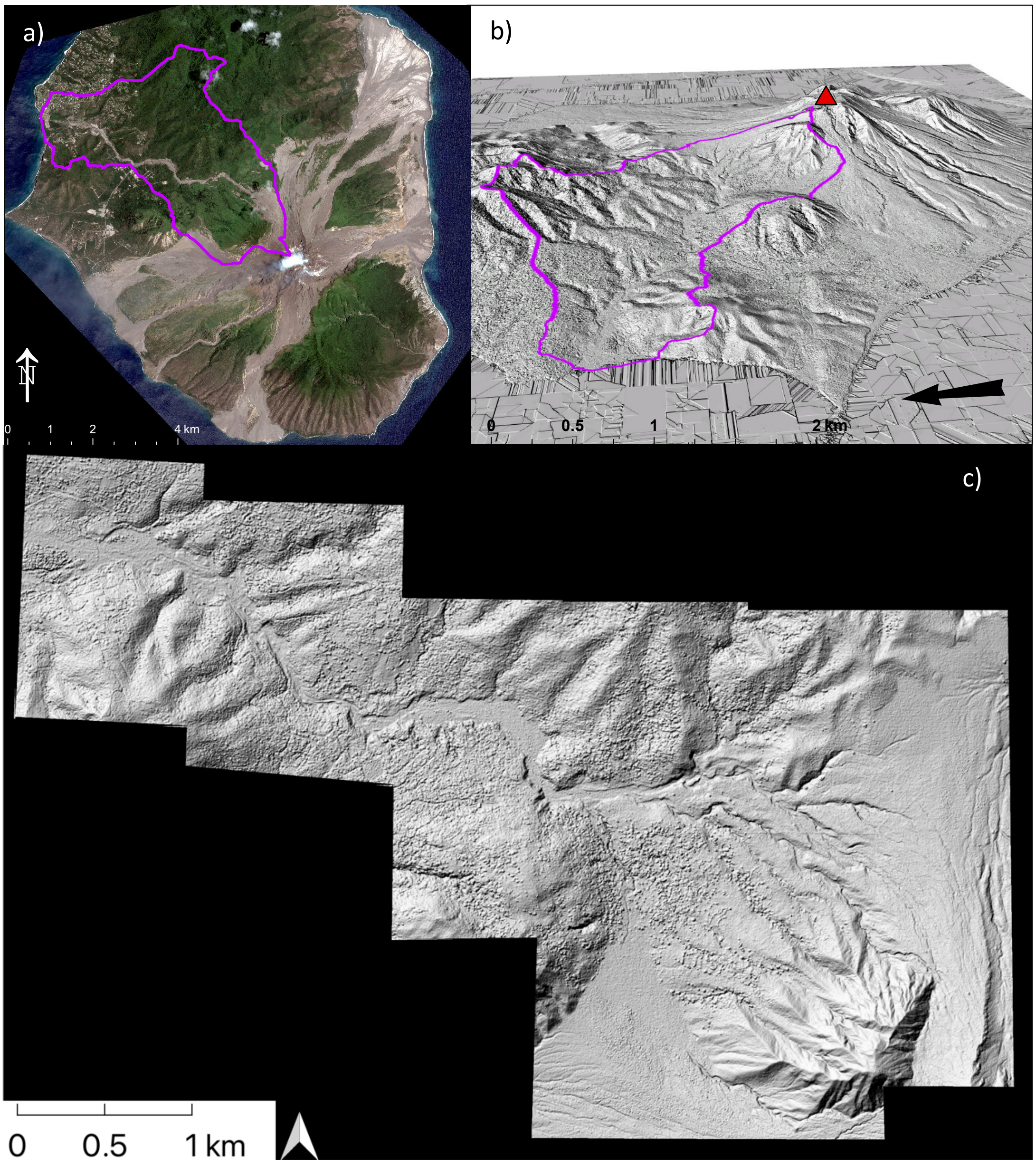


Figure 2.4: a) Multi-spectral Pleiades satellite image of SHV with the Belham Catchment outlined in purple. b) oblique hillshaded view looking southeast over the raw March 2019 Pleiades DSM, Belham Catchment outlined in purple. c) hillshaded co-registered portion of the 2019 DSM.

As part of the CEOS scheme, I received a triplet of panchromatic images with a resolution of 0.5 m; 3 m resolution multi-spectral images were also provided (e.g., Figure 2.4a). I processed the raw panchromatic imagery to generate a DSM using the European Space Agency Geohazards Exploitation Platform (ESA GEP) DSM-OPT software, hosted by Terradue (Stumpf et al., 2017). This platform is mostly black-box in that, following imagery upload, RFM processing and DSM construction are automated aside from a user-defined resolution parameter with a minimum value of 0.5 m. I set this resolution as 0.5 m in keeping with the resolution of the raw images to maximise detail. Possible trade-offs of this are the possibility of noise in the surface model and that processing higher-resolution DSMs is comparatively more memory-intensive; in retrospect, down-sampling to a resolution of 1 m, i.e., the same resolution as the 2010 DSM, may have been advantageous for processing purposes (see below). This returned a high-resolution DSM of the south of the island (Figure 2.4b) which was slightly displaced in the X, Y and Z domains by approximately 20m with respect to the June 2010 LiDAR DSM; this required co-registration.

Co-registration of DSMs involves matching a new surface model to a reference surface model; in other words, the new model is relocated in space to best fit the reference model (Akca et al., 2007; Bertin et al., 2022). Owing to software access limitations, I used the trial version of the Least Squares 3D (LS3D) surface matching software (Akca et al., 2007). This software package has a limited memory capacity and was unable to process the co-registration of the entire new DSM. To address this memory limitation I fragmented the DSM into a series of much smaller sections (~3-4 km^2). Via trial and error (i.e., experimenting with the area that the software could handle without crashing), I created 7 overlapping rectangular polygons to extract DSM data from both the new DSM and the 2010 reference DSM. Extraction therefore created 7 pairs of new/reference DSMs which I then processed individually with the LS3D software. 7 co-registered versions of the fragments of the new DSM were returned, which I then merged into one raster covering the volcanic deposits in the upper catchment and the main Belham Valley channel (Figure 2.4c). This excludes portions of the surrounding hills as no significant deposition has occurred here, and the coast because DSMs including the coast caused LS3D to crash; the reason for this is unclear but may be a function of the noise in the DSM over the sea (Figure 2.4b).

Together with the co-registered DSM, LS3D produces files of vertical residuals; I calculated the root mean square error (RMSE) from these residuals which returned RMSE = 2.7 m. Understanding that these residuals included geomorphic changes, changes in vegetation cover and growth of pre-existing vegetation, I manually selected stable benchmarks from across the catchment (large boulders, buildings) identifiable in both DSMs to constrain a new RMSE of 2.3m. This error is high compared to some other DSMs used in this study (Table 2.2), and higher than other DSMs generated with Pleiades data e.g., <0.8 m (Bisson et al., 2021) and 1.8m (Walk et al., 2019). However, the latter Pleiades DSMs were both generated for surfaces with little or no vegetation or anthropogenic structures; they are not affected by overlying surface changes in the same way. Thus, a higher error is expected and not unreasonable given the vegetated surfaces included in the new 2019 DSM. I argue that in light of the challenges outlined above this constitutes a success; indeed, two of the DSMs used in this study have higher errors than this (pre-eruption and 1999 DSMs have an error of 5 m).

Correction of 1999 DSM

Inspection of the 1999 DSM (Wadge, 2000) revealed a significant spatial (X and Y domains) offset of Tyer's Ghaut compared to the pre-eruption and 2010 DSM; the thalweg of Tyer's Ghaut, the location of spurs in the ghaut wall, and the north-eastern peak of Gage's Mountain were all displaced to the east by approximately 200m. This had significant implications for DSM differencing tasks. There is a dearth of evidence to suggest that the spurs within Tyer's Ghaut and Gage's Mountain were eroded during Phase 1 of the eruption, thus I assumed these to be stable benchmarks to use to re-georeference this portion of the 1999 DSM. This was performed using the ESRI ArcMap georeferencing tool using ~200 ground control points.

DSM differencing

DSM differencing was performed using the ESRI ArcMap plugin, '*Geomorphic Change Detection*', or '*GCD*', developed by Wheaton et al. (2010). GCD incorporates user-defined vertical errors of each of the compared DSMs into its calculations of geomorphic change and automatically generates error bounds which inform a Minimum Level of Detection (LoD). The LoD thus enables the masking of apparent geomorphic change that may be due to error. The catchment-wide DSMs from pre-1995, 1999, 2010 and 2019 (Table 2.2) were processed in GCD to elucidate the net changes in the upper catchment over the periods pre-1995 – 1999, 1999 – 2010, 2010 – 2019, and the overall change between pre-1995 – 2019. Other channel-limited DEMs listed in Table 2.2 above contribute to the analysis of channel change in the Middle and Lower Belham (see below); differencing was conducted in the same way as for the larger DSMs.

Watershed delineation

Topographic change can induce migration of watershed boundaries (e.g., Gran and Montgomery 2005), thereby increasing or decreasing watershed size. This has a knock-on effect on the quantity of rainfall incident within a catchment boundary, the quantity of water available for runoff and thus the potential discharge and sediment transport capacity of flows; this is thus an important consideration. Watershed delineation requires analysis of catchment-scale, or larger, DSMs. I extracted the watershed areas for pre-1995, 1999 and 2010 in ESRI ArcMap. The Watershed tool can be used following a series of steps. First, with the Fill tool, a 'filled' DSM/DEM must be generated to remove any 'sinks' in the model which might interfere with flow direction calculations. I then used the Flow Direction tool on this filled raster to generate a D8-type flow direction raster (i.e., from each pixel water flow can go in 1 of 8. Directions), which can then be used by the Watershed tool. For best results, I selected a 'Snap Pour Point' for the Watershed tool. This point represents the outlet of the watershed, which I placed at the mouth of the main

Belham channel on each DSM. The Watershed tool then generates a shapefile demarking the boundary around all the cells in the DEM/DSM that drain to that point.

Supplementary analysis of deposition and erosion

The 1999 DSM is limited to the upper catchment and thus does not provide information relating to the degree of deposition in the middle and lower Belham. This DSM was originally constructed using high resolution aerial imagery which was available via my MVO data agreement. I estimated channel/valley fill volume by establishing a filled channel width at 30 transects along the middle and lower reaches. By extracting topographic cross-sections from the pre-eruption DSM at each transect (Figure 2.5), I calculated the cross-sectional area of the filled channel using a free online area calculation tool (https://www.sketchandcalc.com). I then took the average of these areas and integrated along it the length of the middle and lower reaches (4 km) to gain a volume. The error of this calculation is very high owing to the large vertical error of the pre-eruption DSM (+/- 5 m); in some places this error exceeds the depth of deposit.

Similarly, the DSM differencing between 2010 and 2019 permits measurement of the *net* erosion of pyroclastic deposits between these dates. However, constraining the rate of this erosion is of interest. With the use of high-resolution RapidEye (3 m resolution) and Pleiades (0.5 m resolution) satellite data (Table 2.3), I measured lateral erosion of channel margins at 20 evenly spaced

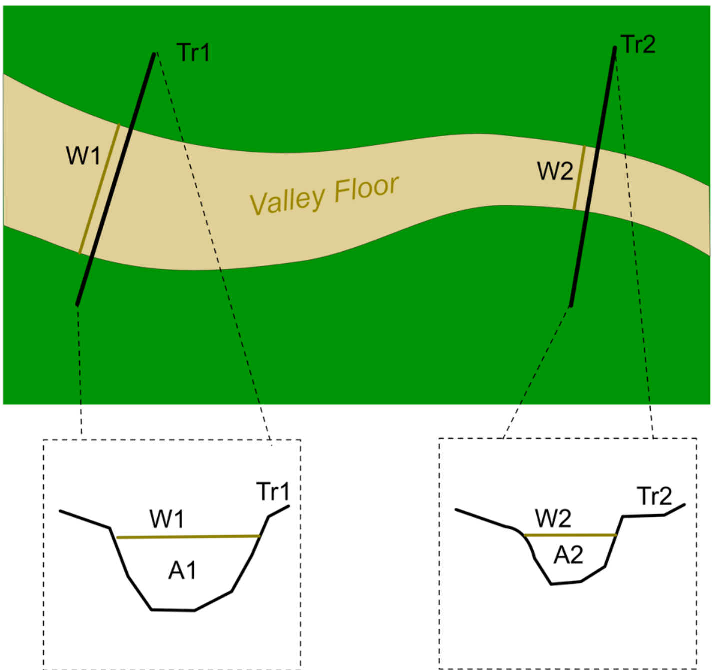


Figure 2.5: Schematic of method of valley fill estimation using transects to extract pre-eruption topography (Tr1 and Tr2) and measurements of valley fill widths (W1 and W2) to calculate cross-sectional areas of valley fill (A1 and A2).

transects long a 650 m section of Dyer's River (upstream and downstream of D2, Figure 2.2) from 2010-2011, 2011-2014, 2014-2019, to establish relative rates of erosion in the upper catchment (e.g. Waythomas et al., 2018). I selected this reach owing to simpler channel morphology compared to upper Dyer's River and Tyer's Ghaut, i.e., this section of the valley is straight. I then divided the net erosion (as calculated by GCD) proportionately between these time periods according to measured rates of lateral erosion to establish variation in erosion rate. In doing this I assume that lateral erosion is proportional to vertical erosion, and is therefore an adequate proxy of total erosion. Whether this assumption is realistic is uncertain, as factors controlling the rate of channel widening and incision are complex (see Finnegan et al. 2005).

With my new analysis, combined with the catalogue of activity and geomorphic changes compiled by Froude (2015), I have produced: 1) a timeseries of the estimated *average* deposition for each day on which pyroclastic flows were recorded entering Tyer's Ghaut and the North Gage's Fan (data is more limited for the latter). This record accounts for days on which large pyroclastic flows have occurred (large enough to warrant their own volume estimation in reports or publications); and 2) a timeseries of the estimated volume of sediment removed, i.e., sediment yield, from upper catchment by erosion (mostly limited to Tyer's Ghaut owing to a lack of data).

Sensor	Available bands	Red (nm)	Infrared (nm)	Resolution (m)	Acquisition Date
Aerial Photography (Wadge 2000; supplied by MVO)	-	-	-	0.73	--/02/1999
ASTER	V/NIR = 3 (Until 2008) SWIR = 4	630 – 690	760 – 860	15	13/04/2002; 14/09/2003; 26/07/2005; 06/05/2007; 21/02/2010; 24/02/2017
Landsat-7	V/NIR = 4 SWIR = 2 TIR = 1	630 – 690	770 – 900	30	Jan-Dec 2000 C; Jan-Dec 2001 C; Jan-Dec 2004 C; Jan-Mar 2006 C; Jan – Jun 2007 C; Jan – Sep 2008 C; Feb – May 2009 C
Quickbird (supplied by MVO)	V/NIR = 4	630 – 690	760 – 900	2.4	26/06/2006; 18/11/2007
RapidEye	V/NIR = 5	630 – 685	760 – 850	5	09/04/2011; 14/02/2012; 07/01/2014
Pleiades (provided by CEOS)	V/NIR = 4	600 – 720	750 – 950	0.5	11/04/2014; 06/04/2017; 30/01/2018; 29/03/2019
PlanetScope	V/NIR = 4	590 – 670	780 – 860	3	07/10/2020; 16/11/2020

Table 2.3: Data sources, relevant statistics and acquisition dates of synoptic aerial/satellite imagery used during this study. 'C' indicates median composite image over the time span indicated.

2.2.1.2 Vegetation

Due to its importance in mediating the rainfall-runoff response, my next consideration was the spatio-temporal variation of vegetation cover throughout the study period. Observations of vegetation cover over the catchment are limited in photographic archives and in the literature. The following descriptions of vegetation cover were available: 1) Prior to eruption, the upper catchment is known to have been densely forested (e.g., Barclay et al. 2007; Froude 2015); 2) Alexander et al. (2010) present estimates of vegetation change between March and November 2006. The MVO photography archive includes a range of aerial photographs over the study period, but these only offer a view of a limited area and are thus not helpful for establishing vegetation cover over the whole catchment.

Fortunately, some multi-spectral satellite imagery is available from 2000 onwards, covering much of the study period. This provides a good opportunity to collate a long-term picture of changes in vegetation cover. Multi-spectral imagery consists of a series of bands of wwavelengths of light, typically ranging from visible blue to thermal infrared; different sensors have different sensitivity ranges. A fortunate by product of this is that it is possible to compare the amount of light of a different wavelengths that are reflected back to the sensor. This can provide insights into the type of land cover represented by each pixel.

Leaves and other chlorophyll-laden parts of plants absorb red light for photosynthesis and reflect infrared light to mitigate thermal tissue damage. As such, observing the difference between the reflectance of these two bands of light provides an indication of the intensity of photosynthesis within a pixel, and thus can be used as a proxy measure of plant health. This is known as the Normalised Difference Vegetation Index (NDVI). NDVI is a commonly used proxy measure of photosynthetic activity on a land surface and has been previously used to detect vegetation impacts of landscape disturbances such as wildfire (Leeuwen et al., 2010; Buma, 2012; Lanorte et al., 2014; Yang et al., 2017; João et al., 2018) , landslides, hurricanes (Rodgers et al., 2009, Cortés-Ramos et al., 2020, Delaporte et al., , 2022; Lindsay et al., 2022), tsunamis (Reddy and Prasad 2018), and volcanism (Houlié et al., 2006; Kassouk et al., 2014; Raynolds et al., 2015; Easdale and Bruzzone, 2018; Teltscher and Fassnacht, 2018; Lai et al., 2022). The following equation calculates NDVI for each pixel:

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

In this case, I use NDVI primarily to estimate the area of the catchment covered by vegetation at points in time through the study period. NDVI is the preferred means of analysis as it detects photosynthesis, not simply a green surface. Thus, in summary, data points have been derived from published literature (e.g., Alexander et al., 2010), aerial photography from 1999, and, primarily, NDVI analysis of satellite images acquired between 2000 and 2020.

Image processing, classification, masking and validation

Satellite Imagery:

Satellite images have come from various sensors, shown in Table 2.3. Figure 2.6 shows the process from acquisition to usage. All satellite images were first reprojected to the WGS84_20N coordinate reference system to be consistent with pre-existing data (DSMs/imagery provided by MVO), and if necessary, further georeferenced and orthorectified in ESRI ArcMap. Depending on the type and nature of available data, satellite images need to be processed prior to being useful for analytic purposes. NDVI analysis requires reflectance data and for clouds/cloud shadows to be masked; in NDVI clouds can be mistaken for bare surface (e.g., Buma, 2012; Lai et al., 2022; Lindsay et al., 2022). Cloud cover is very common in Montserrat, particularly over the volcano summit and parts of the upper Belham catchment. This dramatically reduces data availability, a problem common to many tropical regions (Hilker et al., 2012, Chandra et al., 2019). I manually chose images to ensure at least 75% of the images were cloud-free and, where possible (i.e., with LandSat-7 data), temporal composites were developed to mitigate data loss (e.g., Yan and Roy 2014; Shelestov et al., 2017; Lindsay et al., 2022), with due consideration of the dates of known

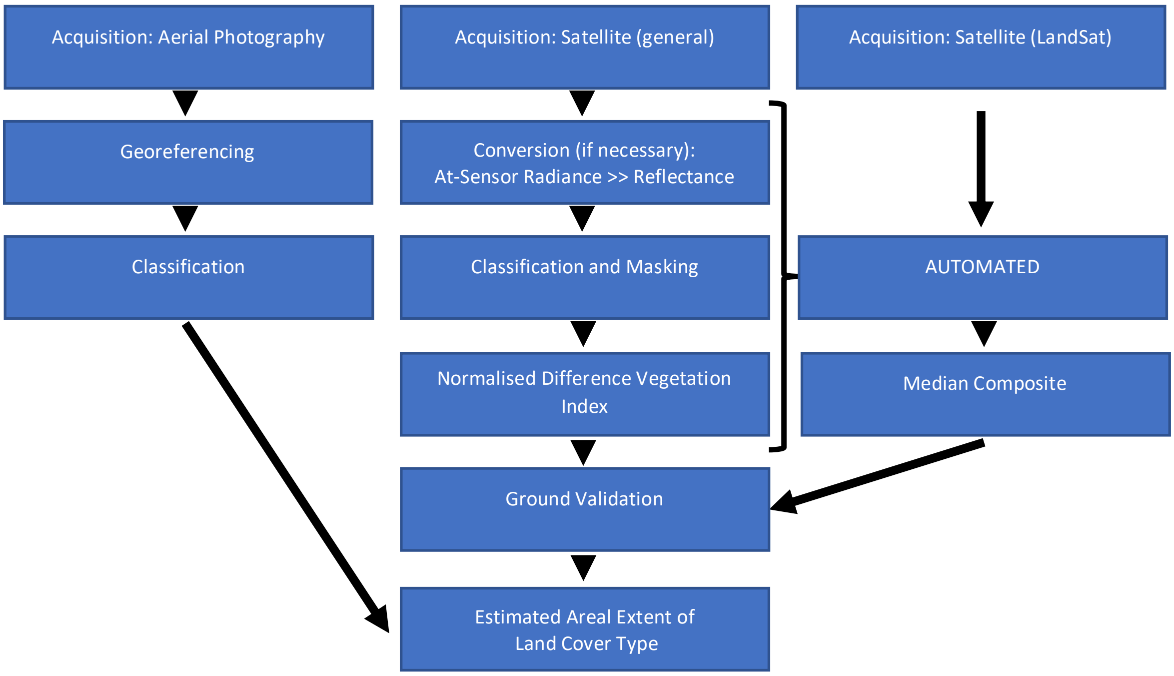


Figure 2.6: Schematic of image processing sequence.

large disturbances to avoid a mixed signal across the image (i.e. where part of the composite has been captured before a known tephra-generating eruptive event, and part after, potentially impacting the median NDVI). The latter was unfortunately not possible in 2000 and 2001; these may contain some mixed signal owing to impacts from transient tephra fall events associated with eastward-directed dome collapses (e.g., Carn et al., 2004). Following selection, the data required varying degrees of processing prior to NDVI, depending on the source. The LandSat-7 data acquired for this work was processed automatically through Google Earth Engine, which returned cloud-masked (i.e., cloud pixels removed, see below) surface reflectance (i.e., atmospheric effects accounted for) data which was then composited to further reduce data loss from cloud cover. Data from Pleiades, RapidEye and PlanetScope were provided in surface reflectance but required manual cloud masking (see below). ASTER data was provided as At-Sensor Radiance data which required conversion to reflectance values using a program provided by the NASA Land Processes Distributed Active Archive Center (LP DAAC). All data can be found in Appendix 1.1 (redacted from publically available thesis due to third-party copyright).

The sea and clouds have a different spectral response compared to both vegetated and bare land surfaces across the Visible (V), Near Infrared (NIR), short wave infrared (SWIR), and thermal infrared (TIR) bands (Chandra et al., 2016). Cloud masking is the removal of cloud pixels from images. This is important for analytical purposes owing to the spectral response of clouds; in NDVI analysis, clouds return low NDVI values which are not representative of the land surface beneath the cloud. Clouds therefore must be removed to avoid cloud-induced bias in the measurements. Thus, once all the data was in an appropriate format, with exception of LandSat-7 data, all available constituent bands for each sensor were merged into a single mosaic raster and then cloud masked using the Supervised Maximum Likelihood classification tool within ESRI ArcMap. Note in Table 2.3 the different range of available bands for each sensor varies. Merging into a single mosaic multi-band raster enables the classification tool to classify according to the variance of pixel values across all bands, rather than considering bands individually.

Supervised classification requires the provision of manually selected training data which is created via delineation of areas containing pixels that are representative of different classes of landcover types (i.e., volcanic deposit vs vegetation), sea, or clouds. Table 2.4 shows the classes of landcover types I designated for this analysis and whether a mask was applied to them to remove them from the image. I selected these classes based on the types of features/landcover I could identify in the optical imagery. To select training data, I manually drew polygons over an RGB image which enveloped only features belonging to each respective class. Once classified, the multi-band mosaic rasters were masked, eliminating any pixels contaminated by cloud or cloud shadow

(Table 2.4). I then isolated the Red and NIR bands from the masked mosaic rasters, before running them through the NDVI function within ArcMap.

Following Rodgers et al. (2009), NDVI thresholds were adopted to identify land surface cover of three main types: Type 1, NDVI <0.2 = bare surface/emergent vegetation/severe vegetation damage, Type 2, NDVI 0.2-0.6 = thin - moderate density vegetation (scrubland/grassland/low density forest); Type 3, NDVI >0.6 = high density vegetation (i.e., forest). For this work I am particularly interested in the balance between bare surface/severe damage, and any vegetated surface, so adopt a ratio of Type 1 to Type 2+3.

To help ensure an accurate assessment of vegetation cover via NDVI, these images required validation; this was a challenge. The most sophisticated validation methods incorporate the comparison of NDVI values obtained from multispectral satellite imagery with NDVI values obtained by multispectral aerial or UAV imagery (e.g., Sotille et al., 2020; Tang et al., 2020; Thapa et al., 2021), however, such a comparison was not possible in this case. In other cases, ground truthing and validation/verification of NDVI findings have been performed with use of ground/aerial photography (Rivas-Torres et al., 2018, Valderrama-Landeros et al., 2018). Aerial photography of the whole Belham catchment is very limited; most images are of small areas within the catchment and are temporally disparate. As such I have been able to perform a limited

Class	**Description**	**Mask**
Vegetation (Forest)	Forested land surface	NO
Vegetation (Thin)	Land surface vegetated by non-forest vegetation	NO
Vegetation (Damage)	Land surface covered by damaged vegetation (discoloured)	NO
Vegetation (Cloud Shadow)	Any vegetated surface shadowed by cloud	YES
Deposit	Bare volcanic deposit	NO
Deposit (Bright)	Bare volcanic deposit that appears unusually bright	NO
Deposit (Cloud Shadow)	Any deposit shadowed by cloud	YES
Cloud	Cloud tops	YES
Cloud edge (Vegetation)	Any cloud edge above a vegetated land surface	YES
Cloud edge (Deposit)	Any cloud edge above a volcanic deposit	YES
Sea	Any part of the image that contains the sea.	YES

Table 2.4: Details of classes defined in the image classification process and masking status.

validation process using photography available from the MVO archive taken from known and identifiable locations at various dates.

In line with the outlined land surface types (Types 1, 2 and 3, identified above) I have identified areas of bare surface (i.e., deposit) or dense vegetation (including forested) that have appeared in a similar state in aerial photographs taken at various times throughout the study period and are temporally congruent with satellite imagery from the 4 satellite sources (ASTER, LandSat-7, RapidEye, PlanetScope). Areas of thinner or vegetation have been more variable owing to spatio-temporal variability of volcanic impacts, so finding areas common across both aerial and satellite images was more challenging. In these cases, I have instead identified known locations (e.g., along the banks of Tyer's Ghaut, islands of vegetation in the lower Belham) where aerial photography that is contemporaneous with individual satellite images indicates the presence of thin\low-lying or damaged vegetation. I then examined the associated NDVI values by taking >100 randomly selected point samples over the identified areas. Thus, I have a range of NDVI values for each of the 3 land cover types (i.e., Types 1, 2 and 3) for the 4 sensors. These are shown in Figure 2.7; there is clearly variance between the NDVI values measured by each sensor for each land cover type. This may be an artifact of both variable plant health between imagery dates (e.g., as a result of seasonal effects) and variable wavelength bands detected by the sensors (see Table 2.3). However, most crucially, the 0.2 threshold is consistently, albeit not perfectly, between the values for deposits and thin/damaged vegetation. These values, combined with the literature-sourced threshold (Rodgers et al., 2009), have therefore informed the decision to set the threshold of bare surface/severe damage/emergent vegetation as NDVI = 0.2.

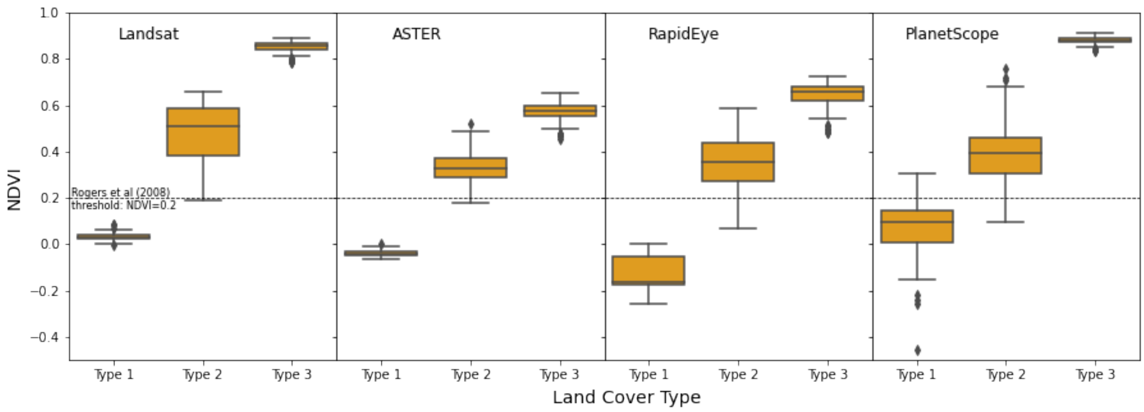


Figure 2.7: Validation plots for NDVI. Values extracted from NDVI images at locations of photographed/documented land surface types. The Rodgers et al. (2009) threshold is marked. NV = no vegetation, TV = thin vegetation, FV = full vegetation.

Land cover from aerial Imagery:

The February 1999 aerial photography covered the entire south of the island; some of this imagery was used to generate the 1999 DSM (Wadge, 2000). It consists of a series of images that form an overlapping mosaic; four of these images cover the Belham Valley. I georeferenced the four relevant images using ArcGIS Pro using buildings identifiable in the 2010 DSM as benchmarks, then merged the images into one raster file. The resulting image had a spatial resolution of 0.73m. Unusually, the image was cloud free, so no cloud masking was required prior to classification of land-cover types. The image was classified using Maximum Likelihood Supervised Classification native to ESRI ArcMap and areal extents estimated for each landcover type.

2.2.1.3 Rainfall and climatological variability

Rainfall is the primary driver of lahar activity on Montserrat (Barclay et al., 2007; Alexander et al., 2010). Previous studies of the Belham Valley have utilised data from rain gauges, but the record is incomplete owing to temporal gaps in coverage (at times no gauges were installed) or gauge malfunctions (ash/debris clogging, infestation by insects, etc) (Matthews et al., 2002, 2009; Froude, 2015). Furthermore, rainfall over Montserrat is highly heterogenous and rainfall may be up to 60% greater over the volcano summit (Matthews et al., 2002; Barclay et al., 2006; Hemmings et al., 2015). Most gauges have been installed in various locations across the valley from the volcano on the Centre Hills (e.g., at the Montserrat Volcano Observatory; Figure 2.8), thereby failing to detect important and frequent orogenic and volcano-driven mesoscale convective rainfall events over the summit the volcano were rapidly destroyed by volcanic activity (Matthews et al., 2002).

To improve the chance of detecting summit rainfall, and in light of its prior success for mass flow analysis in regions of high rainfall variability and/or scarce data coverage (e.g. Pratama et al., 2017; Monsieurs et al., 2018; Karki et al., 2019; Getirana et al., 2020; Abancó et al., 2021; Brunetti et al., 2021), I acquired satellite precipitation data from the joint NASA/JAXA Integrated Multi-satellitE Retrievals for Global Precipitation Measurement (IMERG, hereafter referred to as GPM). This provides a continuous record of rainfall between January 2001 and September 2019 (Figure 2.9). Data is collected by a constellation of satellites equipped with either passive microwave radiometers, able to detect the presence of hydrometeors, or infrared sensors, which measure cloud top temperatures (Huffman et al., 2020). All data streams from these satellites are calibrated to the GPM Core Satellite, which is in turn calibrated to ground-based rain gauge measurements.

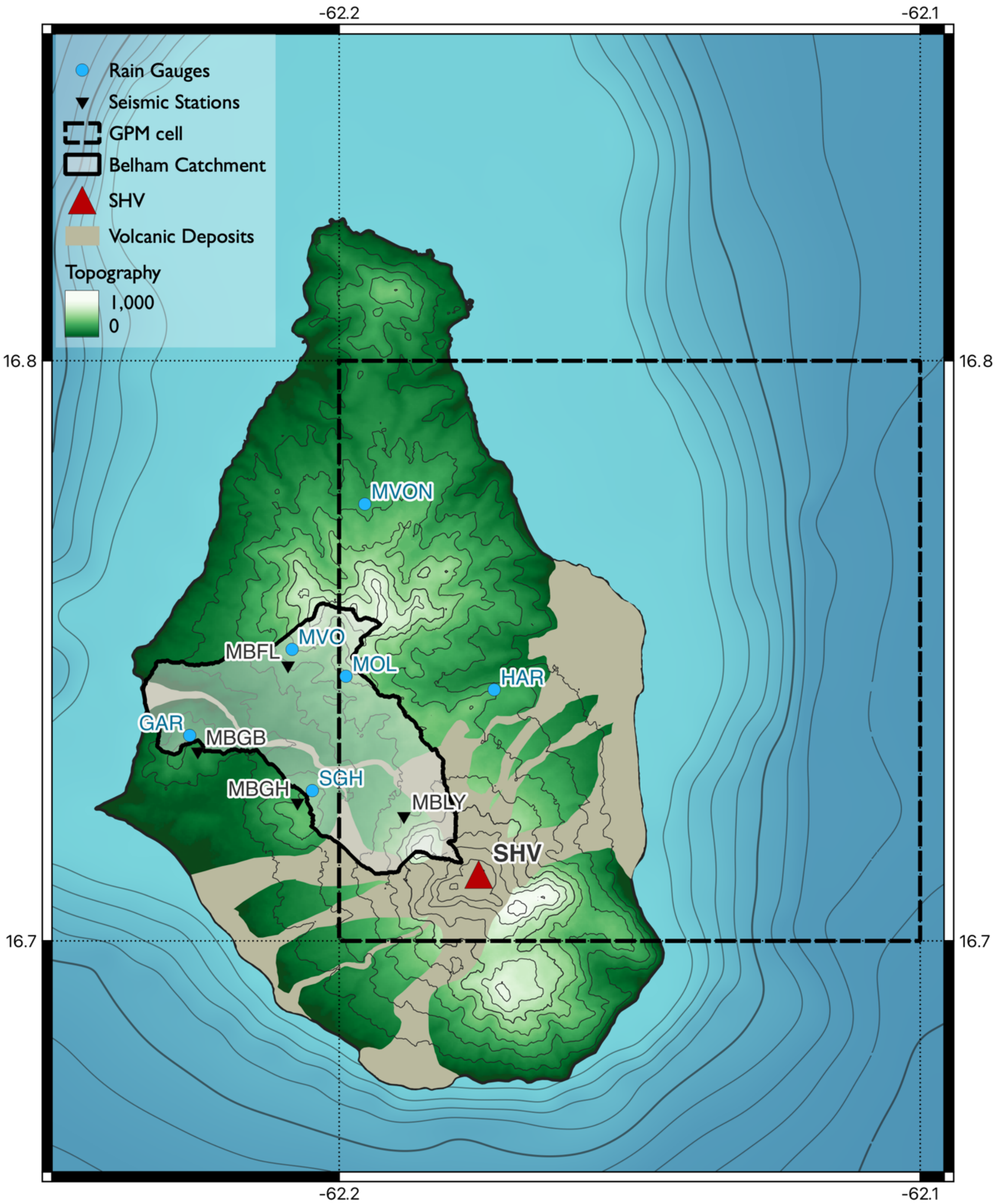


Figure 2.8: Map of Montserrat showing the spatial extent of the GPM grid cell used in this study, the locations of available rain gauge data and the locations of the four seismic stations from which data pertaining to lahar incidence were acquired.

Estimates of average precipitation intensity (mm hr^{-1}) are provided every 30 minutes, with a spatial resolution of 0.1°x0.1° (~10km x 10km). Figure 2.8 shows the spatial extent of the GPM cell used in this study. I anticipate that GPM will be an improvement on the limitations of the rain gauges given its coverage of the summit. However, this data will fail to detect the true magnitude of the smallest scale convective systems and short-term peaks in intensity (i.e., 10 minutes)

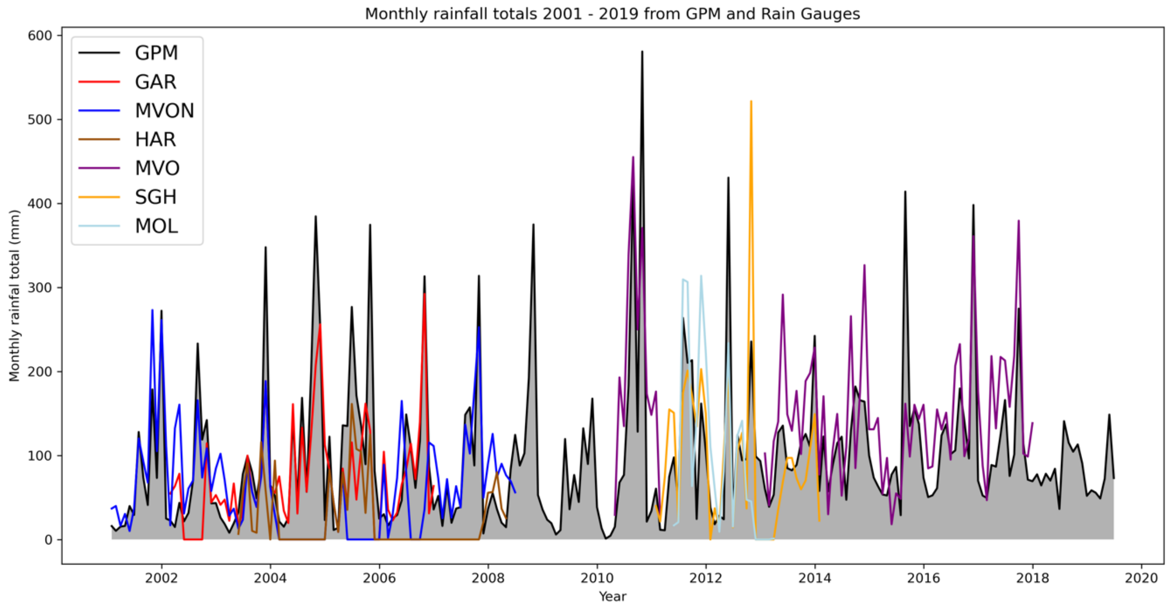


Figure 2.9: Comparison of GPM data with available rain gauge data. Prolonged periods of 0 mm indicate rain gauge malfunction.

known to occur frequently on Montserrat (Matthews et al., 2002; Barclay et al., 2007; Hemmings et al., 2015; Jones et al., 2017). It will inevitably also detect rainfall occurring outside of the catchment, over the eastern flanks of SHV and the Centre Hills, or over the sea.

Figure 2.10 compares monthly GPM rainfall with available rain gauge data. Spearman's Rank correlation analysis of time periods of reliable rain gauge data with GPM data reveals statistically significant moderate correlation of daily rainfall totals with a mean R_s = 0.52 (min = 0.46, max = 0.62), p= <0.01. The same analysis between very limited overlapping rain gauge records indicates moderate to strong correlation, with a mean R_s = 0.72, p= <0.01 (min = 0.62, max = 0.80). Much of the reduced correlation between GPM and Rain Gauge data occurs during low-moderate rainfall, i.e., rain gauge-detected daily totals of between 1 and 10mm. Correlation appears to be stronger for larger rainfall events. The apparently reduced correlation at lower rainfall magnitudes has potential implications for the accuracy of the GPM rainfall estimates, and thus the interpretation of the record I present, however this does not invalidate or negate my choice of GPM.

GPM does not extend back to the beginning of the study period; however, supplementary information related to precipitation in the region is available. Regional weather patterns are strongly affected by the El Niño Southern Oscillation (ENSO), particularly with respect to large tropical cyclones. Tropical cyclone activity is enhanced during La Niña phases owing to weaker vertical wind shear, weaker trade winds and reduced atmospheric stability; opposing conditions prevail during El Niño years (Klotzbach 2011; Schmitt et al., 2020). I acquired data pertaining to ENSO and incidence of tropical cyclone centres passing within 50 km of Montserrat from the National Oceanic and Atmospheric Association (NOAA: https://noaa.gov).

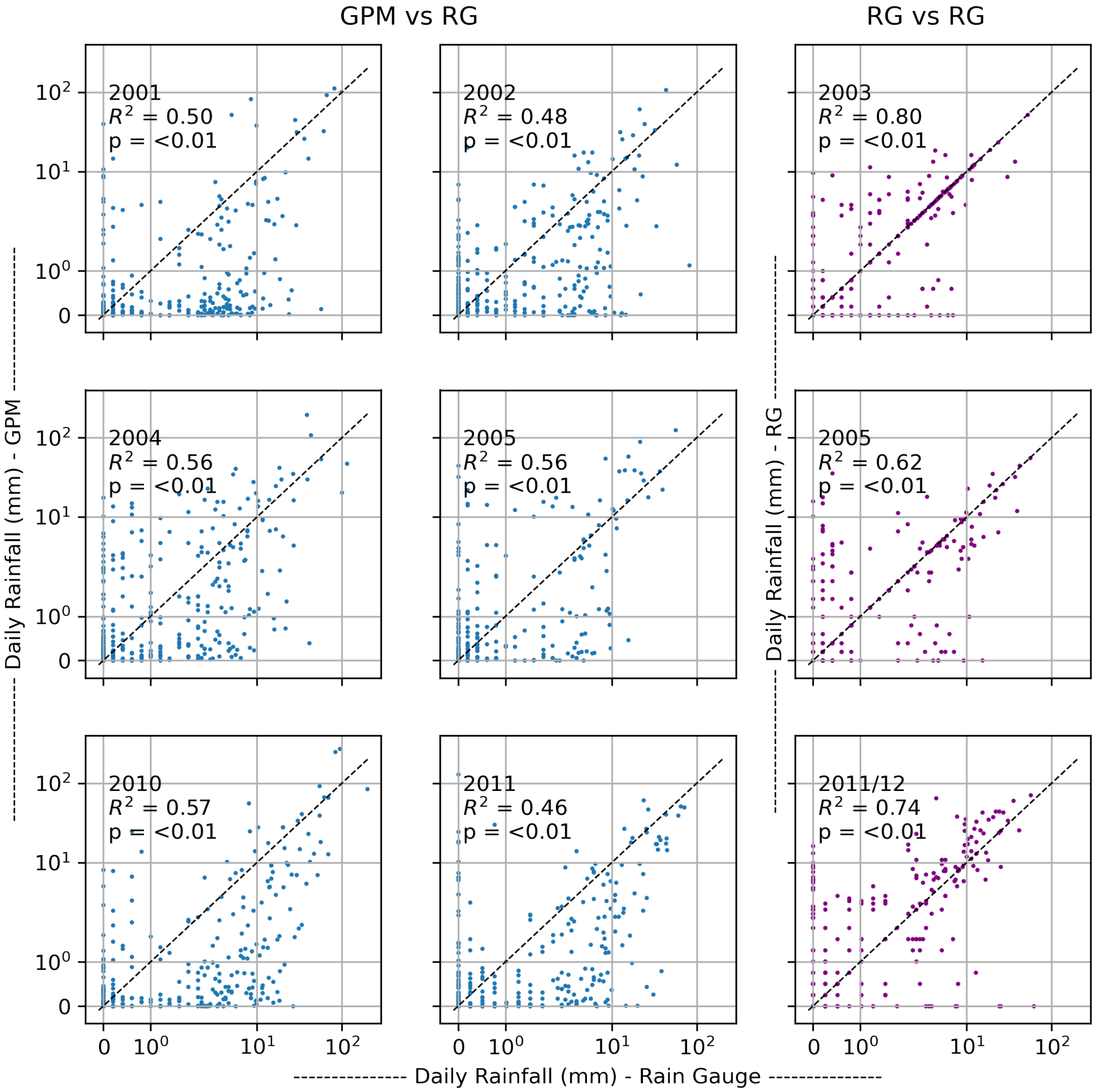


Figure 2.10: Comparison of GPM vs Rain Gauge (blue) and Rain Gauge vs Rain Gauge (purple) daily recorded rainfall. Dates of comparison windows are shown, together with Spearman's Rank correlation R^2 and p values. Data in rain gauge vs rain gauge plots are from overlapping records from two separate rain gauges.

2.2.2 Characterising lahar activity, channel change and sediment yield

The Belham River is not monitored specifically (e.g., with stream gauge, force plate, near-field seismometers). Instead, records of lahars are based upon observations made in the valley (direct observations of flows and/or deposits) and detection by far-field seismometers/helicorders, installed around the island for the purposes of volcano monitoring. Lahars generate a distinct seismic signal (longer in duration, distinct frequency) compared with other volcanic phenomena (PDCs, rockfalls, VT earthquakes) which allows their identification (Zobin et al., 2012; Froude, 2015). The lack of direct monitoring of the valley necessitates a crude definition of lahar magnitude: small, medium, or large, based on a series of criteria set out by Froude (2015). Small lahars are those that last for a few hours, occupy only a limited width of the valley floor and do not reach the sea. Medium lahars may last longer than 12 hours, occupy at least 50% of the valley floor at the Belham Bridge (B4, figure 2.1) and may reach the sea. Large lahars may exceed 24 hours in duration, occupy most of the valley and reach the sea. Froude (2015) compiled a record of lahars between 1995 – 2013. This record contains observations of lahars with varying confidence levels, classified as levels 1 (low), 2 (medium), or 3 (high). In this study I opt to use only level 2 and 3 observations. Simulations run by Darnell et al. (2012) suggest plausible volume estimates by size: ~0.5 $x10^4$ m^3 (small), ~2.5-5.0 $x10^4$ m^3 (medium), ~1.0 $x10^5$ m^3 (large) and ~1.0 $x10^6$ m^3 (extreme). It is important to note that some inconsistency exists between the volume estimations provided by Froude (2015) and Darnell et al. (2012). A principal example is that Darnell et al. (2012) deduce that to reach the sea, a lahar would have to exceed 1 x 10^5 m^3 (i.e., large), whereas Froude state reaching the coast is criteria for designating a medium lahar. I added to this record by consulting MVO activity logs between 2013-2020 and cross referencing with seismometer/helicorder readings provided by MVO.

Geomorphic changes in the Middle and Lower Belham, resulting from lahar activity and the occasional long runout PDC, have been captured in a catalogue of ground-based, aerial and satellite photography, periodic DSM surveys (Table 2.2), and documented in several literature sources (Barclay et al., 2007; Susnik 2008; Alexander et al., 2010; Darnell et al., 2010; Froude, 2015; Froude et al., 2017). This record provides snapshots of the conditions in the valley, capturing the net changes in the channel over elapsed spans of time. I have also compiled a record of changes along the coastline at the mouth of the Belham Valley using satellite and aerial photography. I crudely estimated the depth of the evolving coastal fan either by using ground-based photography by comparing the height of deposit surface with respect to an old jetty, (~1.5m above sea level at the pre-eruption mouth of the Belham River; Froude, 2015), or by point sampling DSMs of the fan. No data are available concerning the sub-marine portion of the fan, so my estimates only apply to the sub-aerial portion.

By combining data derived from both, 1) the estimates of erosion to the upper catchment, and 2) estimates of deposition in the middle and lower reaches, I then estimate the minimum specific sediment yield (SSY) from the Upper Catchment, which has an area of 6.4 km^2. Specific sediment yield is a commonly adopted metric of sediment yield normalised by catchment area and time, with units m^3 km^{-2} yr^{-1}, which enables comparison with other fluvial systems (e.g., Lavigne, 2004; Burt and Allison, 2010; Gran et al., 2011; Thouret et al., 2014; Waythomas et al., 2018). My estimates are strictly minimum estimates because 1) measurements in the upper catchment are relatively sparse and predominantly limited to Tyer’s Ghaut (excluding Farrell’s Plain, Dyer’s River and Gage’s Fan, and 2) I am unable to account for sediment deposition at sea, which is likely to be significant (Le Friant et al., 2010; Karstens et al., 2013).

2.3 Results:

This section will outline the results of the analyses described above. In line with the structure of the Methods (Section 2.2) this section will first outline the findings related to the catchment boundary conditions (volcanic activity, deposition/erosion of pyroclastic sediment, vegetation and rainfall) that affect runoff generation. Following this, details pertaining to lahar activity, subsequent geomorphic change within the middle and lower Belham, and sediment yield will be presented.

2.3.1 Catchment-scale boundary conditions

2.3.1.1 Spatio-temporal patterns of accumulation and erosion of pyroclastic deposits.

Figure 2.11 shows the monthly estimated volume of sediment input into the Tyer's Ghaut/Farrell's Plain and North Gage's sub-catchments from PDCs and major tephra fall events. Sediment input has predominantly occurred during lava extrusion phases (red background), particularly during northward/westward dome growth, with one main exception during inter-phase dome instability in late 1998 (Norton et al., 2002). Each input event has varied in terms of total volume, spatial footprint, and constituent grain size; some in excess of 5 m diameter (Φ = -8) to very fine ($\Phi \leq 11$) respirable tephra particles (e.g., Cole et al., 1998; Loughlin et al., 2002; Horwell et al., 2003; Edmonds et al., 2006; Komorowski et al., 2010; Alexander et al., 2010; Stinton et al., 2014). The most notable deposition events include June-September 1997 and October 1998 (~22 x10^6m^3, Figure 2.11, Table 2.1; Cole et al., 1998, Norton et al,. 2002), 8th January 2007 (4.5 x10^6m^3; De Angelis et al., 2007), 2nd January 2009 (0.5 x10^6m^3, Wadge et al., 2011), 8th January 2010 (3.4 x10^6m^3; Stinton et al., 2014). Figure 2.12 shows the spatial distribution of change to deposits in the upper catchment, which are then represented in as totals in Figure 2.13.

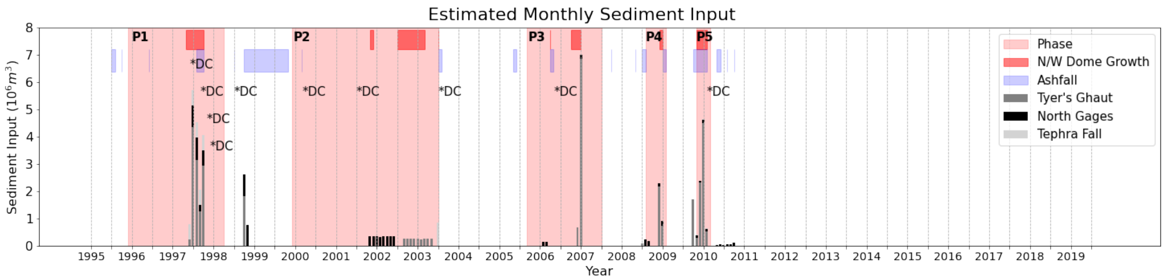


Figure 2.11: Estimated monthly sediment input from PDCs into Tyer's Ghaut and Farrell's Plain (labelled as Tyer's Ghaut), and onto the North Gage's fan, and tephra fall. Also shown are dates of the phases of lava extrusion, north-, northwest-, or west-directed dome growth, and observed tephra fall.

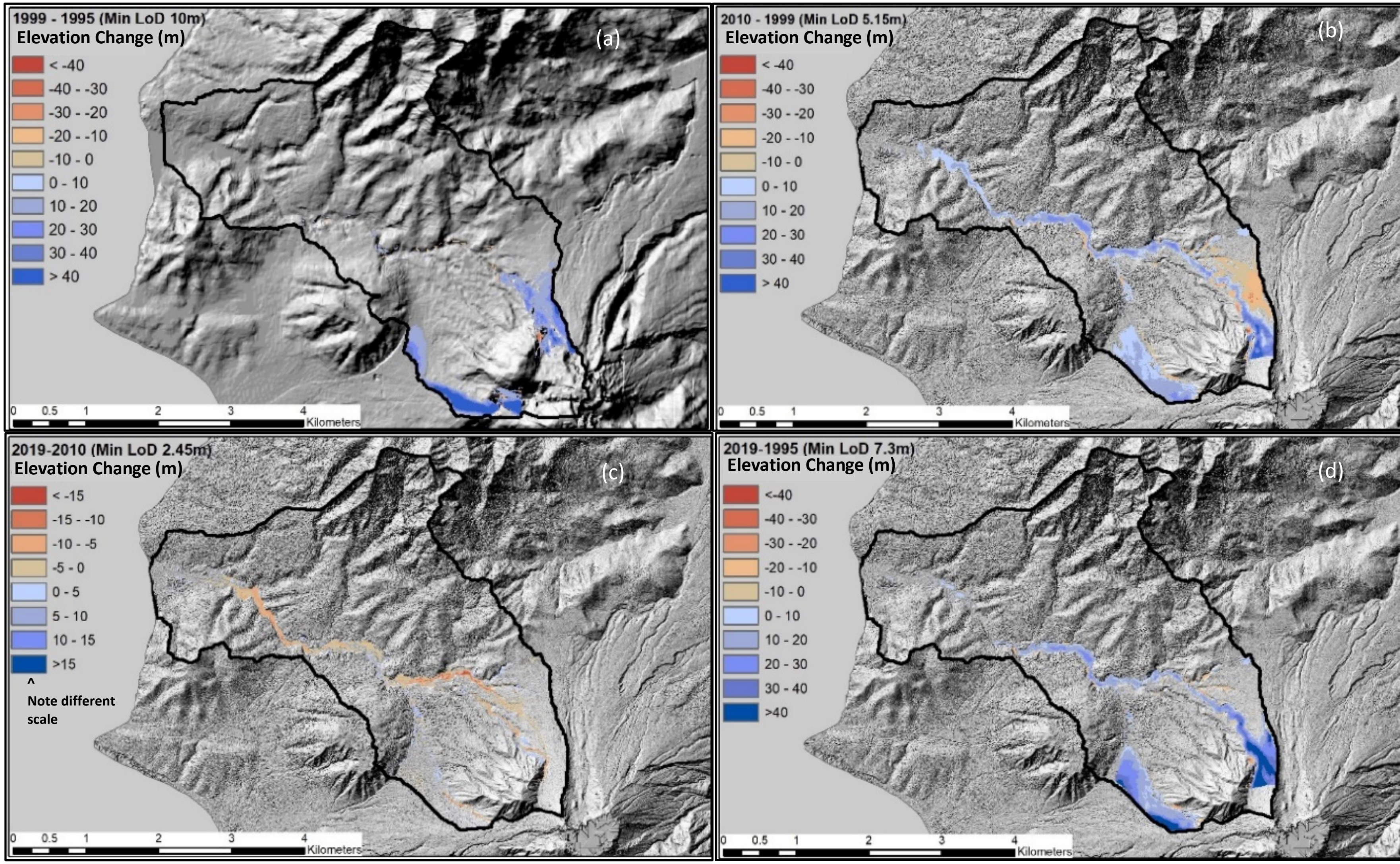


Figure 2.12: Geomorphic Change Detection output maps of elevation change (metres) within the Belham River Catchment, for periods a) pre-eruption to 1999; b) 1999 to 2010, c) 2010-2019, d) pre-eruption to 2019. Blues indicate elevation gain, reds indicate elevation loss. 'Min LoD' = 'Minimum Level of Detection'. Note the different scale in c).

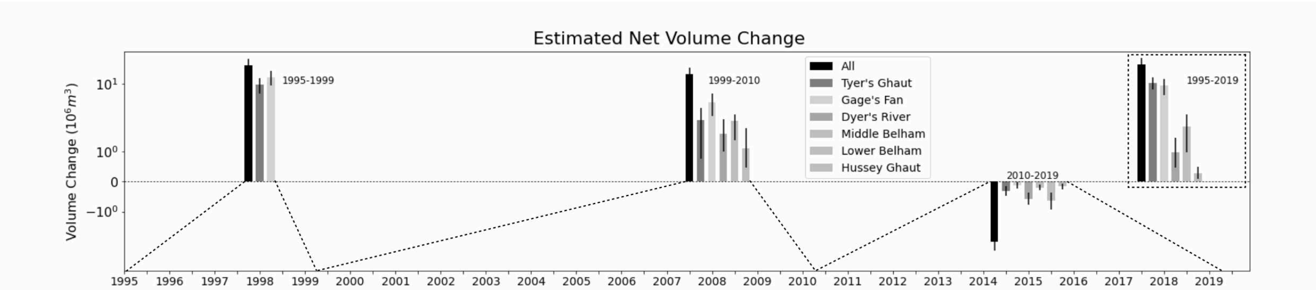


Figure 2.13: Net deposit volume change as acquired by DSM differencing. Dotted lines are to guide the eye and show the time periods represented by each cluster of bar plots.

DSM analysis shows that pyroclastic deposition has been significant (Figures 2.12 and 2.13) and has modified drainage patterns within the catchment (see Figure 2.14). Firstly, by February 1999 (Figure 2.12a), deposition of approximately ~22 x10^6 m^3 into upper Fort Ghaut and onto Farrell's Plain caused the catchment area to increase by 2.7 km^2 (new total catchment area of 15.4 km^2). Much of this is attributable to deposition associated with westward dome growth between June-October 1997 which initiated a stream-capture from the Fort Ghaut catchment via the formation of the North Gage's Fan. This filled the upper reach of Fort Ghaut and diverted some drainage to the north via Lee's Channel (Figure 2.14). A further ~8 x10^6 m^3 were deposited between 1999-2010 (Figure 2.12b). High rates of deposition between late 2008 and February 2010 led to the complete infilling of upper Tyer's Ghaut (Froude, 2015). This caused the amalgamation of Tyer's Ghaut and the Farrell's Plain fan, and overflow of pyroclastic material into the neighbouring Hussey Ghaut to the west. This diverted the primary summit drainage channel from Tyer's Ghaut into Hussey Ghaut which, at the time of writing, now conveys runoff from the lava dome (Figures 2.14 and 2.15f). Concomitant deposition onto Gage's Fan caused a northward migration of the drainage divide to the north portion of the fan, reducing the catchment size by ~0.75km^2 compared with 1999; runoff from the lava dome is now drained to the west via Fort Ghaut (Figure 2.14).

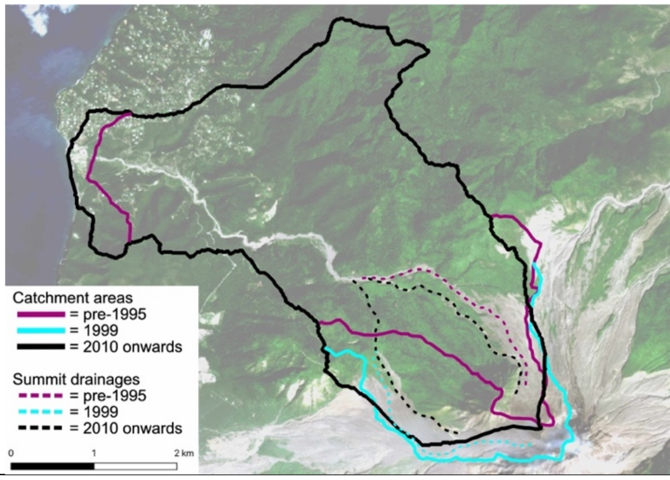


Figure 2.14: Map of the changes to watershed margins and primary summit drainage routes from pre-1995, 1999, and 2010.

Surface erosion has driven removal of pyroclastic deposits from the upper catchment during pauses in deposition (Figures 2.11, 2.12c, 2.15 and 2.16). Owing to a lack of evidence (e.g., scars) to indicate erosion via shallow land sliding, it is likely erosion has occurred predominantly via coalescence of Hortonian sheet flow and subsequent progressive incision and extension of rill and gully networks, as is commonly observed in pyroclastic deposits (Pierson and Major 2014). The most dramatic changes have occurred in Tyer's Ghaut and Dyer's River owing to the higher discharges passing through these reaches; coincidentally most of the available evidence also centres on these reaches. My analysis combined with findings from Froude (2015), demonstrated in part by Figures 2.12, 2.13 and 2.15, and supported by Appendix 1.2 identifies the following periods of net incision in Tyer's Ghaut: October 1998 - February 1999; February 1999 - January 2002; July 2003 – June 2005; June 2005 - November 2006; January 2007 – December 2008; February 2010 - March 2019. Lahars and activity and channel aggradation downstream (discussed below) also suggest significant erosion in 2007- 2008 though there is no direct observational data.

Comparison of my new 2019 DSM with that of June 2010 (Figure 2.12c) demonstrates the incision into pyroclastic deposits within the catchment over this period amounts to a total volume of 1.2 $x10^6m^3$ +/- 0.5 $x10^6m^3$. Analysis supplemented by high-resolution satellite imagery indicates that much of this erosion occurred in the first 9 months after June 2010. By March 2011, the ~650m-long section of valley floor centred approximately on cross section D2 (Figure 2.2) underwent an average widening of ~26 +/- 1.5 m. Assuming an average channel depth of ~6m through this area

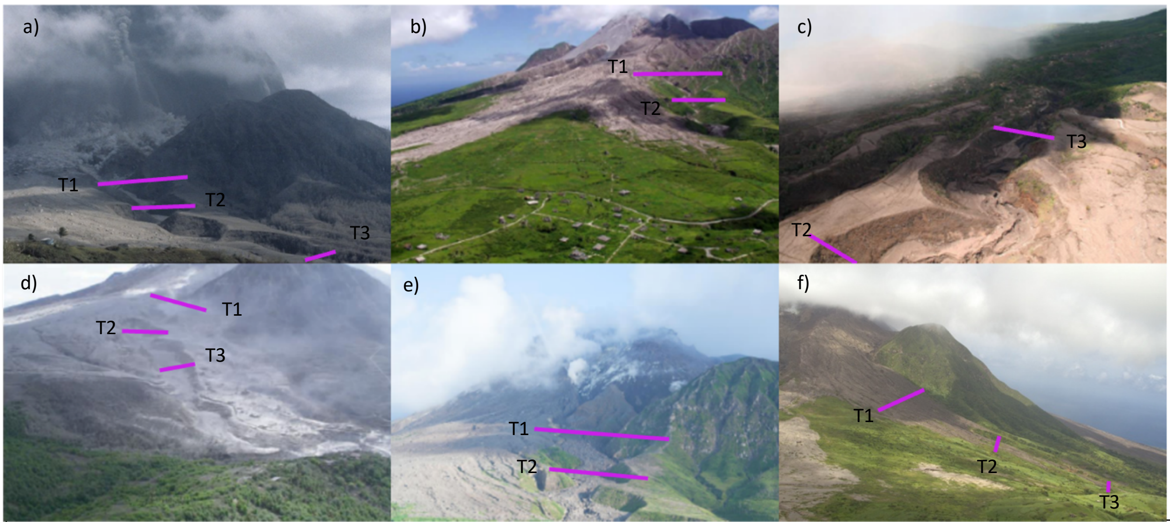


Figure 2.15: Example photographs of Tyer's Ghaut throughout the study period. Cross sections are annotated. a) view to the south of PDC entering Tyer's Ghaut during vulcanian explosion in August 1998 (Credit: MVO, Paul Cole); b) view to the southeast over Farrell's Plain fan in September 2002 (Credit: BGS) c) view to the northwest down into Tyer's Ghaut in September 2006 (Credit: MVO); d) view to the southeast in early January 2007 (Credit: MVO) view to the southeast onto upper Farrell's Plain and Tyer's Ghaut in September 2009, with the actively degassing dome in view (Credit: MVO, Paul Cole); f) view to the south over Farrell's Plain in May 2018 showing the filling and overflow into Hussey Ghaut at T1 (Credit: Christie, J.).

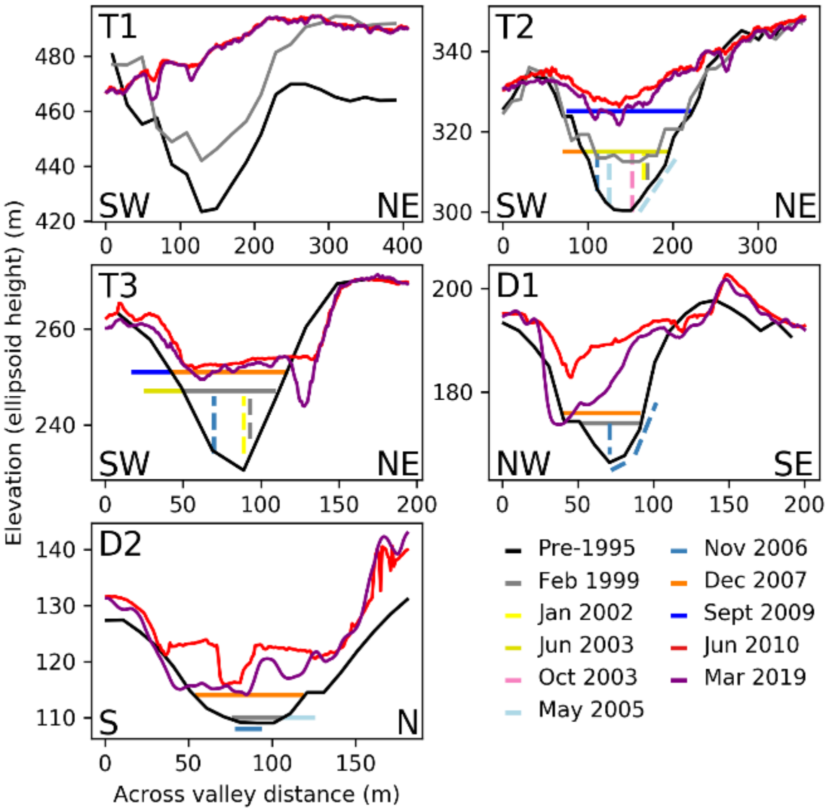


Figure 2.16: Valley cross sections showing geomorphic changes between 1995 and 2019. Vertical dotted lines indicate the location of incised channel margins. Horizontal lines extending beyond the pre-1995 line represent equivalent valley fill depths measured at different dates. Dotted lines outside of the pre-1995 line represent regions of observed bedrock erosion. Estimated valley fill for 2002 – 2009 derived from data from Froude (2015)

(as acquired from the June 2010 DSM, Figure 2.13), this equates to erosion of ~1.1 x10^5 +/- 1 x10^3 m^3. By April 2014, a further average 2.75 +/- 0.25 m of channel widening had occurred (~1.2 x10^4 +/- 1 x10^2 m^3), followed by a further 1.75 +/- 0.25 m of channel widening by March 2019 (~0.7 x10^4 +/- 0.7 x10^2 m^3). This calculation assumes no incision to the bed of the June 2010 channels and does not account for erosion to the top surface of marginal PDC terraces, and thus is an underestimate.

Observable changes to Tyer's Ghaut, Hussey Ghaut and Farrell's Plain are qualitatively of similar magnitude; estimation of erosion in these areas is precluded by more complex channel forms in Upper Dyer's and Lower Tyer's. As such, here I make the assumption that this observed non-linear rate of erosion is representative across the whole of the Upper Catchment. I use this ratio to divide the total volume removed to estimate the total yield for each time window. Thus, I estimate that the yield from the Upper Catchment varied as follows: 1.06 +/- 0.52 x 10^{6}m^3 (2010-2011), 0.10 +/- 0.05 x10^{6}m^3 (2011-2014), 0.06 +/- 0.05 x10^{6}m^3 (2014-2019). Figure 2.16 shows that erosion to deposits in Tyer's Ghaut (transects T1 – 3) has been of much lower magnitude than previously. This is likely a result of the diversion of primary drainage into Hussey Ghaut, thereby reducing the discharge passing through Tyer's Ghaut post-2010 and restricting erosion. This has potentially important implications for the runout potential of future PDCs in the event of renewed eruption at SHV (Stinton et al., 2014).

Observations of the North Gage's Fan are much less abundant; volumetric estimates of deposition and erosion through time were not possible in the same way as Tyer's Ghaut. Lee's channel has undergone significant incision and widening to accommodate heightened discharges driven by the formation of North Gage's Fan and subsequent stream capture. Consistent with observations from Tyer's Ghaut, satellite imagery from June 2006 shows a dense network of deeply incised channels within the Gage's fan, which suggests significant removal of pyroclastic material during the preceding period of limited sediment supply; these channels were largely infilled in satellite imagery from December 2007. Patterns of deposition around the outlet of the main channel on Gage's Fan between 2010 and 2017 suggests continued redistribution of material; lateral migration of channels over a small alluvial fan and progressive upslope migration of the outlet is visible in satellite imagery. DSM analysis indicates that erosion to North Gage's fan between 2010 and 2019 was relatively minor (0.12 +/- 0.06 $x10^6 m^3$) and restricted to one primary channel which skirts along the base of Gage's Mountain (see Figure 2.12c).

In general, observable geomorphic changes induced by fluvial activity have been very limited across the upper catchment since 2014. Only channel bed reworking and minor erosion to short portions of the north bank PDC terraces near D1 and D2 were evident in helicopter surveys before and after the passage of Hurricane Maria in September 2017. The limited erosion to deposits has allowed widespread revegetation on PDC terraces and along the southern bank in Lower Dyer's River, the lowermost portions of Farrell's Plain, as well as over a large portion of the lower North Gage's Fan (Appendix 1.3). A notable deviation from this trend occurred during an extreme rainfall event on 8^{th} November 2020 (MVO, 2020) which generated a lahar. Satellite imagery from before and after this event (Appendix 1.3) shows removal of vegetation from Hussey Ghaut, some channels draining Farrell's Plain, and in Dyer's River. Most significantly, a new deposit with an area of ~6.2 $x10^4 m^2$ had formed emanating from the outlet of the main channel of the North Gage's Fan, spreading north-westwards towards and partly into Lee's Channel; the thickness of this deposit is unknown.

Overall, erosion has been of much lower magnitude compared to volcanic deposition; my DSM analysis reveals that 23.3 +/- 7.4 $x10^6 m^3$ of pyroclastic and volcaniclastic material remained stored in deposits within the catchment as of March 2019 (Figure 2.12d, Table 2.5). This has potential implications for ongoing lahar hazard (i.e., sediment remains available for entrainment), and any future PDC hazard with respect to runout (e.g., Stinton et al., 2014).

Reach	Tyer's/FP	Hussey	N. Gage's	Dyer's	Middle Belham	Lower Belham	All
Jul 1995 – Feb 1999	8.2 +/- 3.7	-	13.6 +/- 4.0	-	-	-	22.0 +/- 7.9
Jul 1995 – Jan 2002	-	-	-	-	-	0.68 +/- 0.07	-
Jan 2002 – May 2003	-	-	-	-	-	0.06 +/- 0.01	-
May 2003 – May 2005	-	-	-	-	-	*-0.008 +/- 0.005*	-
May 2005 – Nov 2006	-	-	-	-	-	0.51 +/- 0.06	-
Nov 2006 – Nov 2007	-	-	-	-	0.83 +/- 0.07	0.3 +/- 0.2	-
Nov 2007 – Jun 2010	-	-	-	-	0.50 +/- 0.03	0.13 +/- 0.07	
Feb 1999 – Jun 2010	**2.2 +/- 1.5**	**-**	**4.7 +/- 2.1**	**1.6 +/- 0.6**	**2.1 +/- 0.7**	**1.1 +/- 0.7**	**12.0 +/- 5.7**
Jun 2010 – Mar 2011	-	-	-	-	0.06 +/- 0.05	*0.53 +/- 0.05*	-
Mar 2011 – Mar 2012	-	-	-	-	*-0.02 +/- 0.03*	*-0.10 +/- 0.03*	-
Mar 2012 – Mar 2013	-	-	-	-	*-0.02 +/- 0.03*	*-0.02 +/- 0.01*	-
Mar 2013 – Mar 2019	-	-	-	-	*-0.28 +/- 0.01*	*-0.62 +/- 0.03*	-
Jun 2010 – Mar 2019	***-0.3 +/- 0.2***	***-0.16 +/- 0.08***	***-0.12 +/- 0.06***	***-0.6 +/- 0.2***	***-0.2 +/- 0.1***	***-0.6 +/- 0.3***	***-2.0 +/ -0.9***
Jul 1995 – Mar 2019	**10.6 +/- 2.7**	**-**	**9.5 +/- 3.1**	**1.0 +/- 0.5**	**1.8 +/- 0.9**	**0.3 +/- 0.2**	**23.3 +/- 7.4**

Table 2.5: Tabulated net deposition/erosion derived from Geomorphic Change Detection for each reach over survey periods. Units are $x10^6 m^3$. +/- values are GCD-propagated error from DSM errors. Bold indicates measures of net change from volcano-wide DSMs. Italic and grey highlight indicates erosion. '-' indicates no data, 'FP' = Farrell's Plain. Note: the DEMs from 2002, 2003 and 2005 were channel-limited (see Table 2.2) and are thus indicative only of local changes.

2.3.1.2 Vegetation

Figure 2.17 presents the available data pertaining to the evolution of vegetation cover throughout the study period. Figure 2.18 presents NDVI maps from which many of these data points are derived. The changes shown here may be due to a combination of seasonal and volcanic influences. The expected seasonal variation is not known, depends on water supply and vegetation type, and it has not been possible to measure this in this case. Anecdotally, the mesic vegetation at lower altitudes flourishes during the rainy seasons due to ample water supply and dries during the dry season; this may lead to variation in plant health and canopy cover (e.g., Neeti et al., 2011). However, the sparseness of data precludes the quantification of seasonal patterns.

Prior to eruption, the upper catchment was fully forested (Froude, 2015). Pronounced reductions in vegetation cover are apparent in: February 1999, the first observation following the start of the eruption; July 2003 driven by widespread and significant tephra fall (up to 15 cm in Old Towne) following a major dome collapse (Herd et al., 2005, Edmonds et al., 2005, Figure 2.11); March – May 2006 following several months of hydrogen chloride emissions being blown north-westwards by unusual wind direction, and tephra fall associated with a dome collapse on 20th May (Alexander et al., 2010; not shown in Figure 2.14); 2007 following the extensive northwest-directed explosion-derived PDC on 8th January (de Angelis et al., 2007); 2010 following the large partial dome collapse of 11th February (Stinton et al., 2014). Revegetation rate has varied spatially over the catchment. The thickest deposits, where complete removal or burial of vegetation has been observed, and those frequently disturbed by lahar activity, have remained bare to the present day. Distal areas impacted by relatively minor damage (e.g., defoliation) have recovered rapidly, often within a year, as is evident between 2003-2004, May-August 2006 (shown in Figure 2.17), 2007-2008, and 2010-2011. Appendix 1.3 shows the evolution of vegetation cover in the Lower and Middle Belham between April 2011 and November 2020. By October 2020, much of the Middle Belham was revegetated (Figure 2.18) aside from narrow (~6m) single threaded – anastomosing channel.

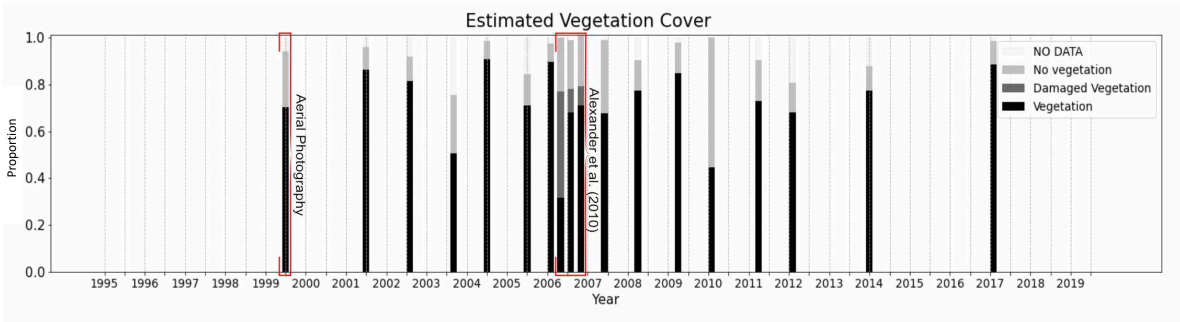


Figure 2.17: Estimated vegetation cover for study period. Non-NDVI sources are shown and indicated by red brackets.

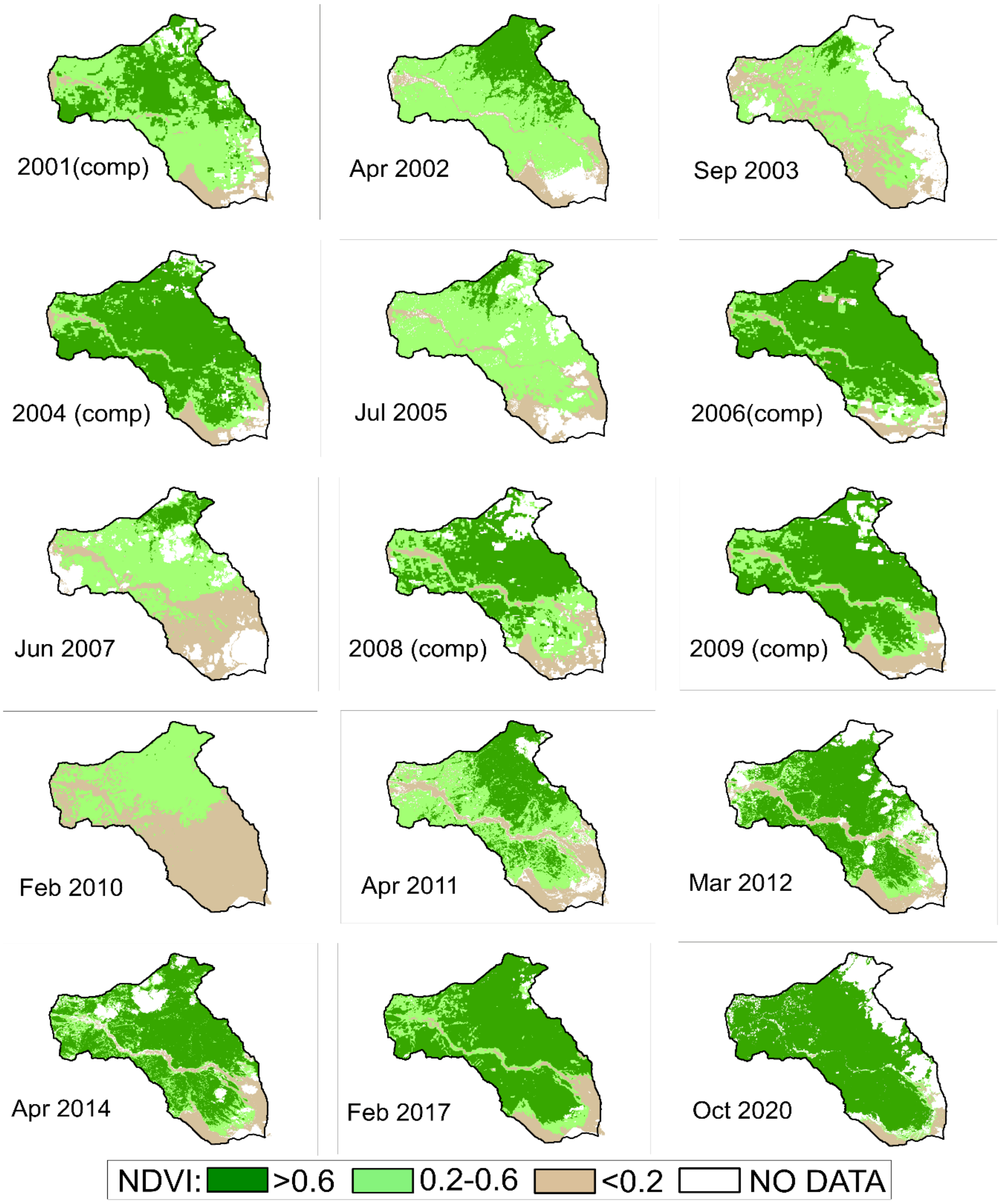


Figure 2.18: Maps of vegetation coverage in the Belham Catchment between 2001-2020, derived from NDVI analysis. Comp = Composite. Data sources: ASTER (NASA), LandSat (USGS), RapidEye and PlanetScope (Planet)

2.3.1.3 Rainfall

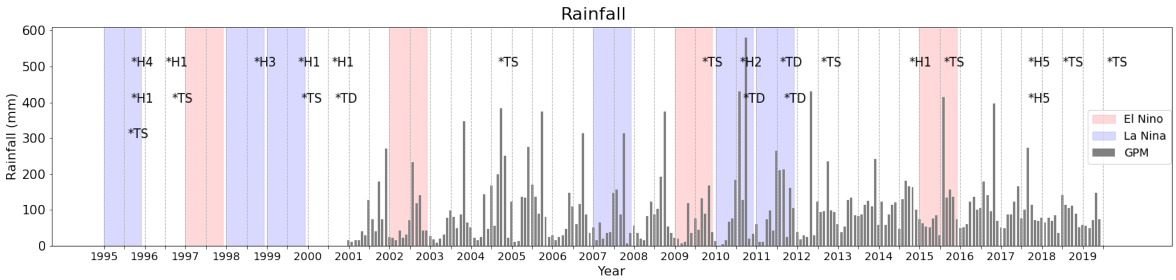
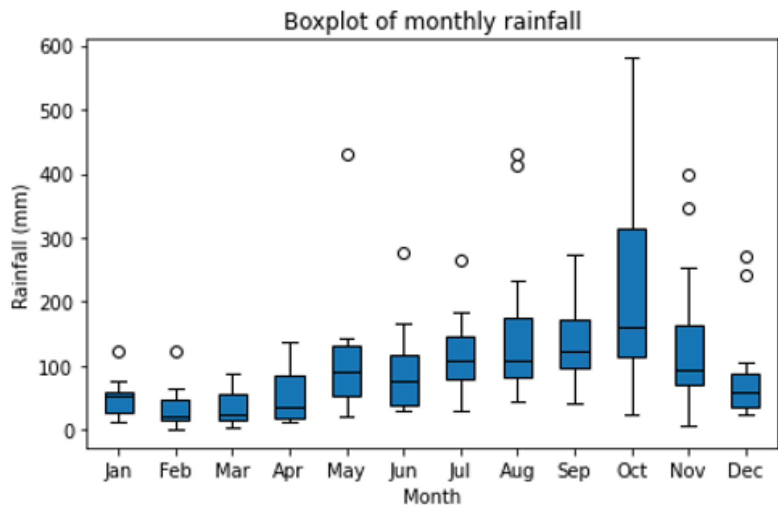


Figure 2.19: Monthly rainfall estimates acquired from IMERG. Also shown are instances and categories of named storms, and phases of ENSO.

Figure 2.19 presents monthly rainfall estimates over the catchment (see also Figure 2.6), ENSO phases, and the passage of named storms. This is supplemented by Figure 2.20, which shows the monthly variance of rainfall, and Table 2.6 (overleaf) which shows the association between ENSO and named storms and annual rainfall delivery using data available from GPM. The seasonality and interannual variability of rainfall is evident in both Figures 2.19 and 2.20. The mean annual rainfall is 1200 mm, which is consistent findings of other studies (e.g., Matthews et al., 2002; Barclay et al., 2007; Hemmings et al., 2015); the minimum was 764 mm in 2009, and the maximum was 1570 mm in 2005. Figure 2.20 demonstrates the variability between the dry (December – April) and wet seasons (June – November). October is on average the wettest month, with a mean rainfall of 214.9 mm; in October 2010, 580.6 mm of rain was recorded, almost half the annual mean. February appears to be the driest, with a mean total of 33 mm, and in one instance only 1 mm was recorded by GPM.



Month	Mean	Max	Min
Jan	49.1	122.3	13.4
Feb	33.0	122.5	1.0
Mar	34.3	88.6	4.4
Apr	54.2	135.8	11.1
May	107.1	430.5	21.6
Jun	86.4	276.6	29.1
Jul	117.3	263.6	28.9
Aug	150.4	429.5	44.6
Sep	134.2	274.6	41.0
Oct	214.9	580.6	24.4
Nov	131.4	397.9	7.1
Dec	78.5	272.1	23.1

Figure 2.20: Variability of monthly rainfall estimates acquired from GPM.

ENSO	Frequency	No. Named Storms	Mean Storms/year	Mean Annual Precipitation (mm)
El Niño	4	2	0.5	974.7 (n=3)
La Niña	6	10	1.7	1270.1 (n=3)
Neutral	14	11	0.8	1205.9 (n=13)

Table 2.6: Statistics related to ENSO phases, associated occurrence of named storms and mean annual rainfall, 1995 – 2019. Note that mean annual rainfall estimates are only available for 2001-2019.

Table 2.6 shows that, compared to years of ENSO neutrality, the passage of a named Tropical Cyclone was ~40% less likely, and more than twice as likely, in El Niño and La Niña years, respectively. This means that the passage of a named storm within 50 km of Montserrat is three times as likely in La Niña phases compared with El Niño phases. Note that this is a very small sample size, so it is difficult to draw conclusions. Despite this apparent difference in tropical cyclone activity, La Niña appears to be associated with only a minor increase of mean annual rainfall; Table demonstrates an associated increase of just 5%. Conversely, the potential influence of El Niño is more apparent; El Niño years are associated with a ~25% reduction in mean annual rainfall. This has potentially important implications in terms of the occurrence of high intensity and long duration water supply events in Montserrat. The apparent influence of ENSO on the occurrence of Tropical Cyclones and rainfall delivery has potentially important implications for timing of high intensity and long-duration precipitation events in Montserrat and the subsequent initiation of sediment transport events. Rainfall and its relation to specific lahar incidence is explored in more detail in Chapter 3.

2.3.2 Lahars and channel evolution in the Middle and Lower Belham Valley:

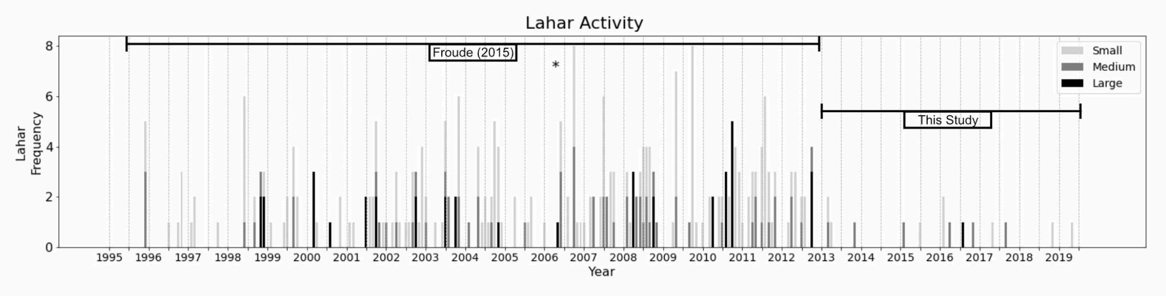


Figure 2.21: Monthly lahar activity frequency and magnitude of lahars. The asterisk marks the significant lahar in May 2006. Horizontal bars show the time period of the lahar record produced by Froude 2015 and the supplementation by this study.

Lahars have been a common feature over the period of study; Figure 2.21 shows the monthly frequency of lahars and their approximate magnitude (small, medium or large). In all, 298 have been recorded with high confidence; this is inevitably an underestimate owing to underreporting and lack of confidence in observations (Barclay et al., 2007, Darnell 2010, Froude, 2015). Lahar activity is strongly seasonal (DJF, n=31; MAM, n=64; JJA, n=86; SON, n=117), which is a function of seasonal rainfall patterns and may also be suggestive of an influence of antecedent rainfall. Chapter 3 explores the conditions controlling the incidence of individual lahars in more depth.

The Belham River Valley is ephemeral, so lahars are the only means of sediment transport. They have driven progressive geomorphic modification of the Middle and Lower Belham. In general, the valley has undergone net aggradation with associated coastal progradation. This net aggradational pattern is shown by Figures 2.22, 2.23 and 2.24, 2.25, Table 2.5, and supplemented by additional evidence Appendix 1.2. Key periods of net aggradation, typically characterised by increases in bed elevation, infilling of sub-channels, bed surface fining, and coastal progradation (see Appendix 1.2 for more details of evolving channel characteristics), have occurred between 1997- 1999, 2002-2004, August 2006 – December 2006, January 2007 – 2011. This aggradational pattern has been punctuated by periods of relative stability or minor degradation in 1999-2002 (punctuated by two transient aggradation events in 2000 and 2001; Carn et al., 2000, Barclay et al., 2007), late 2004 - early 2006, one significant acute 1-2 day degradation event in May 2006 caused by an extreme lahar (marked by asterisk on Figure 2.21; Alexander et al., 2010), and 2012 onwards (Figure 2.23). These periods have typically been characterised by localised scour, the establishment of incised single-threaded channels, terracing, bed surface coarsening, a decrease in bed surface elevation, reestablishment of riparian vegetation, and at times, coastal retrogradation (Figures 2.22, 2.23, 2.24, 2.25, and Appendix 1.2 and 1.3).

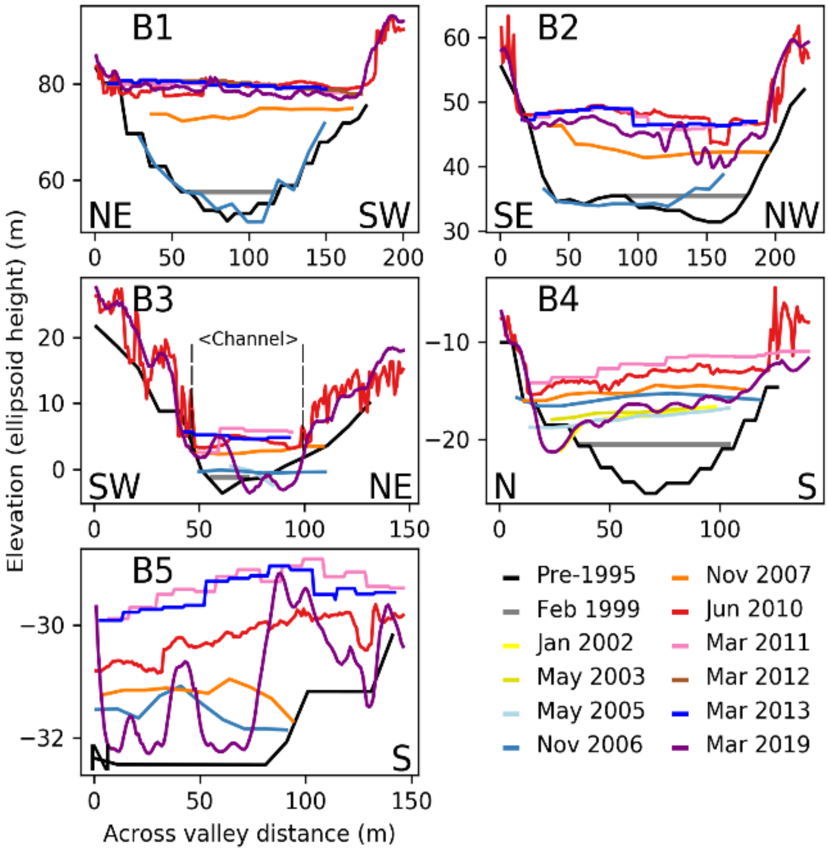


Figure 2.22: Valley cross section profiles at transects B1-5 over the study period. Note that sand extraction has occurred between 2013 and 2019 around transects B3-5. This activity had not reached B2 by March 2019; B1 and B2 reflect changes solely driven by fluvial activity.

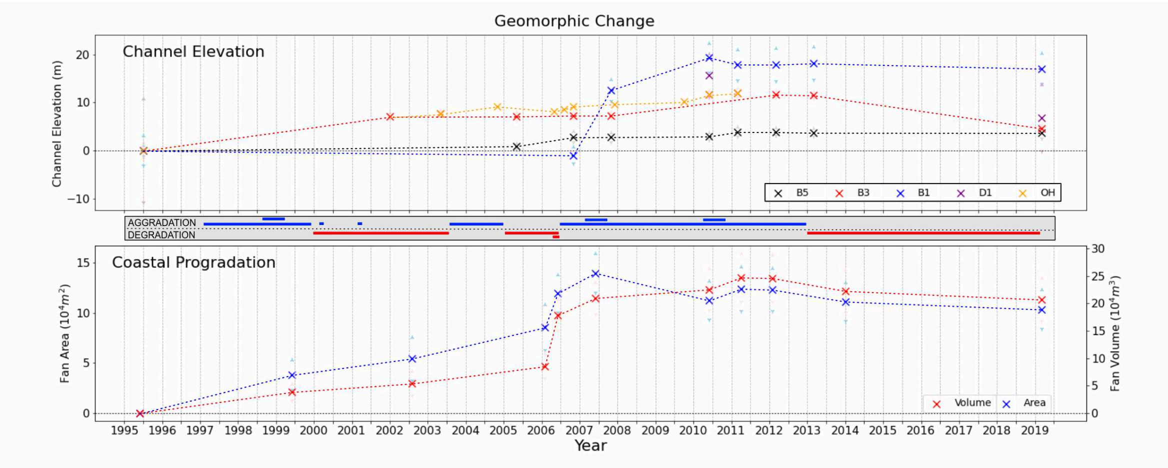


Figure 2.23: a) Channel elevation change relative to pre-eruption channel bed at selected cross sections/points of interest. Below this, the grey box shows periods of aggradation and degradation as inferred from additional evidence in Appendix 1.2. Note that aggradation and degradation are not necessarily equal in magnitude. Double lines indicate high magnitude changes.; b) Coastal progradation presented as the estimated area and volume of the fan through the study period. Dotted lines on both plots are intended to guide the eye and demonstrate the relative position of points to show trends in changes.

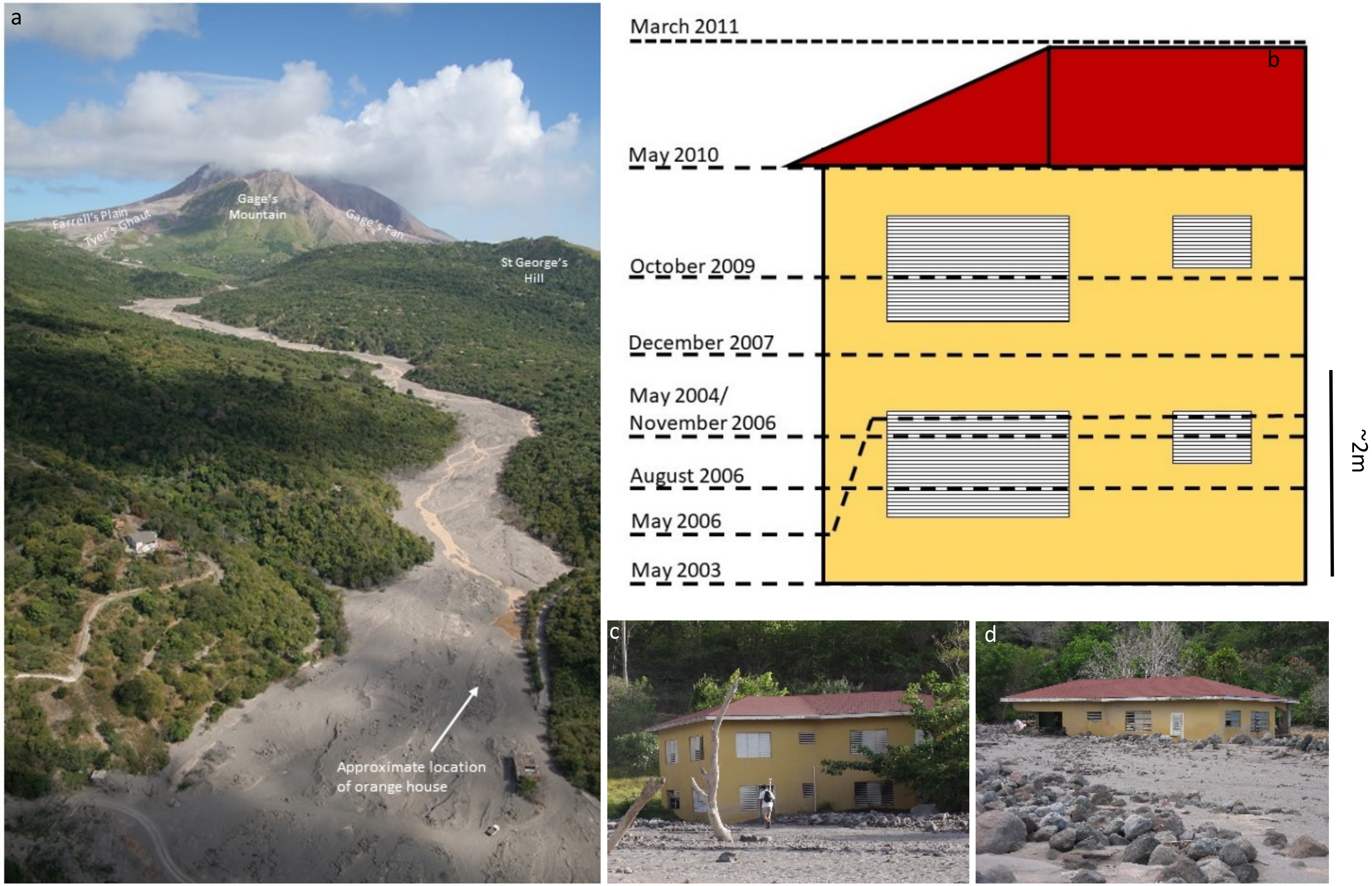


Figure 2.24: a) Looking upstream from above the Belham Bridge along the Belham River Valley towards the Soufriere Hills Volcano in April 2011. Arrow shows the approximate location of the now-buried Orange House. b) Schematic demonstrating the progressive burial of the Orange House throughout the study period. Dotted lines show the level of burial by sediment as shown by photographs taken on the respective dates. c) The Orange House in May 2003. d) The Orange House in December 2007, image captured from slightly downstream from C. Photo evidence used to generate this schematic can be found in Appendix 1.1.

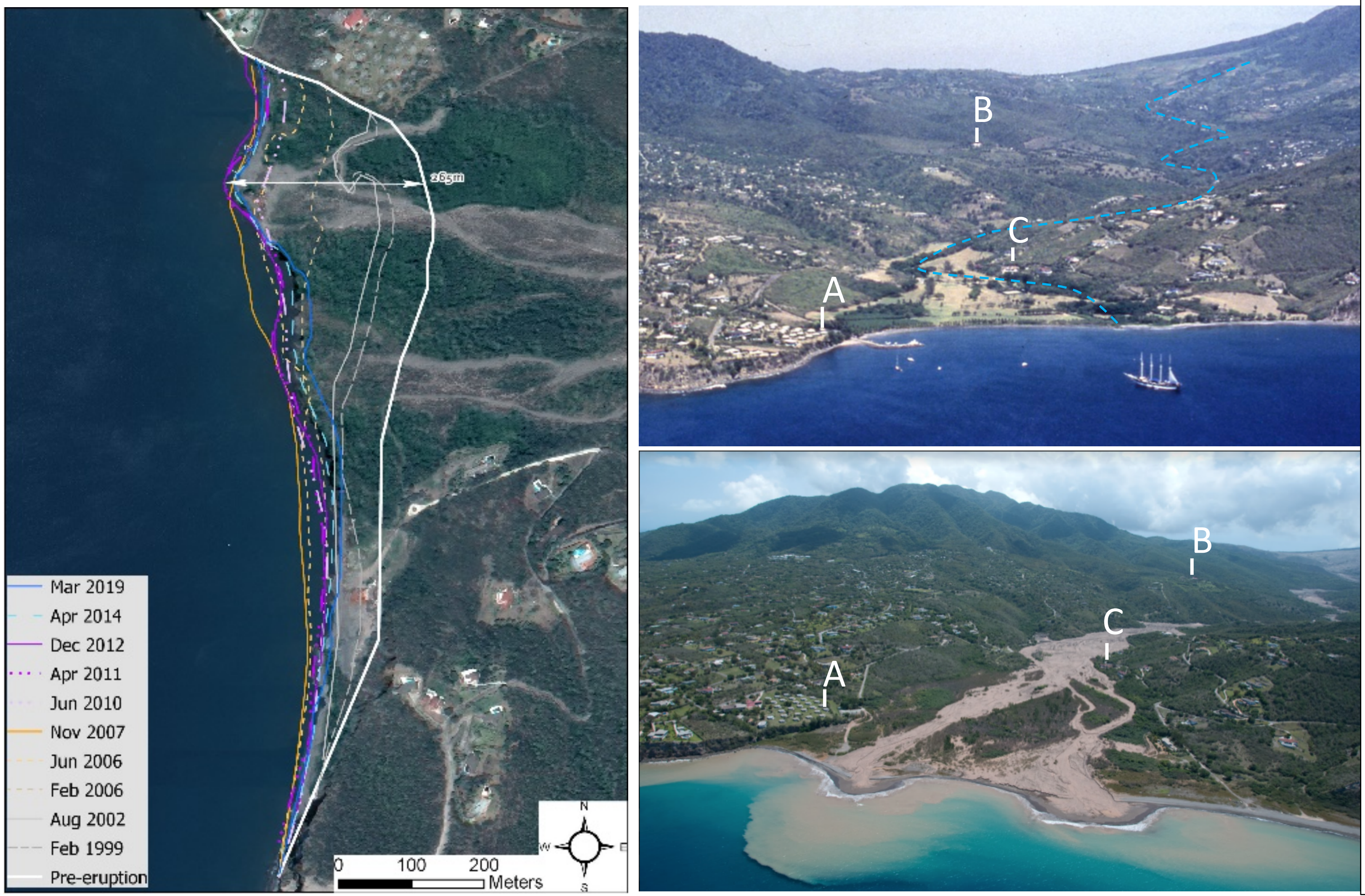


Figure 2.25: a) Annotated Satellite image demonstrating the development and evolution of the Belham Coastal Fan. Lines are coloured according to temporal windows: White/Greys = Phase 1-2 progradation (1992-Aug 2002); Yellows Phase 3 progradation (Feb 2006 – Nov 2007); Purples = post-Phase 5 progradation (Jun 2010 – Dec 2012); Blues = post-2012 retrogradation (Apr 2014 – Mar2019). The two-headed arrow indicates the maximum progradation distance of 265m, at the outlet of the northern channel, measured in December 2012; b) aerial photo of the mouth of the Belham River taken in April 1995. The blue line marks the approximate location of the pre-eruption Belham River channel. A, B and C identify three landmarks. Photo credit David Watters.; c) aerial photo of the mouth of the Belham River in 2010. Credit: Henry Odbert/MVO. A, B and C identify the same 3 landmarks as in Figure 2.17b to assist orientation.

In general, switches between aggradation/degradation patterns are most evident between cross sections B1- B4, where the geomorphic characteristics of the valley are similar. Downstream of B4, the valley widens significantly which promotes flow spreading and deposition. Accordingly, observations at B5 and at the coast (Figures 2.22, 2.23, 2.24 and 2.25) are dominated by aggradation/progradation, including when the channel upstream of B4 has undergone degradation. Exceptions to this include early 2002 (Appendix 1.2, e.g., Barclay et al., 2007) and 2012 onwards (Figures 2.23 and 2.25), when coastal retrogradation has been observed, likely due to reduced sediment supply from upstream. Interestingly, between 2007-2010, slight retrogradation (approx. 30 m) is observed (Figures 2.23 and 2.25a) despite an abundance of sediment supply and lahar activity (Figures 2.11 and 2.21).

Observed geomorphic changes have occurred both gradually, resulting from cumulative action by numerous small-moderate lahars, and rapidly due to the action of large lahars or direct input from rare long-runout PDCs (e.g., June 1997, January 2007, January 2010). The most dramatic changes have been attributed to the largest lahars, some of which (May 2006 and inferred in April and August/September 2010) are known to have had stream power sufficient to transport boulders with diameters exceeding 2 m (Susnik 2008, Alexander et al., 2010, Froude, 2015). The most notable large and geomorphically significant lahars have been recorded during the 1998 rainy season (Froude, 2015), March 2000 (Carn et al., 2000), July 2001 (Barclay et al., 2007), July 2003 (Herd et al., 2005), May 2006 (Alexander et al., 2010), the 2008 rainy season (Froude, 2015), and April and August/September 2010 (Froude, 2015). All of these events, with the exception of May 2006 (Alexander et al., 2010), have been associated with aggradation of the Belham Valley floor. Cumulative action by small to moderate lahars has contributed to both net aggradational/degradational changes (see also Barclay et al., 2007, Froude, 2015).

Concurrent with observations of the upper catchment, geomorphic change in the Middle and Lower Belham have been relatively limited since 2013. Lahar activity has dramatically reduced during this period (Figure 2.20) which has allowed extensive revegetation over the valley floor, particularly in the Middle Belham onwards. The reduction in frequency and magnitude of flow in this reach of the valley had allowed revegetation and restriction of the main channel, reducing its width to ~6m by October 2020. This is shown in Appendix 1.3, greyscale NDVI images of the Middle Belham over the period April 2011 – October 2020. Sand mining has become a major economic activity in the Belham Valley owing to the value of volcanic aggregates for the manufacture of building materials. The Lower Belham River Valley has been extensively mined since 2010; by March 2019 mining activities had extracted an estimated 6.4 $x10^5m^3$ (Figures 2.12 and 2.13, Table 2.5). In November 2020, an anomalously large rainfall event triggered the most significant sediment transport event since 2012. This lahar was boulder-laden, overwhelmed the narrow channel in the Middle Belham, destroyed and burying vegetation, infilled mining pits by up to 2 m, damaging mining equipment in the process, and reached the sea (Figure 2.26, Appendix 1.3). A helicopter survey in March 2022 revealed that this deposit is now widely revegetated in the Middle Belham (see video file *'03_2020_All.mov'* in Appendix 1.1).

Figure 2.26: Photos of the Belham River Valley captured in mid-November 2020 a) looking upstream from B1, where previously the valley floor was vegetated with a single 6 m channel; St George's Hill is visible in the distance. Credit: Pascal, K. b) an excavator in a mining pit downstream of B2, buried to a depth of up to 2 m. Credit: Pascal, K.

2.3.3 Variable sediment yield from the upper catchment

By combining observations of erosion in source deposits and deposition in the Middle/Lower Belham I am able to produce minimum estimates of specific sediment yields (x10^3 $m^3km^{-2}year^{-1}$) from the Upper Catchment (6.4km^2) for a number of windows of time throughout the study period (Figure 2.10f). Table 2.6 presents my estimates and the methods used to derive them. Specific sediment yields have varied by 2 orders of magnitude over the study period, reaching a peak of approximately 300 x10^3 $m^3km^{-2}yr^{-1}$ in 1998, with three lower-magnitude peaks of around 180 – 195 x10^3 $m^3km^{-2}yr^{-1}$ observed for the periods July 2003 – June 2005, November 2006 – November 2007, and April 2010 – April 2011. Note that between July 2003 and June 2005 the system had switched to a sediment depleted state (degradation observed, Figure 2.10g, Figure 2.15, Table 2.5, Appendix 1.2), and lahars were limited in 2005 (Figure 2.10e). Thus, most of this sediment yield will have occurred in late 2003 and into 2004. Specific sediment yield is time sensitive – it represents yield per unit area per unit time - so my estimate of specific sediment yield here will underestimate the true magnitude. Between these periods of heightened yield,

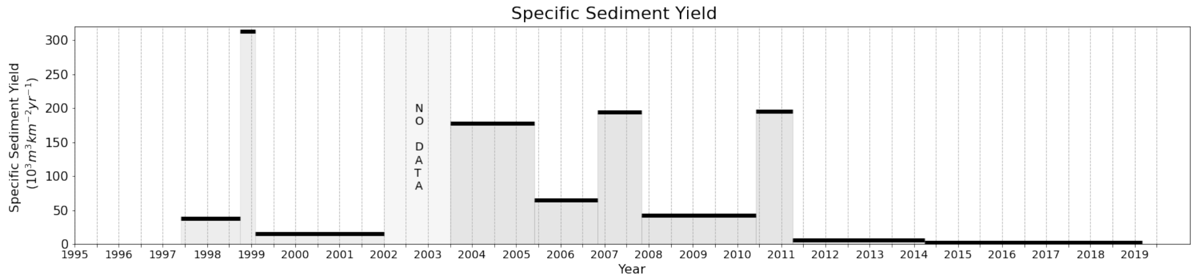


Figure 2.27: Estimated specific sediment yield variation throughout the study period

specific sediment yields fell by more than 60%. The specific sediment yield for the period April 2014 – March 2019 (1.9 x10^3 $m^3km^{-2}yr^{-1}$) is two orders of magnitude lower than that of April 2010 – April 2011 (195 x10^3 $m^3km^{-2}yr^{-1}$). I have made these calculations for only the Upper Catchment as the available data relates to sediment either being removed from the Upper Catchment by erosion (i.e., derived from estimates of erosion in Tyer's Ghaut, performed by Froude, 2015 or via DSM analysis) or being deposited in the Middle and Lower catchment (DSM analysis, aerial photographs). These are necessarily minimum estimates owing to limitations of measurement (e.g., erosion estimates are only available from Tyer's Ghaut) and I am unable to account for significant offshore deposition. It is important to also note that the DSM measurements for between November 2006 - November 2007, and November 2007 – June 2010 include deposition from long-runout PDCs in January 2007 (de Angelis et al., 2010) and February 2010 (Stinton et al., 2014). Thus, these surveys capture a combination of deposition by PDC and lahars and therefore do not represent yield exclusively driven by lahars; this cannot be rectified.

Date range	Estimated Yield ($x10^6 m^3$)	Yield Uncertainty ($x10^6$ m^3)	Estimated Specific Sediment Yield ($x10^3$ $m^3 km^{-2} yr^{-1}$)	Method
Jun97 - Feb99	1.20	0.6	78.1	Deposition: Aerial photographs of mid/low Belham vs pre-eruption DSM
Oct98 - Feb99	0.84	0.03	313.5	Erosion: Tyer's Ghaut erosion from aerial photographs (Froude, 2015)
Feb99 - Jan02	0.29	0.03	15.2	Erosion: Tyer's Ghaut erosion from aerial photographs (Froude, 2015)
Jan02 – Jul03	-	-	-	No data: Tyer's Ghaut was infilling
Jul03 - Jun05	2.28	0.03	178.1	Erosion: Tyer's Ghaut erosion from aerial photographs (Froude, 2015)
Jun05 - Nov06	0.58	0.03	64.2	Erosion: Tyer's Ghaut erosion from aerial photographs (Froude, 2015)
Nov06 - Nov07	1.24	0.32	194.7	Deposition: Middle and lower Belham DSM difference
Nov07 - Jun10	0.67	0.16	41.9	Deposition: Middle and lower Belham DSM difference
Apr10 - Apr11	1.04	0.52	195.8	Erosion: DSM differencing and satellite imagery
Apr11 - Apr14	0.10	0.05	5.4	Erosion: DSM differencing and satellite imagery
Apr14 - Mar19	0.06	0.03	1.9	Erosion: DSM differencing and satellite imagery
Jun97 – Mar19	**7.46**	**-**	**108.9**	**Total and average over study period**

Table 2.7: Estimated Net Yield and Specific Sediment Yield for the Upper Belham Catchment for windows of time over the study period

2.4 Discussion

Gran and Montgomery (2005) present a conceptual model (Figure 1.1) for fluvial recovery in response to disturbance by transient large-magnitude volcanic eruptions. This describes how dramatically heightened sediment supply is accompanied by commensurately high sediment yields and major channel aggradation and widening downstream. This initial period of high sediment flux is followed by a rapid decline in sediment yield, which then leads to a decline in the rate of aggradation and the establishment of a longer-lived and lower-magnitude degrading regime in lower reaches. Through this discussion I seek to examine how the recovery pathway in the Belham River Valley in response to episodic eruption shares similarities with, or differs from, this model. I first develop a conceptual model for the disturbance response of the BRV, before going on to discuss the implications this model has for lahar hazard. I then situate the recovery of the BRV within a global context, comparing it to recovery pathways of fluvial systems disturbed by other types of eruption.

2.4.1 A conceptual model for the response of the Belham River Valley to episodic disturbance

The first emission of PDCs to the North and the West of SHV in 1997 constituted a considerable perturbation to the pre-eruption dynamics of the Belham River Valley. Within a matter of months (June to October 1997) large quantities of pyroclastic sediment (~22 x$10^6$$m^3$) had been deposited into the Upper Catchment, vegetation was damaged or removed, and 2.7km^2 had been added to the catchment area due to topographic changes. To begin, expansion of catchments increases the surface area onto which rain falls, which enhances runoff generation, thereby increasing the maximum potential discharge at a catchment outlet. Matthai (1990) present an empirical relationship between catchment size and maximum potential discharge of catchments smaller of area <$10^6$$km^2$:

$$logQ_{flood} = -0.07(logA)^{2} + 0.865logA + 2.084$$

(Equation 1.1)

Where Q_{flood} is the maximum potential flood discharge (m^3s^{-1}) and A is the catchment area (km^2). Applying this relation to the different sizes of the Belham catchment over the study period (1995 = 12.6km^2, 1999 = 15.4km^2), I estimate that the maximum potential discharge increased from 895

m^3s^{-1} before the onset of eruption, to 1030 m^3s^{-1} in 1999: an increase of 15%. This is only an indicative calculation to show potential relative increase, as discharge is controlled by a wide variety of factors (i.e., additional runoff controls, e.g., vegetation cover, deposit surface sediment grain size distribution). Nonetheless, increased discharge potential has important implications for both lahar hazard and sediment transport, both of which are likely to have been enhanced as a result.

This increase in catchment size and subsequent increased discharge potential has then been superposed by varying sediment supply and vegetation cover, driven by episodic volcanic activity, all occurring within the context of varying water supply, driven by climatic variability. In response, the Belham Valley has exhibited significantly increased sediment and water flux, and a complex pattern of subsequent geomorphic change, resulting in intermittent net aggradation, valley widening, and coastal progradation (shown in Figures 2.22 through 2.25). To make sense of the drivers of these changes, here I develop a conceptual model that relates the catchment conditions with the observed lahar activity and channel evolution, using my synthesised datasets. Figure 2.28 presents a schematic of this conceptual model which brings together the influence of what I will identify here as the three main controlling variables: sediment supply, water supply, and vegetation cover.

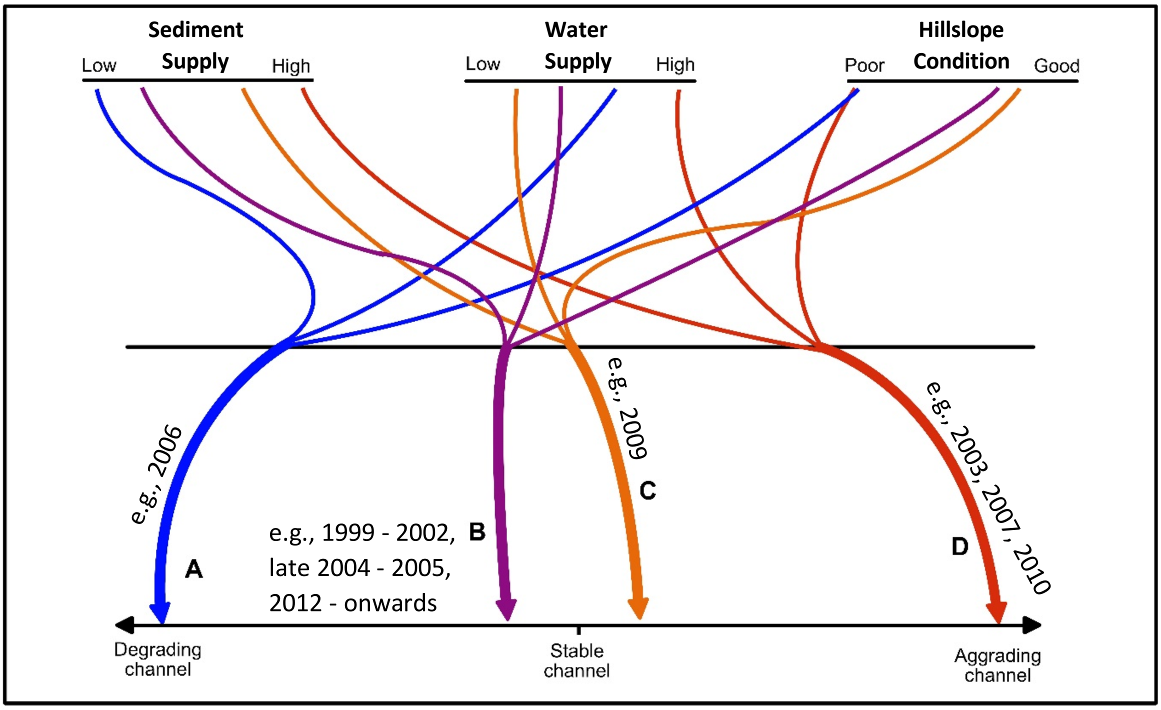


Figure 2.28: Conceptual model of channel change regimes as determined by the states of sediment supply, water supply and hillslope condition.

It helps to first understand the conditions that typically lead to high sedimentation and aggradation in lower reaches before exploring exceptions to these cases. High rates of aggradation were observed in 1998, 2003-4, 2007-8, and 2010. These periods (except 1998, discussed further below) immediately followed volcanic disturbance and the conditions in the upper catchment were primed for the generation of high-magnitude sediment-transporting flows by 1) ample fresh pyroclastic material, 2) ample rainfall during wet seasons (1998, 2007 and 2010 were La Niña years), and 3) recently reduced vegetation cover caused by preceding volcanic activity (see Figures 2.17 and 2.18). Consequently, during high-magnitude rainfall events, large sediment-rich flows were generated with ease, leading to the downstream transportation and deposition of large quantities of sediment, including large (>2 m) boulders (Alexander et al., 2010; Froude, 2015). In Figure 2.27 I have shown that specific sediment yields have risen by 2 orders of magnitude from the inferred near-zero pre-eruption yield in these periods (Susnik 2008; Froude, 2015). These high yields from the Upper Catchment overwhelmed any recipient channels downstream, driving avulsion and major aggradation (Figures 2.22 through 2.25). These patterns are consistent with observations of immediate post-disturbance responses that informed the Gran and Montgomery (2005) model, as described in Chapter 1, and are represented by Line D in Figure 2.28.

By contrast, 1997 and 2009, both of which immediately follow disturbance, did not exhibit significant aggradation. In both cases, deposition (Figures 2.11, 2.15 and 2.16) had occurred prior to or during the rainy season; in 1997 deposition was particularly significant (22 $x10^6$ m^3) and vegetation had been drastically reduced by the initiation of disturbance to the previously forested Upper Catchment. However, only limited downstream responses followed. Both years were El Niño years; 2009 was the driest during the study period, and conjecturally, in 1997 some rainfall may have been absorbed the newly formed Farrell's Plain/Gage's Fan fan as ground water adjusted. In these cases, I propose that the system was primed by pyroclastic deposition, however the lack of water supply drove a comparatively limited or negligible aggradational response (Line C in Figure 2.28). As such, sediment yields remained relatively low; most deposited material remained in storage in the upper catchment until subsequent rainfall was sufficient to remobilise the material in following years. It is this storage of sediment in 1997 that enabled the high sediment yield and acute aggradation observed during 1998.

According to the Gran and Montgomery (2005) model, sediment yield rapidly declines as the landscape recovers after the initial response to disturbance (sediment removed, rill/gully/channel stabilisation, vegetation recovery). As upstream sediment supply declines, flows transition from a transport-limited state (i.e., flows are at sediment transport capacity when reaching lower reaches) to a supply-limited state (i.e., flows are not at sediment transport capacity) (Pierson and Major, 2014). Runoff is also reduced by vegetation regrowth and changes to deposit hydrology (i.e., removal of fines) which reduces the magnitude of these flows. Thus, subsequent flows are smaller and capable of lower-magnitude geomorphic work, but their progressively supply-limited state promotes downstream erosion. This first leads to waning aggradation downstream, which may transition into a prolonged state of relative stability or low-magnitude degradation. The smaller size of flows tends to encourage localised scour and the establishment of narrow single-threaded channels that become incised into the channel bed downstream, flanked by terraces of pre-existing deposits; these changes encourage the establishment of riparian vegetation as portions of the valley floor are abandoned. Note that this is a generalised pattern of evolution; Major et al. (2021) demonstrate that channel adjustment can be much more complex than simple degradation and may involve a range of geometric changes to the channel cross-sectional area.

As expected, these degrading conditions have been observed in the Belham Valley in periods of reduced sediment yield, in pauses in sediment supply, and following initial high yields and aggradational responses to disturbance; for example, 1999 – 2002 (with exceptions, discussed below), late 2004 – May 2006, and 2012 onwards (Figure 2.11, 2.16, 2,22, 2.27, Table 2.5, and Appendix 1.2). By October 2020 readjustment was so advanced it had allowed establishment of vegetation over most of the valley floor of the Middle Belham (Figure 2.18, Appendix 1.3) which surrounded a narrow (6 m) single-threaded channel indicating highly restricted flow. These patterns are represented by Line B in Figure 2.28. The rate and degree of degradation within the Belham River Valley is low compared to other systems and likely reduced by the ephemeral nature of flow here. Elsewhere, systems with permanent stream flow have a constant background rate of erosion from source deposits and downstream channels (Gran et al., 2011; Pierson et al., 2013; Major et al., 2020); in ephemeral systems, this background rate is closer to zero, thereby slowing the recovery of the system to a new post-eruption equilibrium state.

The findings above are all consistent with the Gran and Montgomery (2005) model insofar as each phase of sediment supply appears to have initiated its own disturbance-recovery cycle. However, these patterns of hillslope and channel recovery in the Belham Valley are complicated by extreme events. For instance, by 2000/2001 sediment input had been negligible since 1998 as the dome grew away from the catchment (Wadge et al., 2014) and sediment yields had declined; evidence suggests that downstream the system had adopted a stable to degrading regime over this time (Figure 2.10g, Appendix 1.2, Froude, 2015). However, in March 2000 and July 2001 (Carn et al., 2004; Barclay et al., 2007; Alexander et al., 2010), two large syn-eruptive lahars occurred simultaneously with dome collapses that were coincident with heavy rainfall (there is evidence to suggest rainfall triggering of dome collapses at Soufrière Hills; Matthews et al., 2002, 2009); these were associated with aggradation in the Lower Belham Valley (Figure 2.23, Appendix 1.2). These lahars were supplied with sediment directly by tephra fall and are likely to have enabled the transport of pyroclastic material not yet remobilised within the Upper Catchment, as a consequence of the larger fraction of suspended fallout-supplied sand which is known to enhance the erosive capacity of flows (Carn et al., 2004; Alexander et al., 2010). The increased magnitude and sediment content of these extreme events thus drove the observed and somewhat unexpected and seemingly out-of-place episodes of acute aggradation within the background context of a stable-degrading regime (Figure 2.23).

May and the latter half of 2006 present another extreme exception. This period has been studied in detail by Susnik (2009) and Alexander et al. (2010). By this time, there had been no major deposition by PDCs into the Upper Catchment since July 2003 (Figure 2.11) and much of the available sediment had been depleted over the intervening period (Figures 2.15 and 2.16, Appendix 1.2). However, a key difference between this time and others during the study period was the widespread damage to vegetation, shown in Figure 2.17 (not captured in Figure 2.18), caused by north-westward diversion of the volcanic gas plume by unusual wind direction over the previous two months (Alexander et al., 2010). Crucially, this vegetation damage occurred in the absence of sediment supply, so on 20th/21st May, a combination of 1) the widespread damage to vegetation, 2) depletion of sediment in the upper catchment, 3) heavy, though not extreme, rainfall, and 4) tephra fall from a coincident dome collapse, greatly enhanced the runoff magnitude, and thereby increased the transport capacity and erosive potential of the resulting flow as it entered the Middle Belham. This drove the acute erosion observed in the valley floor (Figures 2.22 through 2.25) and transported much of the material into the sea (Figures 2.10h and 2.17). This behaviour is represented by Line A in Figure 2.28. The rapid aggradation that followed this event (Figures 2.22 and 2.24) is surprising given the sediment-depleted state of the catchment at this time (Figures 2.11 and 2.16). The driver of this, and the source of this sediment, is uncertain given the degradation that preceded the May event. My findings here reinforce those of Alexander et al. (2010) in terms of how unusual the channel response in May 2006 was within the context of the whole eruptive period and this example clearly demonstrates the important role that vegetation cover plays in mediating channel dynamics.

The final exception is the lahar of November 2020. At this time, a decade had passed since the most recent disturbance (February 2010; Figure 2.11), vegetation on the hillslopes was well recovered (Figure 2.18), sediment yields had declined dramatically (Figure 2.27), and the valley floor had recovered sufficiently to allow the formation of a narrow (6 m) single threaded channel flanked by riparian vegetation (Appendix 1.3). In this event, extreme rainfall (as reported by MVO,

2020) generated flows high on the flanks of SHV, presumably with sufficient discharge to access and erode channel margins in the upper catchment, enabling sediment remobilisation and transport downstream (Appendix 1.3 shows the reactivation of channels in Hussey/Tyer's Ghauts and on North Gage's Fan). The narrow channel that had formed in the Middle Belham by October 2020 was overwhelmed and subsequently avulsed, effectively leading to a reset of the valley floor between D2 and B1; downstream of B2, quarrying pits were filled by up to 2 m of sediment (Figure 2.26). The infill of quarrying pits is likely in large part due to reorganisation of valley floor sediments (i.e., the collapse of steep upstream pit walls), rather than necessarily transport from upstream. In this case it was the extreme rainfall, rather than runoff mediating factors, that caused this event.

In summary, episodic eruption of SHV has induced a subsequently episodic fluvio-geomorphic response in the Belham River Valley. Each new phase of pyroclastic deposition in the Belham Valley has caused a re-disturbance to the headwaters of the fluvial system which then undergoes a repeat recovery phase. Each cycle has been characterised by high sediment yield induced by enhanced runoff caused by vegetation damage and the presence of fine-grained material, and the subsequent incision and establishment of channel networks in upstream deposits. High sediment yields have been accompanied by acute downstream aggradation, however, when water supply has been insufficient, this response has been curtailed and delayed. This has been followed by a transition to waning aggradation and lower-magnitude degradation, as upstream sediment has depleted and vegetation recovered. Each observed episode of disturbance-recovery is thus consistent with the conceptual recovery model presented by Gran and Montgomery (2005), but this setting differs in that disturbances are smaller scale and repeated. Importantly, however, extreme events, driven by influence from isolated, short-lived and transient volcanic events (e.g., tephra fall from dome collapses directed away from affected catchments), major changes to vegetation cover, or extreme rainfall, may temporarily modulate, disrupt or enhance these patterns. This analysis has thus shown that sediment supply, water supply, and vegetation cover are all important mediators of downstream channel change. I further posit that the extreme events driven by volcanic activity are an important and unique component of long-lived episodic eruptions compared to transient disturbances, such as those summarized in the Gran and Montgomery (2005) model.

Into the future, with continued quiescence or a total cessation of eruption, the Belham Valley system is likely to continue to recover towards a new post-eruption equilibrium (e.g., Gran and Montgomery 2005; Pierson et al., 2013). The pattern of channel form (narrow, single thread) and reestablishment of vegetation in the channel by October 2020, and March 2022 following the November 2020 lahar, hints towards a focussing of surface flow, which is likely to lead to further incision and quasi-stabilisation of a new primary channel in the valley floor (Gran et al., 2011; Gob et al., 2016). Evidence from the eruption of Mt Hood (Pierson et al., 2013) demonstrates that even after centuries, channels may not return to pre-eruption elevations, and that the time taken to reach a new equilibrium may be up to a century. This was for a river with permanent stream flow and thus a background rate of sediment transport. In the ephemeral BRV, with no sediment transfer between flows, this process could take some time given the similar degree of aggradation in the depositional reaches of these rivers (approx. 20 m). The sediment that remains in the Upper Catchment (~20 $x10^6$ m^3) will thus likely be kept in storage and contribute to continued edifice growth (Thouret, 1999). Sediment stored in channel walls may be remobilised during anomalously large flows triggered by extreme rainfall which fill and subsequently cause lateral erosion (e.g., Major, 2020); the event of November 2020 is evidence that this type of activity could be expected in the BRV. In the event of re-disturbance by renewed volcanic activity, there are a series of potential outcomes depending on the pattern of dome growth. Firstly, re-establishment of full-scale volcanic activity and dome growth to the north-west would induce replenishment of source deposits and re-damage recovered vegetation. In this case there is renewed potential for large lahars and renewed aggradation of the valley floor. This case may be likely owing to the northward-facing collapse scar left by the February 2010 partial dome collapse (Stinton et al., 2014) which, conjecturally, may contain and direct dome growth to the north. By contrast, if there is renewed volcanic activity, but this involves dome growth away from the catchment, it may be that the catchment is again disturbed by extreme events driven by transient dome collapse-derived tephra fall or vegetation damage by gas emissions and tephra alone. This increases the possibility for acute aggradational or degradational events, such as those observed in March 2000 and July 2001, and May 2006, respectively.

2.4.2 Implications for lahar hazard management

The findings of this work have implications for lahar hazard management in the BRV, particularly considering the possibility of renewed activity at SHV, in what would be a new episode of eruption. It may also be relevant more widely, in catchments affected by episodic eruptions at other volcanoes. I have shown that downstream channel modifications (e.g., aggradation/ degradation), and the drivers of these changes (be it gradual and cumulative changes by small-moderate lahars, or sudden changes by large or extreme lahars) are strongly dependent on the conditions prevalent in the upper catchment. Namely, sediment supply, water supply and vegetation cover. This work demonstrates the importance of regular (ideally sub-annually) and systematic catchment-scale monitoring for better anticipation of potentially hazardous downstream outcomes. The evidence presented above shows that lahar hazard is highest immediately post-disturbance when sediment and water are readily available, and there is an enhancing effect of reduced vegetation cover. In these instances, there is a risk of structures being buried and hazardous boulder transport is more probable. This is evident during 1998, 2003, 2007/8 and 2010 (Figures 2.21 and 2.26). However, I have also shown that significant lahar activity may not be guaranteed immediately following disturbance if water supply by rainfall is insufficient. In these cases (e.g., 1997 and 2009), sediment remains stored in upper reaches which extends the timescale over which there is potential for large and hazardous sediment-laden flows to be generated after sediment supply. With time (i.e., over 2-3 years), lahar hazard nonetheless declines rapidly owing to landscape recovery: flows are generally of smaller magnitude and therefore have a reduced discharge and footprint, thus the probability of structure burial and boulder transport is reduced (Alexander and Cooker, 2016). Importantly, however, my findings show that even when a fluvial system is a number of years into recovery and exhibiting limited lahar activity, extreme events driven by vegetation damage (e.g., 2006), dome-collapse tephra fall (e.g., 2000, 2001 and 2006) and extreme rainfall (e.g., 2020) can transiently increase lahar hazard. Crucially this work also shows that lahars remain a relevant hazard a decade after sediment supply ceases. With the dataset presented here, there is potential to work towards quantifying and simulating the evolution of lahar hazard with changing catchment conditions (see for example van Westen and Daag, 2005; Jones et al., 2017); this is the aim of Chapters 3 and 4 of this thesis.

2.4.3 Global context

The impacts of eruptive disturbance on the Belham River Valley share many characteristics with observations of other river basins disturbed by explosive volcanic eruptions. This analysis has captured:

- Sediment input resulting in topographic changes and drainage system reorganisation and stream capture such as those observed near to Mt St Helens and Mt Pinatubo (Gran et al., 2011; Major et al., 2019);
- Vegetation damage (in common with other volcanic disturbances to vegetated catchments; Pierson and Major, 2014; Major et al., 2016, 2019).
- Starkly elevated sediment yields, rising one to two orders of magnitude, in the immediate post-disturbance period (where rainfall permits), followed by rapid sediment yield

declines within one to two of years of disturbance (consistent with studies on small – moderate disturbances; Lavigne, 2004; Gob et al., 2016; Kataoka et al., 2018);

- Downstream channel responses of aggradation and widening, followed by degradation (in common with responses to transient eruptions; Pierson and Major, 2014).
- The valley floor has undergone significant net aggradation over a prolonged period (consistent with persistent eruptions; Thouret et al., 2014).

However, the key difference for the Belham River Valley is the episodic, stop-start sediment supply which makes the response of the BRV unique compared to responses to both transient and persistent eruptions. After initial aggradation, the channel has at times been able to enter into a degradation cycle after a sufficient amount of time in quiescence. Quiescence is often short lived, or has been disturbed by extreme events, so rather than fully recovering (as would result following transient disturbances), the system goes in and out of disturbance and recovery states, which drives the dynamic switching between aggradational and degradational behaviour observed in the channel. This type of dynamism is not observed in the same way in catchments affected by transient eruptions (Gob et al., 2016; Major et al., 2019), and not observed to the same degree with respect to persistent eruptions (Thouret et al., 2014). Therefore, I posit that episodic eruption induce a distinct pattern of fluvial recovery characterised by cycles of aggradation and degradation, effectively repetitive small transient disturbances, which may uniquely be punctuated and disrupted by extreme events. In Figure 2.29, I present a generalised schematic of hillslope sediment yields and downstream response for a spectrum of volcanic disturbances including:

- Large magnitude transient eruptions (Figure 2.29a, Line A), e.g., Pinatubo (Gran et al., 2011), Mt St Helens (Meadows, 2014; Major et al., 2019), Santa Maria (Kuenzi et al., 1979), characterised by deposition of very large quantities, i.e., in excess of 1 km^3, of sediment into catchment headwaters. Adjustment to this type of disturbance involves very rapid elevation of sediment yields, in some cases more than two orders of magnitude above background levels. This is associated with acute sedimentation in lower reaches of channels which aggrade and widen considerably. Sediment yields decline rapidly in the first 5-10 years but may remain elevated for decades. Sediment yield declines are associated with a reversal from aggradation towards gradual degradation as post-eruptive flows become supply-limited and erode the bed. Channel readjustment towards new equilibrium is prolonged and complex, and may persist beyond a century; elevated sediment yields may endure over this time.

  Small to moderate transient eruptions (Figure 2.29b, Lines B and C), e.g., Ontake (Kataoka et al., 2018), Merapi (VEI 4 eruption in 2010; Gob et al., 2016), Mt Hood (Pierson et al.,

2013) and Chaiten (Major et al., 2016), characterised by deposition of <1 km^3 of sediment into headwaters. Like with larger magnitude disturbances, initial response is acute but elevated sediment yields are relatively short lived due to limited supply. Small eruptions may only induce several months of elevated yields. Downstream responses include the same aggradation and widening of channels, followed by gradual switch to a prolonged degradational regime. Again, due to limited sediment supply, the magnitude of these changes is relatively limited; local geomorphology and climatology may locally induce higher magnitude changes. Recovery to new steady-state may still last decades.

- Persistent eruptions (Figure 2.29c, Line D), e.g., Mt Semeru (Thouret et al., 2014) Tungarahua (Jones et al, 2015) and Santiaguito (Harris et al., 2006), characterised by ~daily input of sediment of varying magnitudes (small tephra fall events to larger explosive events up to the order of ~1 x10^7 m^3). Constant supply of sediment upstream drives an enduring pattern of aggradation downstream; rates of aggradation are controlled by the variable rate of sediment supply. Prolonged periods of relatively reduced sediment supply are associated with reduced aggradational rates or limited degradation.
- Episodic eruptions (Figure 2.29d, Line E) e.g., Soufrière Hills Volcano and Merapi (since late 1700s; Wolpert et al., 2016) characterised by episodes of small to moderate magnitude sediment delivery lasting months/years, punctuated by distinct pauses in eruption and sediment delivery. Pulses of sediment are accompanied by acute sedimentation downstream of a similar magnitude to those induced by small to moderate transient eruptions. Pauses in eruption allow for sediment depletion upstream which instigates a switch towards channel degradation as flows become more supply limited. Degradational patterns are interrupted or do not establish as a consequence of renewed activity in the next episode/phase of eruption. Multi-directional dome forming eruptions, such as that of SHV, may induce a more complex pattern of channel change if drainages are impacted by transient ash supply or vegetation cover changes.

It is important to note that these are generalised categorisations; local variations in climatology (e.g. variable water supply) and geomorphology (e.g., valley constriction) may lead to some deviation from these general trends (e.g. Pierson et al., 2013; Gob et al., 2016).

Figure 2.30 shows the range of sediment yields I have calculated for the upper catchment of the BRV within the context of other catchments from around the world, including steady state rivers with large basins, and catchments disturbed by wildfire, hurricanes landslides and other volcanic eruptions. This figure shows that the specific sediment yields from the BRV are well within the

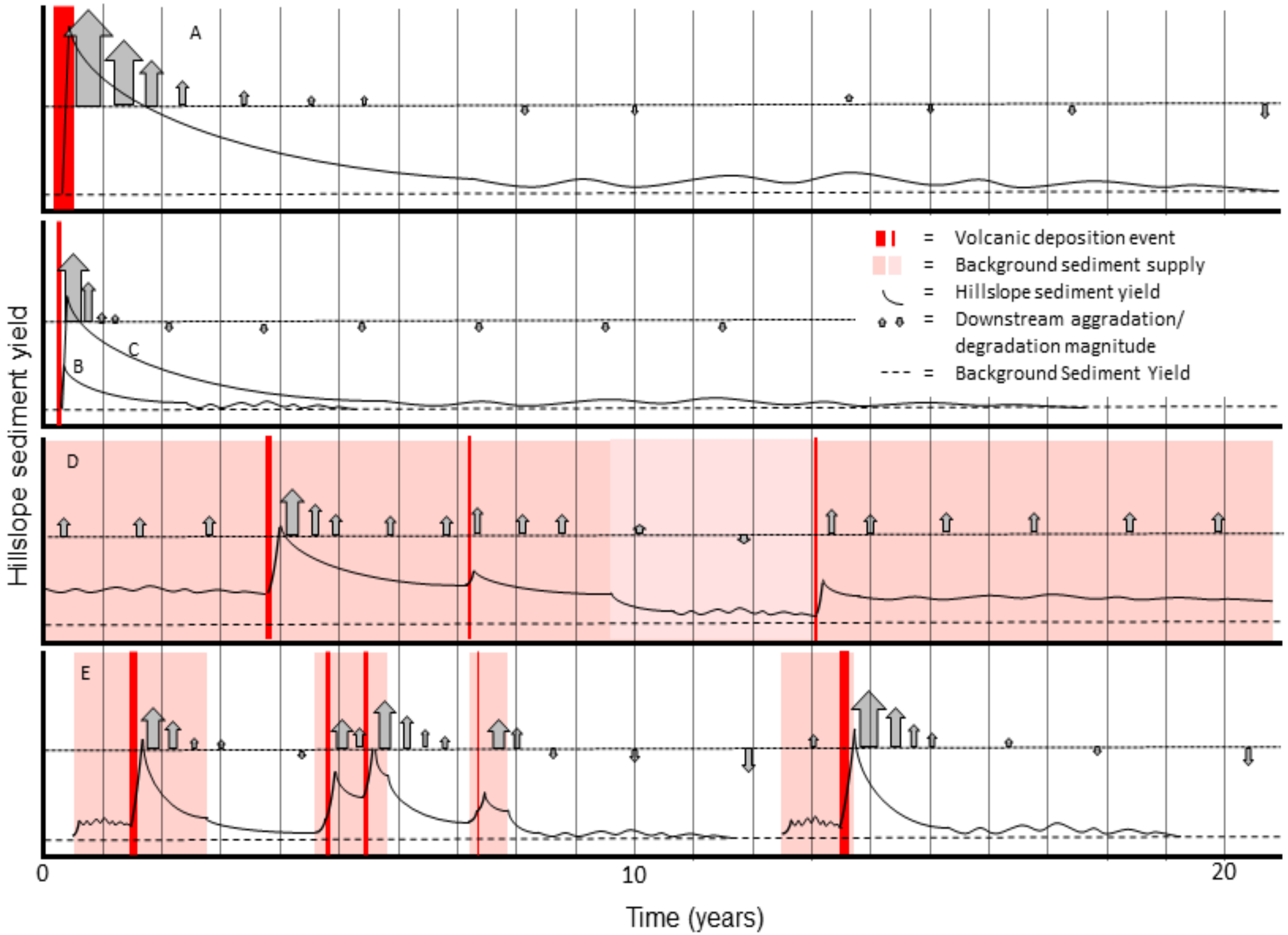


Figure 2.20: Conceptual hillslope sediment yield curves and downstream aggradation/degradation in response to varying eruption disturbance types. A = large, transient eruptions (e.g., Santa Maria, Mount St Helens, Pinatubo); B = small transient eruptions (e.g., Ontake, Yakedake, Unzen); C = moderate transient eruptions (e.g., Merapi VEI 4 2010, Mayon, Mt Hood); D = persistently active volcanoes (e.g., Semeru, Santiaguito, Tungurahua); E = multi-phase eruptions (e.g., Soufrière Hills Volcano).

range generated by other volcanically disturbed systems.and the drainages of Mt Semeru (Thouret et al., 2014). Both are examples of drainages affected by prolonged disturbance, but the former is affected by episodic activity and the latter is affected by persistent activity. Sediment supply is constant and thus higher magnitude at Mt Semeru. Further, annual rainfall at Mt Semeru is significantly higher than at Soufrière Hills, which enhances the potential for greater sediment yields. This is reflected in the similar range (2 orders of magnitude) of sediment yields, but overall higher yields at Mt Semeru. This data also demonstrates that the eruptive episodes affecting the Belham Valley have had a similar impact on sediment yields as small-moderate transient eruptions, such as those at Galungung, Usu, Sakurajima and Unzen (Chinen and Riviere, 1990; Kiyoshi et al., 1993; Lavigne, 2004; Teramoto et al., 2004). In effect, the episodic eruption of Soufriere Hills can be considered a string of small-moderate eruptions, in terms of the impacts of individual eruptive phases.

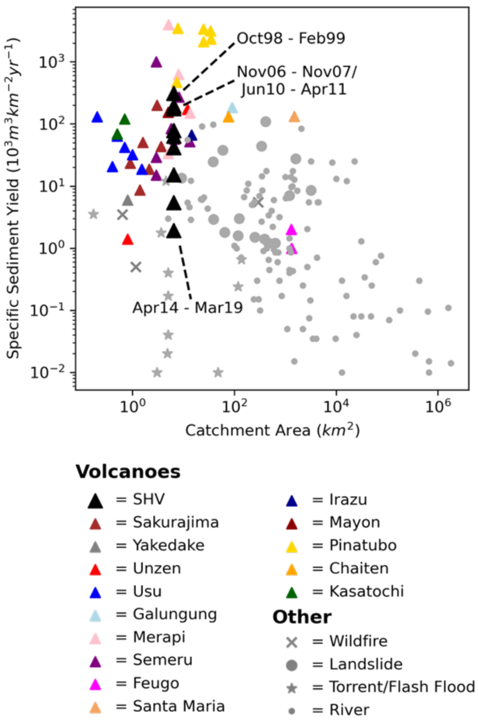


Figure 2.20: Specific sediment yields vs catchment area of a selection of global river systems, including ‘undisturbed’ rivers, debris flow torrents/flash flood basins, and basins affected by landslides, wildfires and volcanic eruptions. Eruption-disturbed basins are identifiable by the coloured triangles. Data from this study are shown as black triangles, periods of highest and lowest sediment yield are indicated. Specific sediment yields acquired from the following sources: Volcanoes – Chinen and Riviere (1990), Kiyoshi et al. (1993), Lavigne (2004), Teramoto et al. (2004), Gran et al. (2011), Suwa et al. (2011), Thouret et al. (2014), Major et al (2016), Hadmoko et al. (2018); Wildfire – Shakesby et al. (2003), Shakesby (2011), Warrick et al. (2012), Fernandez et al. (2019); Landslide – Korup et al. (2004), Mikos and Ribcic (2006), Koi et al. (2008), Matsuoka et al. (2009), Chuang et al. (2009), Fort et al. (2010), Chen et al. (2018) Waythomas et al. (2018); Torrent/Flash Flood – Powell et al. (1996), Lenzi et al. (2003), Schwartz and Greenbaum (2008), Theule et al. (2012), Zableta et al. (2014), Hooke (2019), McArdell and Satori (2020); World rivers –Walling and Webb (1996), Lenzi et al. (2003), Piegay et al. (2004), Filizola and Guyot (2009), Akrasi (2011), Basher et al. (2011).

2.5 Conclusions

In this rare, multi-parameter, longitudinal study, I have examined the Belham River Valley and its response to repeated disturbance by the episodic eruption of Soufriere Hills Volcano, Montserrat, since 1995. This work makes a valuable contribution to the wider literature on fluvio-geomorphic responses to volcanic disturbances by specifically examining the effect of episodic eruptions on rivers. Each episode of the eruption of SHV has consisted of the construction and collapse of andesite lava domes which has supplied the headwaters of this catchment with a total volume of pyroclastic sediment exceeding 30 $x10^6 m^3$. Repeated deposition of pyroclastic sediment has caused cycles of valley filling and vegetation damage, followed by evacuation of material from valleys by runoff-induced surface flow, and recovery of hillslopes (channel establishment and stabilisation, vegetation recovery). Each of these disturbance-recovery cycles has first been associated with high sediment yields (exceeding 100 $x10^3 m^3 km^{-2} yr^{-1}$) from the upper catchment and subsequent aggradation in the middle and lower reaches driven primarily by large and hazardous lahars. Acute phases of aggradation have then been followed by transitions into low-magnitude aggradational and then degradational regimes dominated by moderate – small lahars when upstream sediment is depleted and hillslope recovery restricts runoff generation. These recovery patterns have at times been disrupted by extreme events driven by transient tephra fall events, vegetation and extreme rainfall. In general, the channel has only entered a degradational regime for short periods due to short lived quiescence, resulting in a prolonged but interrupted period of net aggradation since the onset of eruption. I have demonstrated that the fluvial response of the Belham Valley shares many similarities with those induced by both transient and persistently active volcanoes and in effect constitute a hybrid of the two (Pierson and Major et al., 2014; Thouret et al., 2014). However, I argue that episodic eruptions produce a unique dynamism of aggradational and degradational behaviour downstream and that this pattern of response may be considered as distinct.

Aside from its contribution to fluvio-geomorphology, this study also has relevance to lahar hazard management in the BRV, particularly in the event of renewed activity at SHV. Impacts to the BRV from renewed activity may manifest in a variety of ways, from relatively minor tephra fall and gas impacts, to full-scale disturbance from dome growth to the north/west that feeds PDCs into the valley. The ensuing fluvial response and lahar hazard will depend on the nature of the disturbance. The same principles more widely in catchments around other volcanoes that may be affected by similar episodic activity. I therefore recommend that systematic monitoring of affected catchments form part of wider volcano monitoring procedures to better anticipate lahar hazard and channel responses.

Chapter 3: Examining the influence of catchment-scale conditions on the probability of lahar incidence in the Belham River Valley.

3.1 Introduction:

Chapter 1 of this thesis has outlined that fluvial systems disturbed by volcanic eruptions exhibit profound hydrogeomorphic adjustments as they respond and recover. The introduction of volcanic sediment (including fine-grained particles), combined with damage/destruction of vegetation dramatically alters the runoff response to rainfall and increases the likelihood of high discharge, sediment-laden surface flow (Alexander et al., 2010; Pierson et al., 2013; Pierson and Major 2014). In turn, progressive removal of sediment from source deposits, particularly fines via preferential evacuation/winnowing, and the establishment of channel networks, together with regrowth of vegetation, promotes infiltration, inhibits runoff and thereby reduces the probability and potential magnitude of resultant flows (Major et al., 2000, 2018; van Westen and Daag, 2005; Gran et al., 2011; Jones et al., 2017; Gonda et al., 2019). Chapter 2 has demonstrated that the evolution of catchment-scale conditions in the Belham River Valley have exerted control on the nature and timing of sediment transport. Consistent with theoretical expectation, the largest lahars (with exception of some extreme events) have been associated with periods of high sediment availability in the upper catchment, high water supply, and reduced vegetation cover; the frequency/magnitude of lahars has subsequently reduced when one or more of these factors is limited. From this there is an opportunity to quantify how these conditions mediate the likelihood of lahars in the BRV.

The conditions associated with the initiation of geophysical mass flows are widely studied in the interest of developing warning systems or parameterising susceptibility models (e.g., Paguican et al., 2009; Mead and Magill 2017, Baumann et al., 2018; Hapsari et al., 2020; Hirschberg et al., 2021). Rainfall initiates lahars either via infiltration-excess Hortonian overland flow or by initiating shallow landsliding by saturating surface layers of deposits (Mead et al., 2016; Baumann et al., 2018, 2019); evidence suggest the former is the primary driver of lahars in the BRV (e.g., Barclay et al., 2007). Empirical investigations have been conducted to understand the rainfall conditions under which lahars are triggered and focus primarily on incident and antecedent rainfall. These studies seek to identify rainfall thresholds which, when exceeded, generate lahars (Rodolfo and Arguden 1991; Tuñgol and Regalado 1996; Lavigne et al., 2000; Lavigne and Suwa 2004; Paguican et al., 2009; Capra et al., 2010, 2018; Jones et al., 2017). There is evidence that thresholds vary through time following an eruption, or may not exist at all, as a function of complex catchment evolution (e.g., van Westen and Daag, 2005; Jones et al., 2017) with implications for using these thresholds to predict lahars. Thus, in some cases lahar triggering is instead considered in terms of frequentist probability (i.e., based on the ratio of observed events vs the total observed events and non-events) (e.g., Barclay et al., 2007; Jones et al., 2017). Despite catchment evolution being implicated as an influence on lahar incidence, relatively few studies have examined the mediating effect of evolving catchment conditions (e.g., sediment supply and vegetation cover) on the rainfall required to initiate lahars (van Westen and Daag, 2005; Froude, 2015; Jones et al., 2017; Gonda et al., 2019).

This chapter seeks to address one question: in what ways do prevailing catchment conditions appear to mediate the likelihood of lahars in the Belham River Valley? The previous chapter has approached this indirectly by considering broader scale patterns of lahar activity. The present chapter builds upon this analysis by seeking quantitative evidence pertaining to the incidence of lahars. This has the potential to contribute to hazard management in the BRV and may also serve for the development of SedCas_Volcano (Chapter 4). I approach this question by examining how lahar incidence in the BRV evolves with respect to incident rainfall magnitude (intensities considered over 1, 3 and 24 hours), as mediated by antecedent conditions (i.e., antecedent rainfall magnitude, sediment availability or vegetation cover). I use this to assess whether there are conditions under which lahars are more likely and whether any initiation thresholds exist.

3.2 Methods and data

3.2.1 Examining triggering conditions

Numerous studies have examined rainfall intensity-duration relationships associated with lahar triggering, including in the BRV for a short period (2010-2012: Jones et al., 2017a). These analyses enable the estimation of triggering and sustaining rainfall for flow events with known start times (Rodolfo and Arguden 1991; Tuñgol and Regalado 1996; van Westen and Daag, 2005, Jones et al., 2015, 2017). The lahar record compiled by Froude (2015) and added to in Chapter 2 is rare and expansive. It presents an exciting and unprecedented opportunity to examine the evolution of lahar likelihood within this evolving catchment. However, this record details only the *days* on which lahars occur and their approximate magnitude. This means that the timing of lahars is not known, a limitation encountered by other studies (e.g., Abanco et al., 2016; Iadanza et al., 2016). This prevents the analysis of triggering and sustaining rainfall. I instead examine and compare the nature of incident rainfall recorded on days with or without lahars, for different windows/periods of time (1-, 3-, and 24-hours, etc.) for each day.

This presents a challenge, however, in that some lahars are known to be triggered during the early hours of the morning, which might be associated with rainfall carrying over from late the night before (Froude, 2015). Consider Figure 3.1 which shows a lahar occurring in the early hours of day 3. Here, a daily total, i.e., generated by summing rainfall between 00:00:00 and 23:59:59 of day 3, does not capture the entirety of the rainfall event that precedes, and thus may be responsible for, this lahar event. To address this, in a manner inspired by Abanco et al. (2016), I have devised a system of 'rolling windows' which produces the maximum sum of rainfall occurring

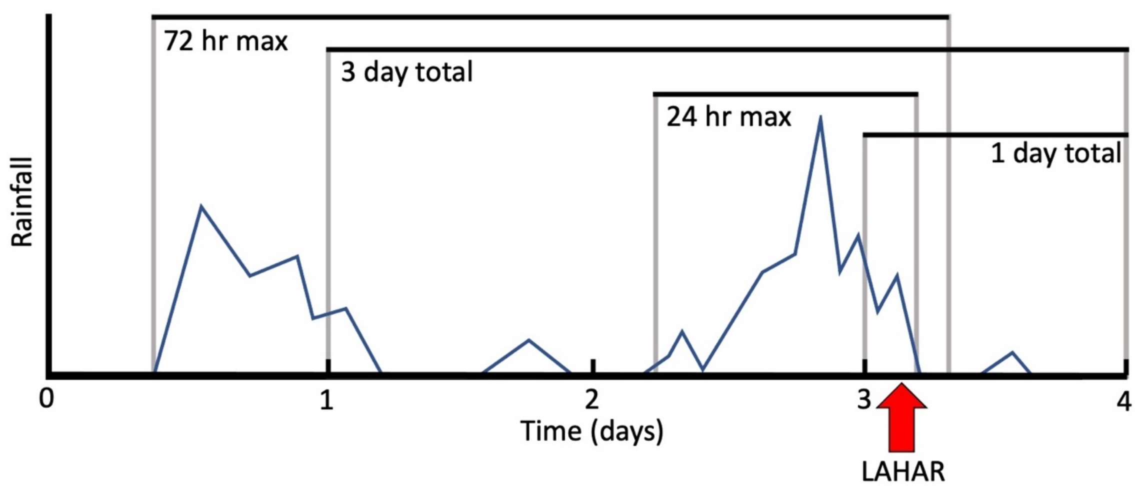


Figure 3.1: Schematic of rainfall sampling process.

in a set number of hours ending on the day a lahar has been recorded. For example, a 24-hour window that ends on day 3 (see Figure 3.1, '24h max'). The drawback of this method is that incident rainfall may contribute to the 24h max of two consecutive days, and thus be sampled twice. For example, the large peak on day 2 in Figure 3.1 would be included in 24h max of both day 2 and day 3, and thus, both days 2 and 3 record high 24h max rainfall. Evidently this leaves much room for improvement and would benefit from further development. However, in terms of matching rainfall to lahars, it offers advantage over using the total of a single individual calendar day.

I first examine the rainfall conditions associated with lahars over the whole study period to examine whether any thresholds are apparent for 1 hour, 3 hour and 24 hour maximum rainfall, considering also the size of generated lahars. I then expand this analysis to consider the preconditions of 1) antecedent rainfall, 2) sediment availability and 3) vegetation cover. These have all previously been implicated as important preconditioners of lahar generation in the BRV both by other studies (e.g., Barclay et al., 2007; Alexander et al., 2010; Froude, 2015; Jones et al., 2017) and Chapter 2, as well as elsewhere (e.g., van Westen and Daag, 2005; Jones et al., 2017). For antecedent rainfall and vegetation cover, I split the dataset into three subsets, grouping each day into low, medium or high categories. For the former, I consider 3, 7, 14, and 21-day antecedent rainfall. Low antecedent rainfall is designated as below the mean antecedent rainfall over the whole study period for the given window of time (i.e., 3 days, 7 days, etc.); medium as between the mean and one standard deviation above the mean; and high as above one standard deviation above the mean. For vegetation cover, days are designated high when they exceed 80% vegetation cover, medium between 65-80%, and low below 65%; these ranges were selected arbitrarily. With respect to sediment availability, I again split the dataset, but this time into 2 subsets, one for high availability and one for low availability. Designation of high and low sediment availability was made according to either direct evidence of upstream sediment availability, or evidence of downstream channel aggradation and degradation, which serves as a proxy measure of upstream sediment availability. This evidence is presented in full in Chapter 2. However, to summarise, periods of high sediment availability tend to follow phases of deposition from eruption such as during 1997 - 1998, 2003, 2007 - 2010). Low sediment availability results from progressive sediment depletion from upstream by lahars. These conditions prevailed during 1999 - 2002, 2004 - 2006, and 2012 – present. Table 3.1 provides details of these categories.

I then assess how the frequentist probability of lahars varies for each category based on rainfall exceedance (ranging from >0 mm to >100 mm) for 1 hour, 3 hour and 24 hour max or 1 day total (1 day total is chosen for antecedent rainfall owing to the autocorrelation of 24h max with antecedent rainfall). The frequentist probability is derived simply from the ratio of observed

Factor	Low	Medium	High
Antecedent Rainfall (3 day)	<10 mm N= 5353 L = 170	10 mm – 34 mm N = 974 L = 54	>34 mm N = 408 L = 42
Antecedent Rainfall (7 day)	<23 mm N = 5023 L = 153	23 mm – 63 mm N = 1199 L = 66	>63 mm N = 526 L = 47
Antecedent Rainfall (14 day)	<45 mm N = 4727 L = 151	45 mm – 100 mm N = 1366 L = 66	>100 mm N = 648 L = 49
Antecedent Rainfall (21 day)	<70 mm N = 4465 L = 155	70 mm – 130 mm N = 1557 L = 66	>130 mm N = 712 L = 45
Sediment availability	Observed upper catchment depletion/degradation in lower reaches: 01/2001 – 04/2002, 01/2005 – 05/2006, 01/2012 – present. N = 3739 L = 202	---	Observed upper catchment repletion/aggradation in lower reaches: 05/2002 – 12/2004, 06/2006 – 01/2012. N = 3017 L = 63
Vegetation Cover	<65% N = 739 L = 53	65% - 80% N = 2552 L = 113	<80% N = 3444 L = 100

Table 3.1: List of mediating factors considered in this analysis and details of their designation into high, medium and low categories, the number of days (N) and number of lahars (L) subsequently assigned to each category. Antecedent rainfall categories have been established as low = below mean, medium = between mean and one standard deviation, high = above one standard deviation.

events vs the sum of observed events and non-events (Equation 3.1; see also Barclay et al., 2007; Jones et al., 2017). It is an interpretation of probability based on observed frequency alone and thus does not represent the true probability of an event, nor does it necessarily indicate the probability of a future occurrence (Bickel and Lehman 2012).

$$\text{P (lahar on day)} \quad = \quad \frac{Lahar\ days}{All\ days}$$

(Equation 3.1)

For example, this enables the comparison of the probability of a lahar on days with a 1-hour maximum rainfall intensity e.g., exceeding 25 mm hr^{-1}, and this can be augmented further under the categories of differing antecedent rainfall, sediment supply and vegetation cover conditions. Equation 3.2 below provides an example.

$$\text{P (lahar on day with } > 25\ \text{mm hr}^{-1}) \quad = \quad \frac{Days\ with\ > 25\ \text{mm hr}^{-1}\ and\ lahar\ occurs}{All\ days\ with\ > 25\ \text{mm hr}^{-1}}$$

(Equation 3.2)

This methodology is similar to one adopted by Jones et al. (2017) who studied the rainfall conditions associated with lahar initiation in the BRV between 2010 – 2012. However, their study conducted a detailed study of seismic records and therefore had access to approximate lahar start times for this period. Thus, they could examine the intensity-duration conditions associated with lahar triggering and assess the impact these had on the likelihood of lahar incidence.

3.2.2 Data acquisition

Data used in this chapter have been derived from the dataset compiled and presented in Chapter 2. There were 266 lahars over the period covered by GPM rainfall estimates (Small = 171, Medium 64, Large = 31). As with chapter 2, I acquired 30-minute estimates of rainfall rate (mm hr^{-1}) dating back to January 2001 from the joint NASA/JAXA Integrated Multi-satellitE Retrievals for GPM (IMERG) mission. I resampled this data to produce a timeseries of hourly estimates of rainfall rate in mm hr^{-1}. Sediment availability in the upper catchment has been inferred from evidence presented in Chapter 2 of either the presence of sediment in the upper catchment, or of aggradation/degradation in the middle and lower Belham, which serves as a proxy for upstream sediment availability. Estimates of vegetation cover throughout the study period are available on a quasi-annual basis, derived from a combination of classified satellite (Normalised Difference Vegetation Index; NDVI), aerial imagery, and literature sources, all of which were compiled in Chapter 2. I have linearly interpolated this dataset to produce a continuous daily record of vegetation cover over the study period. This is not a true representation of changes occurring between observations, rather, it serves as a best available estimate.

3.3 Results

Figure 3.2 shows the temporal distribution of lahars in the BRV, by year (Figure 3.2a) and by month (Figure 3.2b). Figure 3.2a demonstrates 1) lahar activity remained elevated between 2001 and 2011 (apart from 2005), and 2) lahar activity declined significantly between

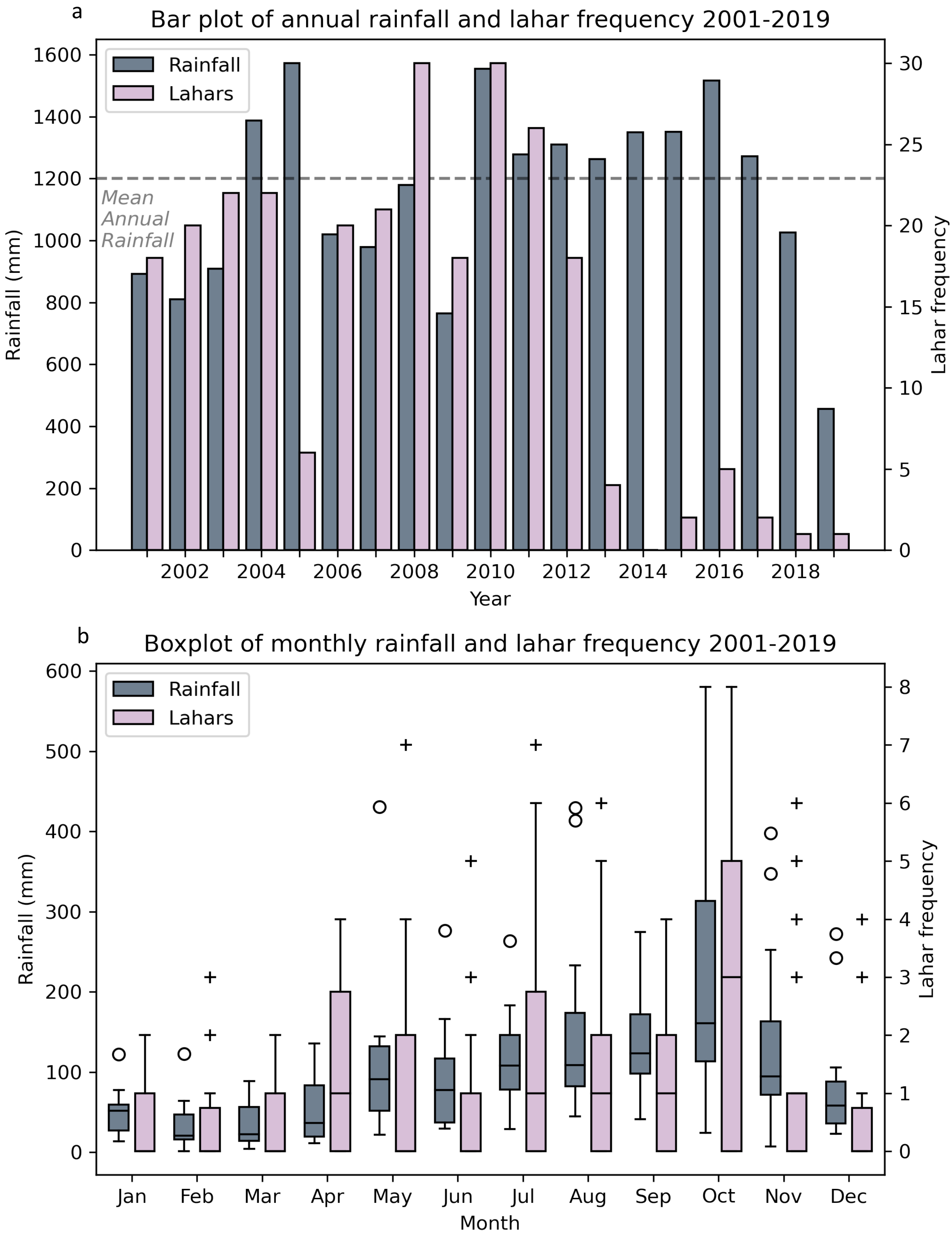


Figure 3.2: a) annual and b) monthly variability of rainfall and lahar incidence. In Figure 1a), note that 2019 only has half a year of rainfall due to data availability at the time of acquisition.

2012-14 and onwards despite several years with above-mean rainfall. Figure 3.2b demonstrates the seasonal pattern of rainfall and lahar activity. The bimodality of rainfall observed by other studies (e.g., Barclay et al., 2007) is evident, with a small elevation of rainfall in May, before the main rainfall peak in October. This bimodality is not so evident in the lahar data; rather it appears to be tri-modal, with a first peak in April/May, and two subsequent peaks in July and October.

Figure 3.3 shows the range of maximum rainfall rates per day sampled over 1, 3 and 24 hours associated with small, medium, or large lahars, as well as when no lahars were recorded, over the study period. This figure shows that there is a difference between the mean rainfall associated with lahar magnitude. This difference is particularly evident when considering large lahars and 24-hour max rainfall (Figure 3.3b). Figure 3.4, which presents scatter plots on incident rainfall, over 1 hour and 1 day, vs antecedent rainfall 3 to 7 days, is the closest to an Intensity-Duration plot I could produce for this analysis. This plot shows very clearly the lack of threshold rainfall condition for initiating lahars of any magnitude. Figure 3.5 then shows how increasing intensity of rainfall over 1, 3 and 24 hours increases the *probability* of lahars. The probability of any magnitude lahar occurring on *any* day (i.e., regardless of incident rainfall) is 4%. Beyond this, for example, on a day on which more than 3 mm of rain is recorded in an hour, there was a 20% chance of a lahar. This probability increases to 40% for more than 15mm, and exceeds 60% when more than 80mm falls in an hour. Crucially, both plots indicate that there is no single threshold rainfall rate that guaranteed lahar incidence when considering the entire study period. Lahars are associated with low and high rainfall magnitudes - 102 lahars were recorded on days with <5mm in 24 hours. Furthermore, numerous high magnitude rainfall events have been associated with no lahars (Figure 3.3).

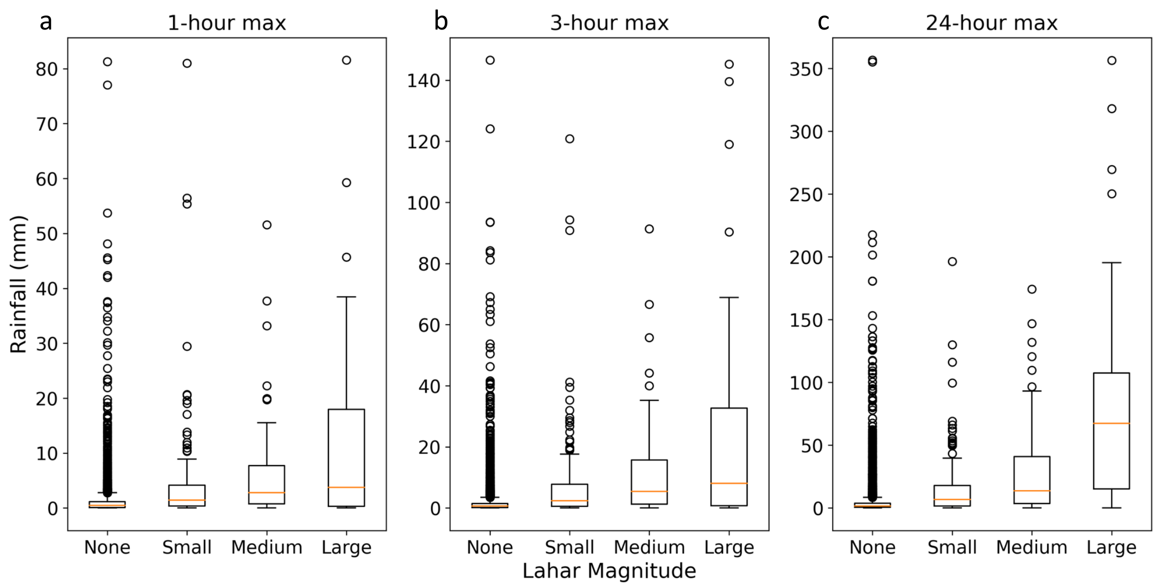


Figure 3.3: Boxplots of recorded rainfall associated with lahars of varying magnitude.

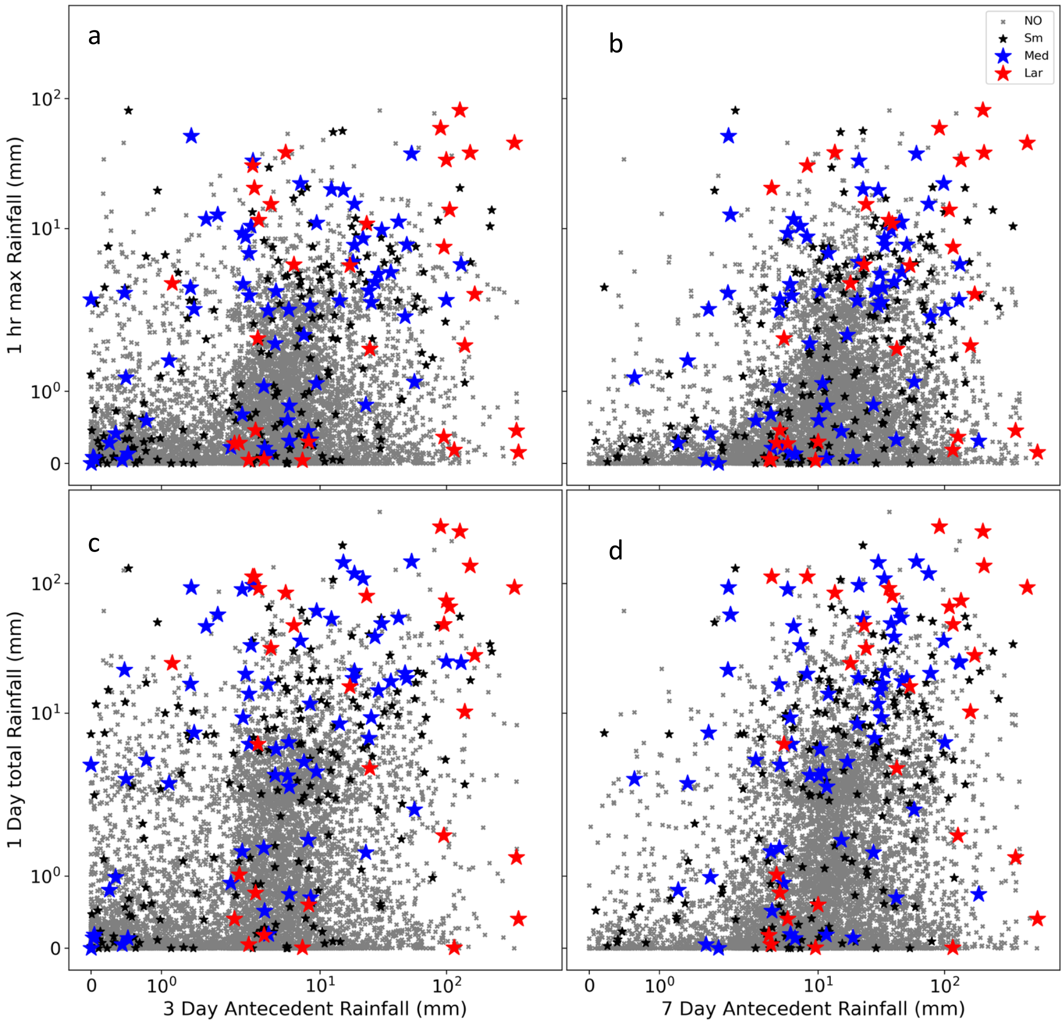


Figure 3.4: Scatterplots of recorded incident and antecedent rainfall associated with lahars of varying magnitude. a) 1 hr max vs 3-day antecedent b) 1 hr max vs 7-day antecedent c) 1-day total vs 3-day antecedent and d) 1-day total vs 7-day antecedent.

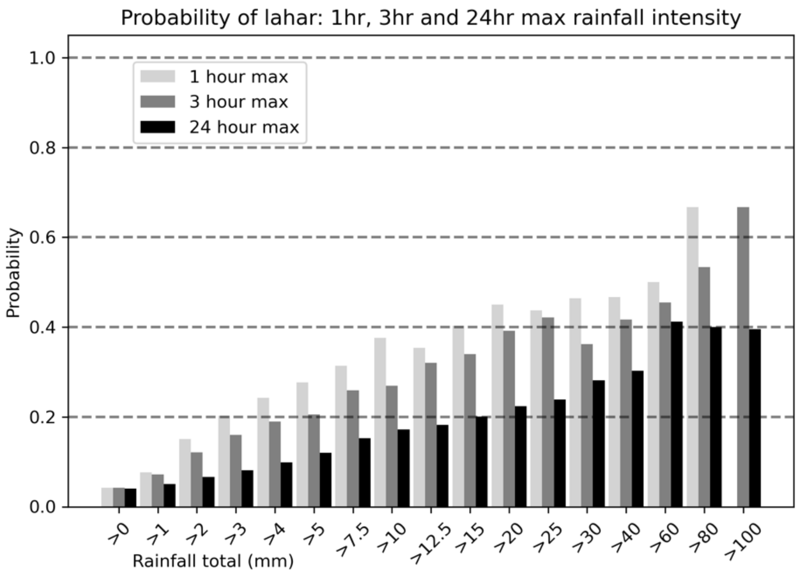


Figure 3.5: Evolving probability of any magnitude lahar being recorded on days with rainfall exceeding given magnitudes for 1-hour, 3-hour and 24-hour maximum recorded rainfall, 2001-2019.

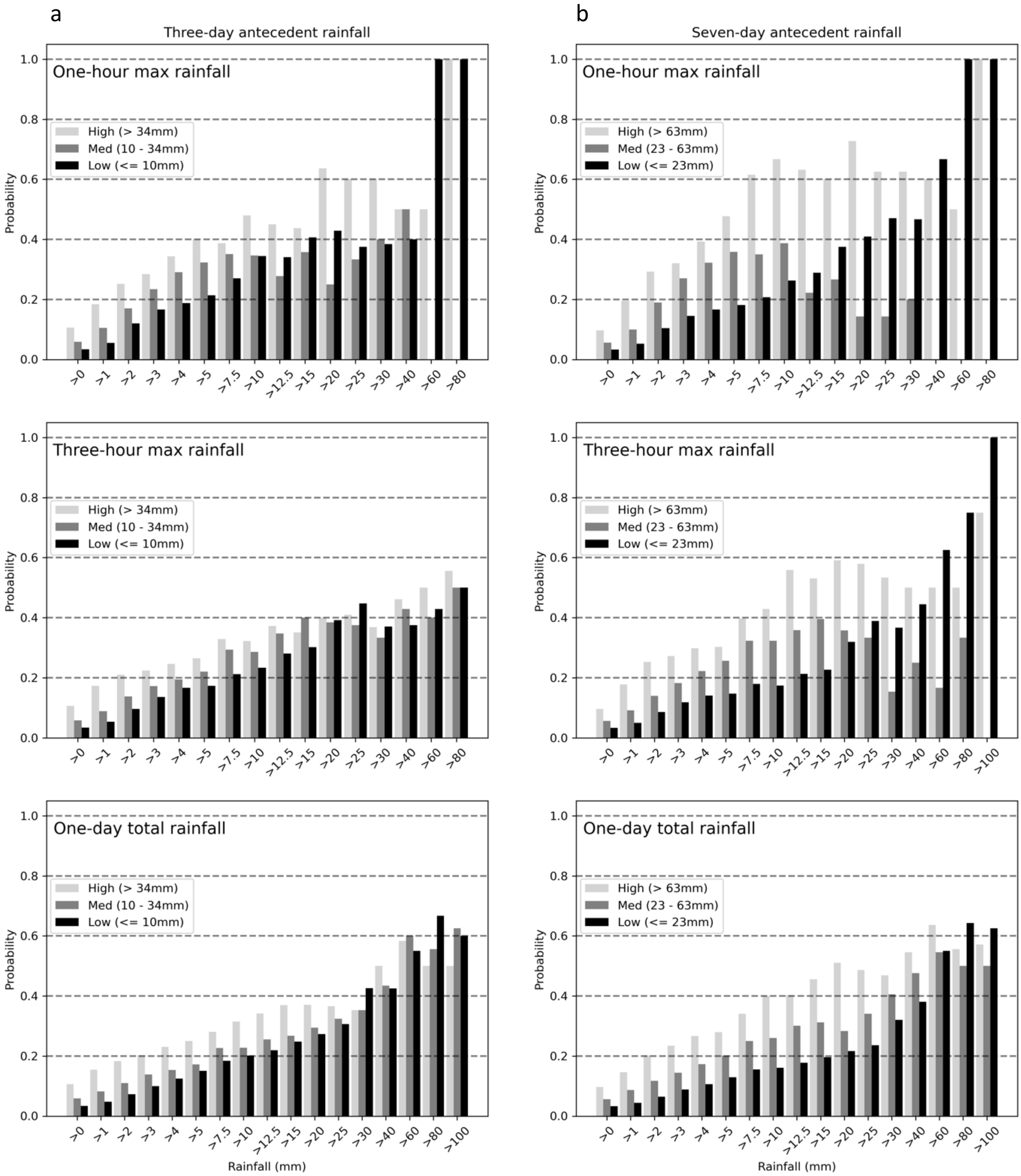


Figure 3.6: Evolving probability of lahars of any magnitude on days with low, medium, or high antecedent rainfall over a) three and b) seven days prior, and on which a given threshold of incident rainfall is exceeded (1 h max, 3 h max, 1 day total).

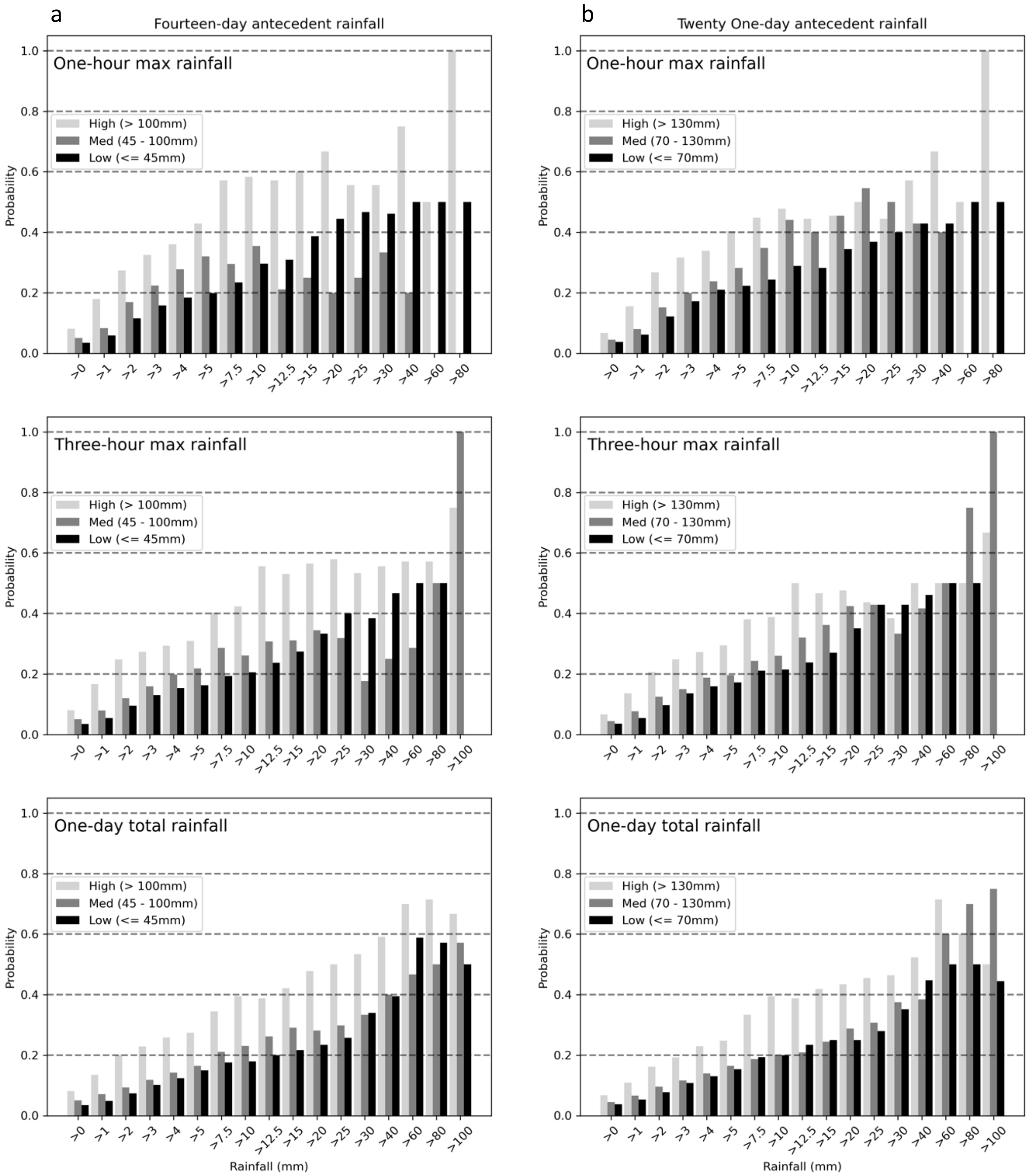


Figure 3.7: Evolving probability of lahars of any magnitude on days with low, medium, or high antecedent rainfall over a) fourteen and b) twenty one days prior, and on which a given threshold of incident rainfall is exceeded (1 h max, 3 h max, 1 day total).

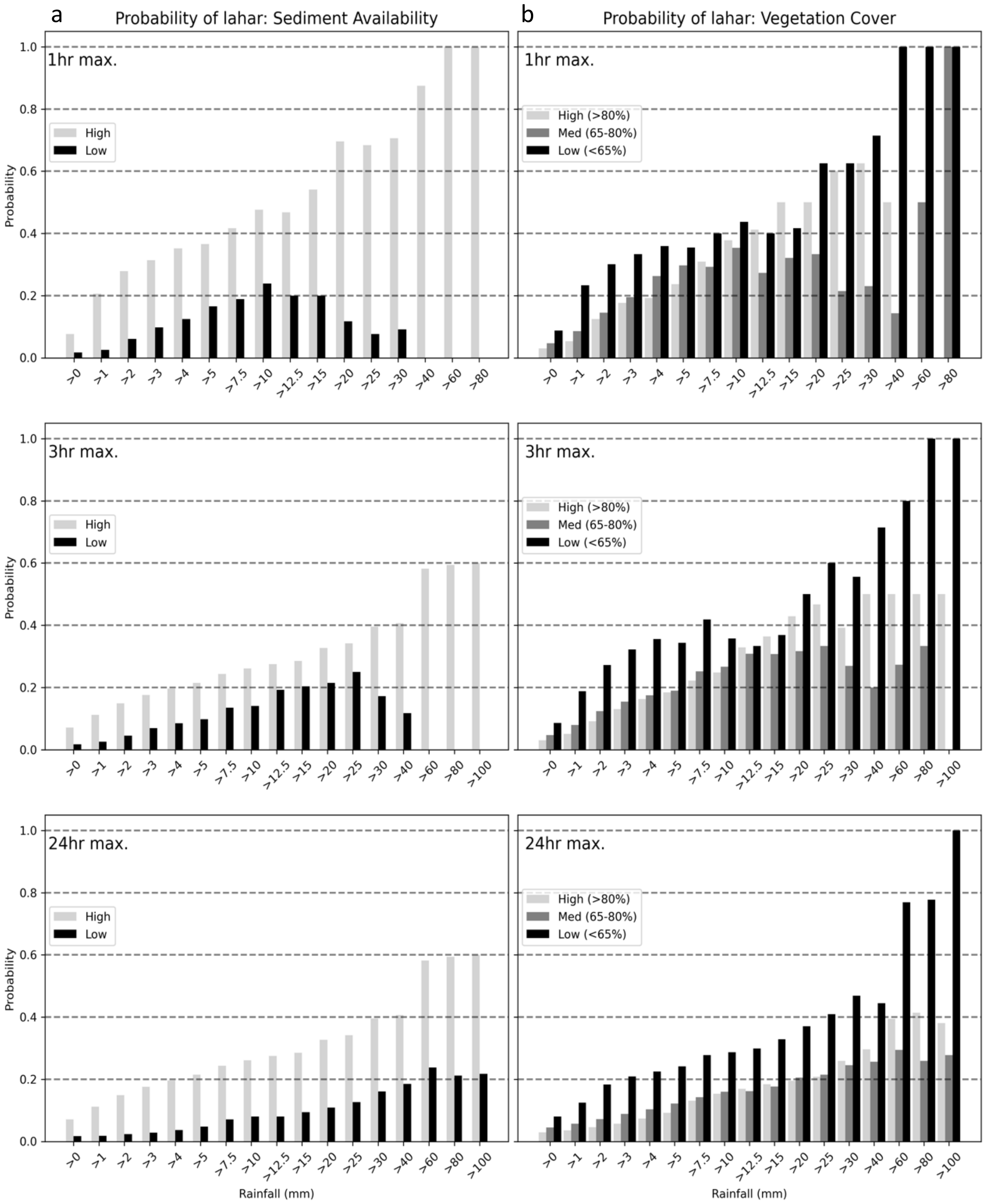


Figure 3.8: Evolving probability of lahars of any magnitude on a) days with high or low sediment availability, and b) high, medium, or low vegetation cover, and on which a given threshold of incident rainfall is exceeded (1 h max, 3 h max, 24 h max).

	Likelihood of lahar on any day		
Factor	**Low**	**Medium**	**High**
Antecedent Rainfall (3 day)	3.2%	5.5%	10.3%
Antecedent Rainfall (7 day)	3.0%	5.5%	8.9%
Antecedent Rainfall (14 day)	3.2%	4.8%	7.6%
Antecedent Rainfall (21 day)	3.4%	4.2%	6.3%
Sediment availability	1.7%	-	6.7%
Vegetation Cover	7.2%	4.4%	2.9%

Table 3.2: List of mediating factors considered in this analysis and the associated probability of a lahar of any magnitude occurring on *any* day, regardless of incident rainfall, under the presented conditions. Lack of 'medium' value for sediment availability is due to the lack of a medium category for this factor.

Examining the additional mediating factors reveals enlightening results. Antecedent rainfall magnitude (Figures 3.5, 3.6 and 3.7, and Table 3.2), over 3-, 7-, 14- and 21-day periods, all appear to have an influence over the likelihood of lahars. Figure 3.5 shows scatter plots of antecedent rainfall (3- and 7-day) and incident rainfall (1-hour max and 1-day total), which clearly demonstrates the lack of absolute rainfall threshold over the study period. However, it does show that lahars become more likely with increasing incident and antecedent rainfall. Collectively, Figures 3.5, 3.6 and 3.7, and Table 3.2, suggest that:

1) On any day, regardless of incident rainfall, the likelihood of a lahar is highest (10%) with high antecedent 3-day rainfall (Table 3.2).
2) High 3-day antecedent rainfall can increase the likelihood of a lahar by up to 20% at low-moderate 1-hr intensities (i.e. < 12.5 mm hr^{-1}), with a lesser impact on 3 hr and 1 day rainfall magnitudes (Figure 3.6a).
3) This effect is heightened over 7 and 14 days, with the likelihood of a lahar being up to 40% greater with high antecedent rainfall (Figure 3.6b and Figure 3.7b).
4) High 7-day antecedent rainfall is associated with the steepest increase in lahar likelihood with increasing 1-hour rainfall intensity. The probability of a lahar on a day with high (>63 mm) antecedent rainfall exceeds 50% with maximum recorded intensity in excess of only 7.5 mm hr^{-1} (Figure 3.6b).
5) The variance of lahar probability between antecedent rainfall categories declines at the highest magnitudes of incident rainfall (i.e., the difference between categories decreases

towards the right-hand side of each plot in Figures 3.6, particularly evident for 7-day antecedent rainfall). For example, lahars were guaranteed with incident rainfall intensities >60 mm hr^{-1} for both low and high antecedent rainfall over 3 and 7 days.

6) The observed effect of antecedent rainfall on lahar likelihood appears to slightly diminish at 21 days (Figure 3.7b).

In general, these results indicate that increasing antecedent rainfall increases the likelihood of a lahar occurring in association with incident rainfall of a given magnitude.

Sediment availability (Figure 3.8a) appears to have the largest influence on the likelihood of lahars. The probability of a lahar is consistently >20% higher for 1-hour maximum intensities above 1 mm hr^{-1}. This difference becomes considerably more pronounced at intensities > 15 mm hr^{-1}. At this point, the likelihood of lahars unexpectedly appears to decrease under conditions of low sediment availability. Conversely, while under conditions of high sediment availability, likelihood continues to increase; this figure suggests that lahars were guaranteed at rainfall intensities greater than 60 mm hr^{-1}. Enhanced likelihood of lahars between low and high sediment availability is also observed when considering 24-hour and 3-hour incident rainfall, though to a lesser extent for the latter.

Vegetation cover (Figure 3.8b), which will be in part correlated with sediment availability owing to their shared dependence on volcanic activity, appears to have a more modest impact on lahar probability compared to both antecedent rainfall and sediment availability. When considering 1-hour intensity, lahar likelihood is enhanced by between 5 – 15% with low vegetation cover at incident rainfall intensities of <10 mm hr^{-1}; above this limit this enhancing effect breaks down. Its effect seems to be largest when considering 24-hour maximum incident rainfall; lahar probability is reliably 10-15% greater with low vegetation cover compared with high cover. These results therefore differ from those of antecedent rainfall and sediment supply. However, Figure 3.8b suggests that rainfall exceeding 40 mm hr^{-1} guaranteed a lahar when associated with low vegetation cover. This is not observed under any other conditions. Furthermore, low vegetation cover is the only condition under which it appears >100 mm of rainfall in 24 hours guaranteed a lahar.

3.4 Discussion

The results presented in Section 3.3 provide valuable insights into lahar behaviour in the Belham River Valley. The drop-off of lahar activity in 2005 and 2013 – onwards (Figure 3.2), despite a prevalence of above-average rainfall over these periods, is related to catchment recovery (see Chapter 2 and further discussion below). The mismatch of seasonal patterns of rainfall (bimodality) and lahar activity (trimodality) (Figure 3.3), is interesting, but consistent with previous findings (Barclay et al., 2007; Froude, 2015). The first peak in lahar activity in April, which precedes the first peak in rainfall in May, may be attributable to enhanced runoff during rainfall related to tephra surface sealing over the dry season. Such behaviour has also been implicated at Volcan de Colima (Capra et al., 2010, 2018).

In general, there is no apparent absolute rainfall threshold that guaranteed lahar activity when considering the study period at large. This is an important but unsurprising finding given the wide variability of catchment conditions and the subsequent variability of landscape hydrology. Further, many lahars have been recorded on days with no, or very low rainfall. Lahar incidence on days with very limited rainfall may be explained by the presence of runoff-enhancing tephra (Major and Yamakoshi, 2005), or limitations of rainfall detection (see below). Both of these results are to some degree consistent with previous studies of lahars in the BRV (Barclay et al., 2007; Froude, 2015; Jones et al., 2017) and elsewhere (van Westen and Daag, 2005; Capra et al., 2019). By and large, increasing magnitude of incident rainfall over 1-, 3- and 24-hour windows increases the likelihood of lahar activity (with some exceptions e.g., Figures 3.8a and b). This is expected as high rainfall magnitude equates to more potential water supply for the initiation of flows (Capra et al., 2010; Jones et al., 2017). Furthermore, as demonstrated by Figures 3.2 – 3.8 and Table 3.2, all the considered mediating variables (rainfall intensity/magnitude, antecedent rainfall, sediment availability, and vegetation cover) appear to exert influence over the likelihood of lahars. This demonstrates the hydrological complexity of this system as it has evolved. The fact that these results only present increasing likelihood, rather than absolute thresholds, is therefore unsurprising. These findings: 1) demonstrate of the complexity of lahar triggering in the BRV and outlines the challenge of predicting their occurrence (in part related to data limitations/uncertainties, see below); 2) emphasise the importance of catchment-scale monitoring; and 3) potentially make an important contribution to hazard assessment in the BRV as they provide a basis for assessing the likelihood of a lahar under varying prevailing catchment conditions.

These results also provide insight into some of the processes that determine lahar occurrence in the BRV. The apparent effect of antecedent rainfall is expected as it has been observed to influence overland flow generation in this system previously and elsewhere (e.g., Barclay et al., 2007; James and Roulet 2009; Jones et al., 2017). Higher antecedent rainfall means more water stored within the system, thereby preconditioning the catchment for flow generation by reducing the lag time to infiltration- and/or saturation-exceedance (Jones et al., 2017; Capra et al., 2018). High antecedent rainfall over 3 days is associated with the highest probability (10%) of a lahar occurring on any day regardless of incident rainfall (Table 3.2). This is consistent with findings of other lahar studies based on the BRV (Jones et al., 2017) and Volcan de Colima (Capra et al., 2010, 2018) which find 3-day antecedent wetness to be most important for preconditioning lahar incidence. However, on days with any amount of measured incident rainfall (i.e., >0 mm), the effect of antecedent rainfall on lahar probability is most significant over the 7-14 day time frame (see Figures 3.6b and 3.7a). This is consistent with findings from Merapi and Semeru, Indonesia which find 7-day antecedent rainfall to be most important (Lavigne et al., 2000; Lavigne and Suwa 2004). My findings differ from other studies which indicate that antecedent rainfall over as short a period as 24 hours is most important (Mt Yake-dake, Japan; Okano et al., 2012); and antecedent rainfall may be irrelevant for the generation of lahars (Mayon, Philippines; Rodolfo and Arguden 1991).

The variability in the antecedent rainfall conditions relevant for lahars between study sites is not surprising; optimal antecedent conditions for lahar generation will depend on local climatology and the hydrology of the landscape and volcanic deposits (Rodolfo and Arguden 1991; Capra et al., 2010, Jones et al., 2017). Intriguingly, however, there is some inconsistency between the results of this study (implicating 7-14 days as most important) and the findings of Jones et al. (2017), also based on the BRV, but implicating 3 days. This may be a function of their study being limited to 2010-2012, when the catchment was in a post-disturbance state with relatively low vegetation cover and high sediment supply. It is likely that their results captured more of the hydrology of recently emplaced volcanic deposits. By contrast, this study considers 2001-2019, thereby capturing an average over a period through which the hydrological conditions of the catchment have changed considerably (as demonstrated by Chapter 2). Nonetheless, these results concur by indicating that antecedent rainfall is important in the BRV. They suggest that water is stored in the landscape for a time, most likely within shallow layers of deposits/soils, and contributes towards a saturation state which promotes runoff generation. The slight decay in this effect by 21 days may reflect that this is the timescale over which percolation to deeper soil layers occurs. It is interesting to also note that the impact of antecedent rainfall seems to decay with higher magnitude incident rainfall. This is likely to reflect that these high magnitude rainfall events are sufficient to overwhelm the saturation capacity of deposits/soils, rendering antecedent moisture less relevant (Jones et al., 2017).

The impact of sediment availability is of particular note, as it is associated with a large difference in the likelihood of lahars (Figure 3.8a). High sediment availability increases the likelihood of lahars consistently by 20% or more across all 1-hour intensities. This is most likely to be a function of the evolution of deposit hydrology as sediment is supplied and removed. Volcanic activity at SHV has produced sediment of a wide range of sizes, from large boulders (some exceeding 5 m diameter, $\Phi = -8$) to very fine ($\Phi \leq 11$) respirable tephra particles (Cole et al., 1998; Loughlin et al., 2002; Horwell et al., 2003; Edmonds et al., 2006; Komorowski et al., 2010; Alexander et al., 2010; Stinton et al., 2014). Existing literature evidence suggests that fines ($\Phi \geq 2$) may account for up to 80% of tephra fallout deposits at SHV (Costa et al., 2016); estimates of the proportion of fines in other types of deposits (e.g., block-and-ash flows, pyroclastic surges) are not presented in literature, though their presence is recorded (e.g., Horwell et al., 2002; Loughlin et al., 2002; Edmonds et al., 2006; Stinton et al., 2014). This is significant because of the runoff enhancing properties of tephra (e.g., Major and Yamakoshi 2005; Capra et al., 2010; Jones et al., 2017). Fresh deposition of pyroclastic material will introduce these fine grains to the deposit surface, thereby elevating runoff generation. In turn, these fine grains are more susceptible to erosion by flow and are removed preferentially by winnowing (Pierson and Major 2014). Thus, as sediment is removed from source deposits, a large proportion of evacuated sediment will be made up of these finer particles, with larger grains remaining in deposits. This will gradually increase infiltration capacity of the deposit, reduce runoff generation and reduce the probability of surface flow (van Westen and Daag, 2005; Pierson and Major 2014). The degree to which lahar likelihood is increased for 1-hour intensities compared with 3-hour and 24-hour is also striking. This is likely indicative of the importance of infiltration impedance and runoff enhancement on volcanic deposits during high intensity rainfall (e.g., Major and Yamakoshi 2005; Jones et al., 2017a,b). The decline in lahar probability with increasing rainfall intensity observed under conditions of low sediment availability, particularly for 1-hour and 3-hour rainfall, is difficult to reconcile. This may be indicative of an unknown process, an artifact of data classification, or the data itself.

Figure 3.8b suggests that vegetation cover exerts influence on the likelihood of lahar incidence, particularly as 1) the probability of a lahar with low vegetation cover exceeds 20% with incident rainfall in excess of just 1 mm hr^{-1}, and 2) low vegetation cover is the only scenario under which rainfall exceeding 40 mm hr^{-1} appears to guarantee a lahar. However, this variance between high, medium and low vegetation cover is smaller than expected, particularly with respect to 1 and 3 h max rainfall. Vegetation cover is widely recognised as an important control on runoff because: 1) leaf surfaces intercept rainfall, impeding their descent to the ground (either by throughfall or stemflow) and temporarily storing water; which encourages, 2) interception losses via evaporation (the water never makes it to the ground); both of which in turn 3) reduce net precipitation rates at ground level. This, combined with the presence of root networks and organic soil which encourage infiltration, reduces the likelihood of runoff. An increase in probability of lahar between high and low vegetation cover is thus expected: without vegetation, rainfall is unimpeded on its way to the ground where it can generate runoff. However, most studies indicate that the impeding effect of vegetation on throughfall and net precipitation operates over a timescale of tens of minutes to hours as opposed to longer periods (e.g., Calvo-Alvarado et al., 2018; Brasil et al., 2020; Cleophas et al., 2022). Thus, it is not immediately clear why the impact of reduced vegetation cover is most pronounced over a 24-hour period. Conjecturally, this may be related to differences in water storage capacity between vegetated and non-vegetated surfaces which reach saturation at different rates. In general, future research could be aimed towards analysis of interception, infiltration, and runoff dynamics of a range of land surface types on Montserrat, and more widely over the volcanic islands of the Eastern Caribbean. This would help elucidate the processes behind these results, as well as assist parameterisation of models, as will be discussed further in Chapter 4.

It is important to recognise that these results are based only on associated rainfall, i.e., rainfall that happens to occur on a day on which a lahar is recorded. This limits the insights gained from them. Associated rainfall does not necessarily provide an indication of the conditions that caused the initiation of a lahar, nor the conditions that sustain the most hazardous medium or large lahars. Ideally this analysis could thus be expanded in future by 1) examining in more detail the likelihood of small, medium and large lahars under the same range of conditions, and 2) performing rainfall intensity-duration analysis, thereby expanding the work of Jones et al. (2017). The latter would require redevelopment of the lahar record by more closely examining the MVO seismic records. In addition, this analysis could be expanded to consider seasonality, given the potential influence of dry season surface sealing suggested by Figure 3.2. The use of frequentist probability also has limitations, owing to its dependence on frequencies of observation alone. While in general terms frequentist probability more closely captures the true probability of events with increasing number of observations, it does not represent the true probability. Its basis on observations alone also does not guarantee that these probabilities apply to future events. Furthermore, it has less utility for rarer events due to the limited number of observations (Bickel and Lehman 2012). Accordingly, these results should be interpreted with some caution.

It is important to also note the limitations of the data used for this analysis. Principally, this analysis is based on the remotely sensed GPM product. This data product was chosen to address the limitations of rain gauge data, namely that they do not sample rainfall over the lahar source areas. However, it is limited in that it may not be representative of all rainfall occurring on the ground. This is because 1) it will inevitably detect rainfall occurring outside of the catchment, and

2) it will miss short-lived (order of minutes or tens of minutes) intense bursts of rainfall known to occur during mesoscale weather events (Matthews et al., 2002; Barclay et al., 2007). Correlation analysis in Chapter 2 also demonstrated that the GPM dataset underestimates low-moderate rainfall. These are a function of its spatio-temporally averaged nature (30 mins, 10 km x 10 km). Nonetheless, despite these limitations, it has provided valuable utility in this analysis and clearly indicates correlation between GPM-measured rainfall and lahar activity. Thus, while acknowledging its limitations, this study serves as evidence to support the use of such data as a basic rainfall data product for rain-triggered mass flow studies, and provides an option in regions where ground-based meteorological observation infrastructure may be lacking (e.g., Dinku et al., 2011; Mashingia et al., 2014; Monsieur et al., 2018; Abanco et al., 2021).

The accuracy of the lahar record also requires consideration on two fronts: confidence of observations and the potential for lahars being missed from the record. The record compiled by Froude (2015) has three confidence categories for observations – low, medium, and high. This analysis is based on medium and high confidence observations, thereby excluding those of low confidence. Furthermore, observations of lahars have been hampered by 1) scientific attention being directed towards more urgent activity at the volcano (Darnell et al., 2012; Froude, 2015), and 2) lahar signals from the far field seismic network being obscured by other seismic activity (Froude, 2015). These facts limit the accuracy of the lahar record and thus impact the validity of the results. Finally, the measure of vegetation cover is a best estimate based on linearly interpolated quasi-annual point/snap-shot data and thus will not be fully representative of the reality on the ground. Further studies would benefit from improvements to data acquisition, which I will discuss in Chapter 6.

There are a few interesting avenues for further development of this analysis. First of all, this analysis considers the probability of *any* lahar occurring, including small lahars which are relatively insignificant both in terms of hazard and geomorphic impact. Further analysis could break the dataset down further to consider the probability of different magnitudes of lahars under the range of conditions. Another approach would be to explore probability/event trees (e.g., Newhall and Hoblitt 2002; Lindsay et al., 2010; Ogburn et al., 2015), in order to assess the probability of a lahar given a set of catchment conditions. An event tree is '*essentially a representation of events in which branches are logical steps from a general prior event through increasingly specific events to final outcomes'*, (Lindsay et al., 2010). So, in this case, an event tree might help answer the question: what is the probability of a lahar on a day with a 1-hour max intensity of 25mm, high sediment availability, low vegetation cover, and low antecedent rainfall? It would also be possible to develop classification models, such as logistic regression/Random Forest algorithms, to statistically forecast lahar activity based on this set of catchment condition classifications (e.g., Cannon et al., 2010; Xu et al., 2013; Kern et al., 2017; Jones et al., 2017; Hirschberg et al., 2021). Beyond this, numerical models designed with the intention of simulating lahar hazard within an evolving catchment may have merit. In the next chapter, I explore the potential for this by presenting SedCas_Volcano, an adaptation of SedCas (Bennett et al., 2014; Hirschberg et al., 2021), a simple, one-dimensional numerical framework that accounts for both incident and antecedent rainfall, sediment supply and vegetation cover for forecasting first order patterns (frequency/magnitude) of sediment laden flows.

3.5 Conclusions

By considering incident rainfall, antecedent rainfall, sediment availability and vegetation cover, this chapter has examined how the likelihood of lahar occurrence in the Belham Valley has evolved under varying catchment conditions. My findings suggest that:

1) There is no apparent single rainfall threshold for lahar triggering in the BRV when considering the whole study period, instead, the *likelihood* of lahars varies under different conditions.
2) All of the examined factors – incident rainfall magnitude, antecedent rainfall, sediment availability and vegetation cover – appear to play important roles in mediating the probability of lahar incidence.
    - In general, increasing intensity/magnitude of incident rainfall progressively increases the likelihood of lahars under all conditions. For example, regardless of antecedent conditions, on a day on which rainfall intensities of more than 3 mm hr^{-1} of is recorded, the likelihood of a lahar is 20%. This likelihood increases to 40% for >15 mm hr^{-1}, and exceeds 60% for >80 mm hr^{-1}.
    - Sediment availability appears to have the strongest control on lahar incidence, particularly when considering the 1-hour maximum intensity of incident rainfall. The likelihood of lahar incidence is reliably 20% greater on days with high sediment availability, and the data suggests that lahars are guaranteed with 1-hour intensities exceeding 60mm hr^{-1}.
    - Antecedent rainfall is an important preconditioner for lahars; its effect is most pronounced on the probability of lahar incidence associated with low-moderate (0-20 mm hr^{-1}) intensity incident rainfall. This effect is most apparent when considering antecedent rainfall over 7 – 14 days prior to the lahar; with high antecedent rainfall incidence of lahars may be up to 40% more likely. However, when considering the likelihood of lahar incidence on *any* day, i.e., irrespective of

incident rainfall, high 3-day antecedent has the strongest effect. The preconditioning effect of antecedent rainfall appears to decline with increasing incident rainfall.

- Vegetation cover appears to drive a 10-15% increase in likelihood of lahars at incident rainfall intensities of <10mm hr^{-1}. Beyond this point the enhancing effect of vegetation loss appears to decline, until high intensities; <40 mm hr^{-1} appears to have guaranteed lahar incidence with low vegetation cover. Low vegetation cover is reliably associated with a 10 – 15% enhancement of lahar likelihood across all considered 24-hour intensities of incident rainfall.

3) Importantly these factors appear to modulate lahar probability over different time scales owing to the differing processes that these factors represent. The likelihood of lahar generation by an incident rainfall event seem to be modulated most by:
    - Sediment availability over hourly time scales, likely related to increased infiltration-exceedance induced by changes to deposit hydrology).
    - Vegetation cover over a 24-hour period, potentially due to prolonged throughfall, though more likely differences in short-term water storage in deposits and vegetated areas.
    - Antecedent rainfall over periods of 3 days to 2 weeks. This is presumably due to medium-term water storage in shallow layers of deposits/soils.

These findings demonstrate that volcanically disturbed catchments are very complex environments, and that lahar activity is controlled by an interplay of processes; they corroborate evidence presented by other authors (e.g. Capra et al., 2010; Jones et al 2017). There remains room for more in-depth analysis to build upon this work, for example, by considering how the probability of lahars is mediated when considering more than one environmental variable at a time. The insights gained in this chapter are important for considering the prospect of any renewed surface activity at SHV and the subsequent lahar hazard that this will induce. Furthermore, the Belham River Valley shares many characteristics with other ephemeral catchments on tropical volcanoes (e.g., Thouret et al., 2014; Jones et al., 2015; Gob et al., 2016). As such, this type of analysis, in which lahar initiation is considered with respect to a range changing antecedent conditions, may also prove useful in these settings for developing a deeper understanding of lahar initiation conditions.

Chapter 4: SedCas_Volcano: modelling lahar hazard and sediment yield in the Belham River Valley, Montserrat.

4.1 Introduction

Chapter 2 presented a timeseries of volcanic and geomorphic activity within the Belham River Valley. It sought to interpret this timeseries to develop a conceptual model to explain the overarching controls on the general patterns of evolution within the catchment. Analysis was predominantly qualitative in nature, with the aim of contextualising the observed patterns within a spectrum of impacts observed in other volcanic systems. Chapter 3 built upon this to examine in more detail the conditions (i.e., incident rainfall, antecedent rainfall, sediment availability and vegetation cover) associated with individual lahar events in a quantitative manner. The present chapter builds upon this work by introducing a simple numerical model, SedCas_Volcano, which seeks to simulate and reproduce the first order patterns (frequency/magnitude) of lahar activity and sediment yield in the Belham River Valley.

Chapter 1 demonstrated that modelling efforts related to lahars typically focus on one of two aspects: initiation or runout. This section presents a brief recap, please refer back to Section 1.3 for a more detailed explanation. Initiation models focus on the conditions that lead to the triggering of lahars. These may be simple empirical or statistical relations derived from rainfall intensity-duration relations, such as those described in Chapter 3 (Rodolfo and Arguden 1991; Tuñgol and Regalado 1996; Lavigne et al., 2000; Lavigne and Suwa 2004; Paguican et al., 2009; Capra et al., 2010, 2018; Jones et al., 2017). Specific to the Belham River Valley, Jones et al. (2017) developed a logistic regression model based on rainfall intensity-durations associated with lahars between 2010 and 2012 to assess how the probability of lahar initiation changes seasonally and with time from eruption under different rainfall magnitudes. Other types of initiation models may be physically-based and spatially-distributed, simulating the behaviour of the substrate under a range of rainfall conditions to assess the spatial footprint of lahar source areas and the potential volume of resulting lahars (Mead et al., 2016; Baumann et al., 2018; 2019).

Runout models on the other hand are all spatially distributed and seek to forecast the runout of individual flows or probabilistic ensembles of flows to assess possible inundation extents and depths. These models enable the assessment of the areal extent of potential hazard posed to life and infrastructure. Again, these models may be simple and empirical, e.g., calibrated to observed runout distances and planimetric footprint of flows of a range of volumes. LAHARZ (Iverson et al., 1998; Schilling et al., 1998, 2014) is an example of a simple empirical model specifically calibrated to lahars with relatively high sediment concentrations and has been used in multiple settings (e.g., Vargas-Franco et al., 2010; Darnell et al., 2012, 2013; Andaru et al., 2022). Darnell et al. (2012) utilise LAHARZ to assess how lahar inundation zones in the Belham River Valley evolved as topography data is updated to account for channel evolution with time; Darnell et al. (2013) then modified the LAHARZ model code to estimate flow speeds of lahars. Other runout models may be more complex, physically-based, data intensive, and computationally expensive. Such models resolve equations of Newtonian motion over each grid cell of the underlying digital topography based on estimated properties of the sediment-water mixture. Titan2D (Pitman and Le 2005) is the most commonly adopted physically-based model for simulating lahars (Procter et al., 2004, 2010; Williams et al., 2008; Vargas-Franco et al., 2010; Cruz-Vázquez and Alatorre-Ibargüengoitia 2021; Kataoka et al., 2021).

Aside from the outlined statistical methods for assessing lahar initiation, the models above tend to consider individual or ensemble flows of specific types. For example, LAHARZ has been calibrated to sediment rich hyperconcentrated-to-debris flows which renders it inappropriate for considering dilute lahars, such as those observed frequently in the Belham River Valley (Barclay et al., 2007; Darnell et al., 2012). Furthermore, to date, very few studies have sought to model the longitudinal, decadal-scale evolution of lahar activity and sediment transport following volcanic disturbance. Gran and Montgommery (2005) present a *conceptual* model of sediment transport, as outlined in Chapter 1 (see also Gran et al., 2011). However, this is not a numerical model; rather it is based on extrapolation of observed trends. One example of numerical modelling of longer-term sediment yield comes from Meadows (2014). They use CAESAR-Lisflood (Coulthard et al., 2013; Lowry and Coulthard 2013) to forecast sediment yields from the North Fork Toutle River, USA, with projections extending to 2100. This model does not specifically consider lahars, though. This thesis has so far demonstrated the relevance of catchment disturbance, evolution and recovery for decadal patterns of lahar hazard and sediment yield in the Belham River Valley. Thus, given the relative lack of longitudinal modelling of lahar activity and sediment yield, there is an opportunity to explore this here.

SedCas (Bennet et al., 2014, Hirschberg et al., 2021), is a simple, zero-dimensional numerical framework designed to simulate the first-order patterns (frequency/magnitude) of debris flow activity and sediment yields in a small alpine catchment, the Illgraben, Switzerland. It is spatially lumped and is based on the linear reservoir concept, whereby segments of the landscape are conceptualised as reservoirs/buckets which can store sediment or water. The system is conceptualised as a sediment cascade (Burt and Allison, 2010); water and sediment are delivered to, stored within, and move along a series of these reservoirs to the outlet of the system. Bennett et al. (2014) demonstrated the model’s success at simulating the observed first-order patterns of debris flow activity; Hirschberg et al. (2021) then went on to present improvements to the model and then use it to forecast debris flow and sediment yields under a range of climate change scenarios. Akin to BRV, sediment supply in the Illgraben is episodic, though it is driven by landsliding triggered by seasonal freeze-thaw or rainfall. Similarly, like the BRV, the Illgraben forms a sediment cascade in which sediment is delivered, stored, and subsequently remobilised by rainfall-runoff events. Importantly, SedCas generates flows with a range of sediment concentrations, from water floods to debris flows, depending on sediment availability. These three points mean this model is appropriate for simulating the evolution of lahar activity in the BRV and the range of associated flow types. Thus, I have chosen to adapt SedCas to experiment with applying this form of longitudinal modelling for an episodic volcanic disturbance setting, using the BRV as a case study. This study is the first time the SedCas modelling framework has been applied to the simulation of sediment transport dynamics in a catchment disturbed by volcanism, and in which sediment transport occurs primarily by hyper-concentrated and stream flows. This chapter describes the adaptations made to SedCas to suit this setting and presents the resultant ‘SedCas_Volcano’. Following this, I ascertain whether SedCas_Volcano shows any promise with respect to simulating a) the first-order patterns of lahar incidence, and b) subsequent sediment yield.

4.2 Data and methods

4.2.1 SedCas_Volcano: model conceptualisation, adaptation, and implementation.

The purpose of SedCas_Volcano is to build upon the general examination of catchment conditions associated with lahars and go a step beyond by attempting to simulate the behaviour within a simple spatially-lumped model. I seek to ascertain whether the measured parameters of sediment supply, vegetation variation, and water supply are sufficient to capture the first-order patterns (seasonal/inter-annual frequency and magnitude) of lahar activity, sediment yield and, by proxy, the net geomorphic changes observed in the Belham River Valley. This exercise is also designed to assess how improvements could be made for such a modelling approach to better suit a volcanic catchment such as the BRV. In this section, I will first describe SedCas in its original form, before detailing my adaptations and their rationale to develop SedCas_Volcano.

4.2.1.1 SedCas: the Illgraben

SedCas was originally presented by Bennett et al. (2014), and further developed by Hirschberg et al. (2021); it was designed to capture the first-order (general magnitude/frequency) patterns of debris flow activity in the Illgraben, Switzerland and subsequently used to conduct a climate change impact assessment on debris flow activity over the 21st century (Hirschberg et al., 2021). This small alpine catchment is supplied with sediment by seasonal landslide activity from the steep slopes of its headwaters. This material is subsequently remobilised during high intensity rainfall events, generating debris flows, which travel along a torrent, the Illbach' where they are detected by a forceplate before entering the River Rhône.

SedCas is a spatially-lumped, one-dimensional model, based on the linear-reservoir concept (e.g., Hannah and Gurnell 2001; Nourani et al., 2009; Mateo Lázaro et al., 2015) whereby the landscape is conceptualised as a series of buckets/reservoirs into which water and/or sediment are supplied, stored (according to storage and residence coefficients) or transferred through. Water and sediment are transferred into, between, or out of reservoirs when certain conditions are met (e.g., capacity is exceeded or discharge exceeds a threshold). All inputs of sediment and water and their storage are processed as millimetres, i.e., a volume (m^3) distributed over the area of the catchment. The model consists of three key components: a sediment production module, a hydrological module and a sediment transfer module.

The sediment production module generates sediment input (S_{in}) via stochastic, thermally triggered, or rainfall-triggered landslides based upon a probability distribution of sediment input magnitudes. This probability distribution was constrained by DSM differencing of the hillslope performed by Bennett et al. (2012). This produces a time series of sediment input which is deposited into the channel network (S_c) where it is stored and can be remobilised. A user-defined portion of s_{in} is deposited into hillslope storage (S_h), according to a redeposition rate parameter (R_{dep}), where it is rendered inaccessible to flows. The hillslope is assigned a capacity (H_{cap}) which, when exceeded, causes the collapse of the hillslope-stored sediment into the channel.

The hydrological module evolved between the original (Bennett et al., 2014) iteration and the new Hirschberg et al. (2021) update. The first iteration had one reservoir for all simulated hydrology, whereas the latter version introduced hydraulic response units (HRUs) to independently account for different land surface types; the Illgraben is part forested and part bedrock, with temporally stable proportions, both having a distinct hydraulic response (Hirschberg et al., 2021). Each HRU is made up of one or a number (n) of stacked reservoirs (r), each of which has an associated water capacity (W_{scap}) and residence time (k_s). Hirschberg et al. (2021) conceptualise bedrock as a single, small-capacity (W_{scap} = 4 mm), short-residence time (k_s = 23 h) reservoir (r_d), to account for the relative impermeability of the bedrock. In contrast, the vegetated surface was conceptualised as two reservoirs; the first (top; r_{v1}) reservoir represents the canopy of the forest and the top soil layer (W_{scap} = 72 mm, k_s = 94 h), and the second (bottom; r_{v2}) represents the deeper soil (W_{scap} = 27 mm, k_s = 235 h). This vegetated HRU is designed to account for the impeding effect of interception on rainfall routing to the soil, and the additional pore space within the soil in which water can be stored which enables the storage of antecedent rainfall (Hirschberg et al., 2021). Figure 4.1a presents a schematic of the HRU structure.

The hydrological module, and thus each constituent HRU, takes timeseries of precipitation, temperature and potential evapotranspiration (PET) on hourly timesteps as inputs. At each timestep snow accumulation and melt are calculated using a degree day model. The change in water storage (ΔW_s, Equation 4.1) for each reservoir is calculated by accounting for both losses from evapotranspiration (a function of available water and PET) and removal by subsurface percolation ($Q_{per/ss}$, Equation 4.2), determined by residence time k_s, and gains from precipitation.

$$\Delta W_s = \mathrm{I}(t) - E(t) - Q(t) \qquad (Equation\ 4.1)$$

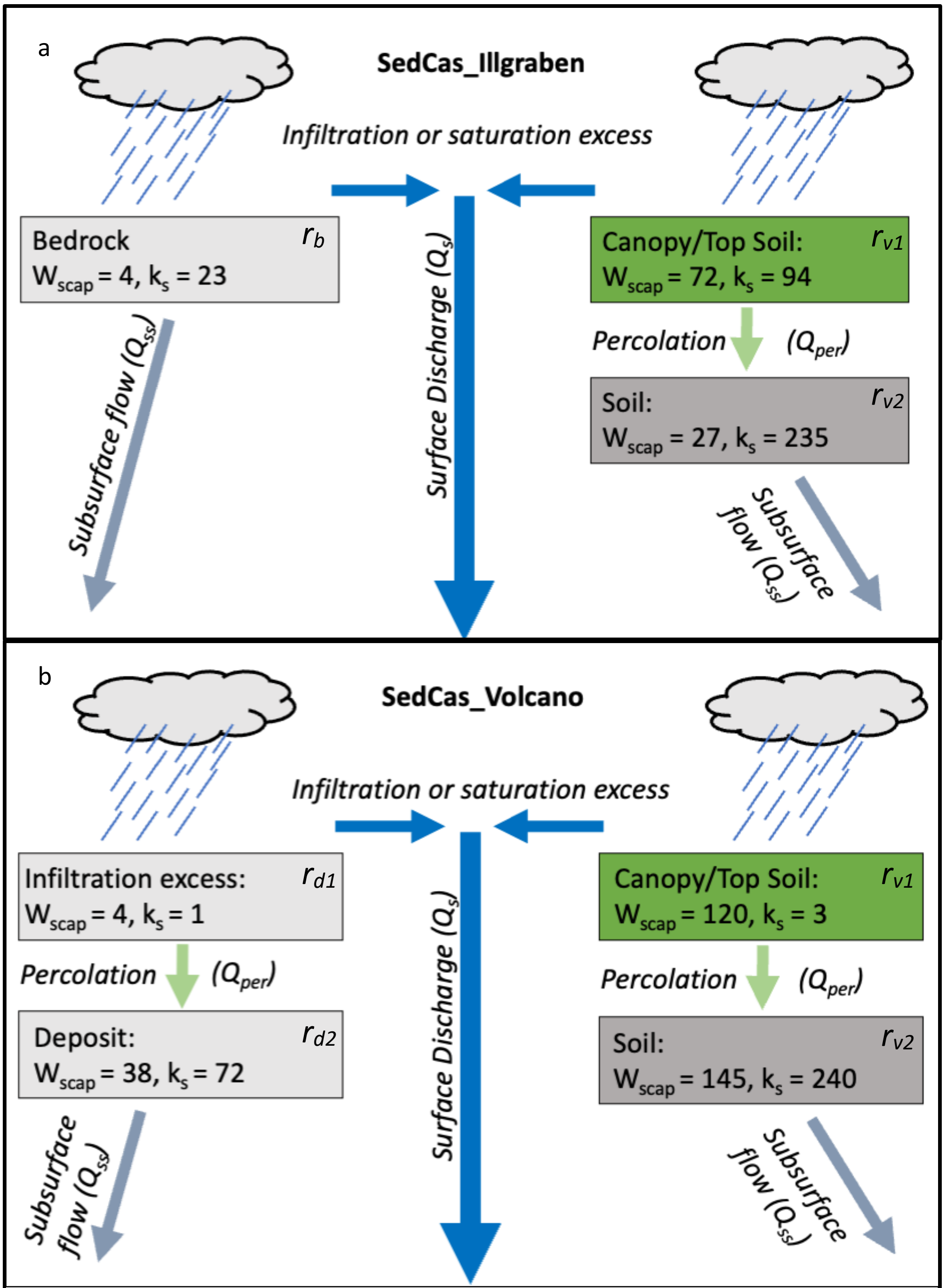


Figure 4.1: Schematic representations of the HRU structure, including the best fit values of water capacity (W_{scap}) and residence time (k_s), of a) SedCas (based on the Illgraben) and b) SedCas_Volcano.

Where I is the water input which may be precipitation (P, mm) and/or melt (mm), or percolation (Q_{per}), E is evapotranspiration (mm), and Q is discharge via percolating/subsurface flow (mm).

$$Q_{per/ss} = \begin{cases} 0, & if \;\; W_s^{r_{i+1}}(t) = W_{scap}^{r_{i+1}} \\ \frac{1}{k_s} \cdot W_s^{r_i}, & if \;\; W_s^{r_{i+1}}(t) < W_{scap}^{r_{i+1}} \;\; or \;\; i = n \end{cases} \qquad (Equation\ 4.2)$$

Percolating water will either enter a reservoir below (Q_{per}), or be drained from the system as subsurface flow (Q_{ss}). ΔW_s is added or subtracted from the water storage of the previous timestep (W_{s-1}). This results in the next instance of W_s. If in a lower reservoir (e.g., r_2) W_s exceeds W_{scap}, the excess will remain in the reservoir above (r_1), thereby reducing its capacity for the next time step (Equation 2). If the capacity of the top reservoir (r_1) is exceeded, this causes the reservoir to 'overflow' and produce a surface discharge, Q_s (Equation 4.3).

$$Q_s = \begin{cases} 0, & if \;\; W_s^{r_1}(t) < W_{scap}^{r_1} \\ W_s^{r_1}(t) - W_{scap}^{r_1}, & if \;\; W_s^{r_1}(t) \geq W_{scap}^{r_1} \end{cases} \qquad (Equation\ 4.3)$$

The hourly timeseries of Q_s is then taken as input by the sediment transfer model. Initiation of sediment transport is mediated by a critical discharge parameter (Q_L). The potential volume of sediment transport (s_{opot}), i.e., the transport capacity, varies according to the process of transport: debris flow or bedload transport. Discharges above Q_L initiate debris flows, whereas below Q_L bedload transport dominates. The s_{opot} (m^3) of resultant discharge is given by Equation 4.4:

$$s_{opot}(t) = \begin{cases} s_{max} \cdot Q_s(t) \cdot A & if \;\; Q_s(t) \geq Q_L \\ a \cdot Q_s(t)^b \cdot A & if \;\; Q_s(t) < Q_L \end{cases} \qquad (Equation\ 4.4)$$

Where s_{max} is the maximum sediment concentration for a debris flow, A is the contributing catchment area, and *a* (scaling parameter) and *b* (shape parameter) are parameters of a fluvial bedload rating curve. Rating curves are a common means of estimating fluvial bedload transport (Morris et al., 2008). *b* is set at 1.5 by default (Hirschberg et al., 2021), allowing *a* to be calculated using Equation 5.5:

$$a \cdot Q_s^b = s_{min} \cdot Q_L \qquad (Equation\ 4.5)$$

Where s_{min} is the minimum sediment concentration for a debris flow. This equation guarantees that the sediment concentration of bedload transport does not exceed that of a debris flow. The actual transport of sediment (s_o) is then further dependent on the availability of sediment in the channel, as per Equation 4.6:

$$s_o(t) = \begin{cases} s_{opot}(t) & if \;\; s_c(t) \geq s_{opot}(t) \\ s_c(t) & if \;\; s_c(t) < s_{opot}(t) \end{cases} \qquad (Equation\ 4.6)$$

The model thus allows sediment concentration of discharge between 0 and s_{max}. This is particularly relevant to the Belham River Valley given the wide range of sediment concentration observed in lahars (Barclay et al., 2007; Froude, 2015). It assumes that when a flow event is initiated and sediment is available, the maximum sediment concentration will be met.

In the Illgraben, there are no measurements available for any of the hydrological parameters within the model (i.e., water capacities and residence times). Subsequently, the model output was calibrated to observed debris flows to acquire values. The occurrence of debris flows and their volume are measured by force plate at the catchment outlet. Bennett et al. (2014) performed this calibration manually, by assessing residuals between model outputs of measured debris flow magnitude-frequency. Hirschberg et al. (2021), with more parameters requiring calibration following the addition of HRUs, utilised Monte Carlo (>10,000) simulations to acquire the best fit outputs.

4.2.1.2 SedCas_Volcano:

SedCas_Volcano is the first adaptation of SedCas to a fluvio-sedimentary system other than the Illgraben. Both the Illgraben and BRV catchments can be conceptualised as sediment cascades in which sediment is delivered episodically and remobilised by rainfall in debris flows/lahars as a function of sediment availability and rainfall runoff supply (Burt and Allison, 2010; Bennett et al., 2014, Hirschberg et al., 2021). I therefore hypothesize that the lumped modelling framework of SedCas will be applicable to a volcanic sediment cascade with some modifications to account for processes specific to volcanic landscape disturbance. However, there are important differences between the alpine Illgraben catchment and the volcanic BRV, that require some model adaptation. Namely, in the BRV there is no snow/ice development and vegetation cover is variable and has an impact on runoff generation. This section outlines the ways in which I have adapted SedCas_Volcano, the selection and calibration of parameters, and provides background rationale for decisions made throughout the process.

Conceptualising the Belham River Valley sediment cascade

The first step in applying SedCas to the BRV is to spatially lump the catchment system into reservoirs through which sediment will be cascaded. I conceptualise the BRV as consisting of the Upper Triggering Reach (UTR; consisting of Upper Catchment as identified in Chapter 2) and the Lower Depositional Reach (LDR; made up of the Lower and Middle reaches identified in Chapter 2). These areas are geomorphologically distinct (Figure 4.2) and dominated by different processes. The UTR incorporates the debris fans (Farrell’s Plain/ North Gage’s Fan) and the network of lower-order channels (e.g., Tyer’s Ghaut/Dyer’s River) onto/into which most pyroclastic sediment is supplied; these are the source areas for lahars in the Belham Valley. It also includes the steep slopes on the volcano (i.e., Gage’s Mountain) where relatively minor pyroclastic deposition has been observed. The LDR begins at the head of the Belham River, the highest order stream in the

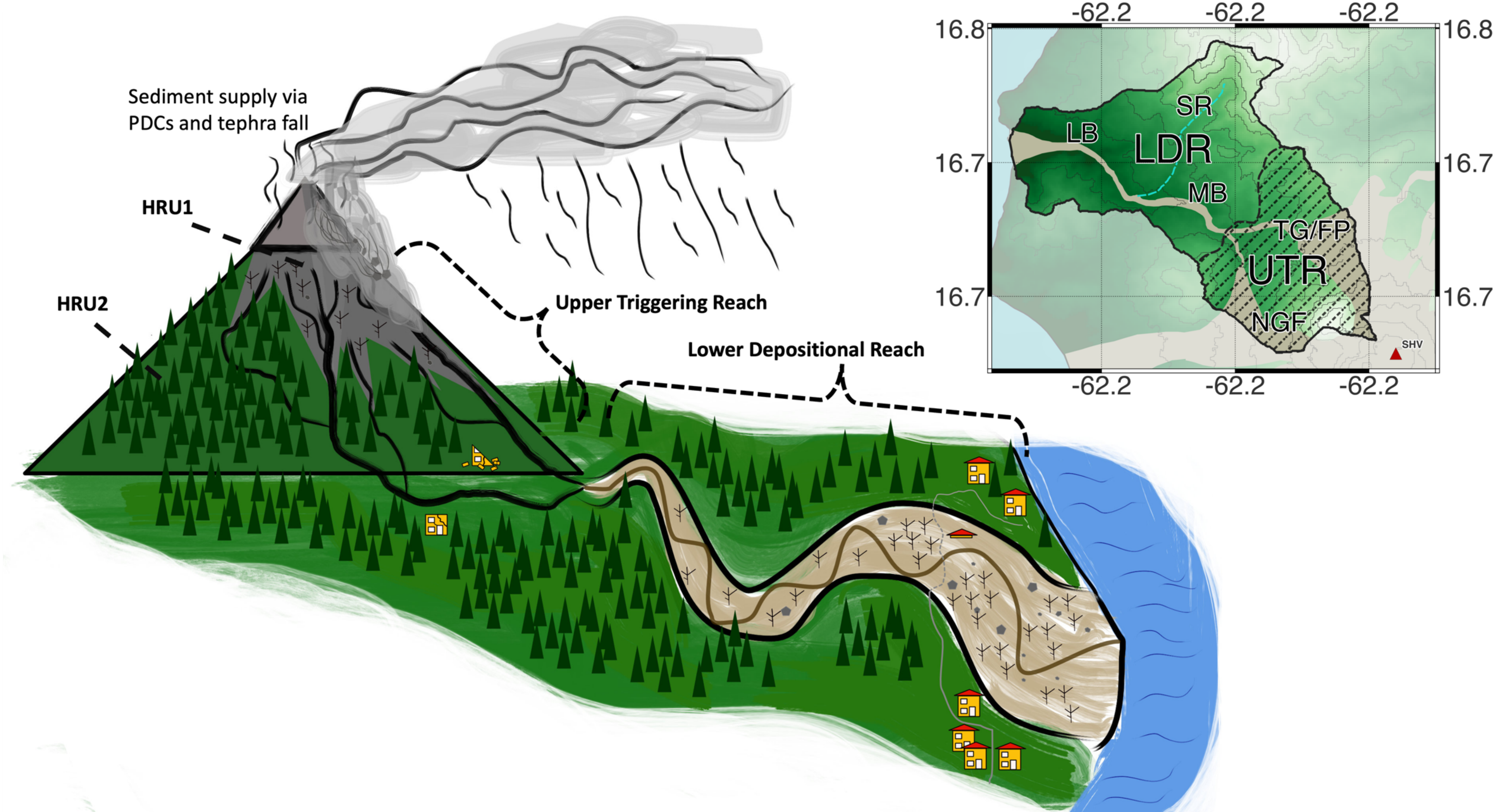


Figure 4.2: a) schematic of conceptual spatial breakdown of SedCas_Volcano demonstrating the general morphological typology of the Upper Triggering Reach (UTR) and Lower Depositional Reach (LDR) of the BRV. HRU = hydraulic response unit. b) inset map of the BRV catchment showing areal extent of UTR and LDR. LB = Lower Belham, MB = Middle Belham, SR = Sappit River, TG/FP = Tyer's Ghaut/Farrel's Plain, NGF = North gage's Fan.

catchment. This point is the confluence of the lower-order streams draining the volcano and where the channel gradient decreases. The Belham River is also supplied with additional runoff from lower order tributaries draining the Centre Hills (e.g., Sappit River). Most volcanic sediment supply has been limited to the UTR, with some exceptions during exceptionally long runout pyroclastic flows (June 1997, January 2007, January/February 2010). Thus, most sediment accumulation in the LDR has occurred as a result of remobilisation and cumulative deposition by lahars. The transition between UTR and LDR is where estimates of sediment yield and its variation are available from Chapter 2. Therefore, for the purposes of SedCas_Volcano, the UTR/LDR transition is considered as the outlet at which sediment yield is calculated by the model. The catchment area upstream of this point is 6.4 km^2, as acquired by watershed delineation. The LDR is not actively modelled, but the modelled yield from the UTR and the transport/supply limited state of modelled flows serves as a proxy of potential downstream aggradation/degradation.

Adaptations of SedCas to produce SedCas_Volcano

SedCas was originally developed as a MatLab script by Bennett et al. (2014), which was translated into python by [insert masters thesis attribution]. Hirschberg et al. (2021) then modified this script in the manner described above. I acquired access to the updated Hirschberg et al. (2021) Python code and modified it with their permission. The SedCas_Volcano code can be found in Appendix 2.

Figure 4.3 presents a schematic of the structure of SedCas_Volcano. Previous studies (e.g., Barclay et al., 2007, Alexander et al., 2010, Froude, 2015, Jones et al., 2017), as well as findings presented in Chapter 3 (Section 3.3), demonstrate that lahar activity is affected by rainfall magnitude and intensity, antecedent rainfall (most strongly over 7-14 days, Chapter 3), sediment availability, and vegetation cover. These factors are largely already accounted for in SedCas as these are important controls on debris flows in the Illgraben catchment too. However, in the case of the BRV, the climate is tropical, estimated rates of sediment supply are available through time (i.e., no need for stochastic processes), vegetation cover is much more dynamic as this is disturbed by volcanic activity, and runoff is generated on the surface of a porous deposit rather than bedrock. Thus, the key modifications I have made are: 1) removal of snow-related code; 2) modified the sediment module to accept a timeseries of sediment input; 3) enabled a variable HRU ratio to account for vegetation changes; 4) modified the HRU structure for the deposit to emulate both infiltration excess and storage of water within the porous deposit to account for antecedent wetness.

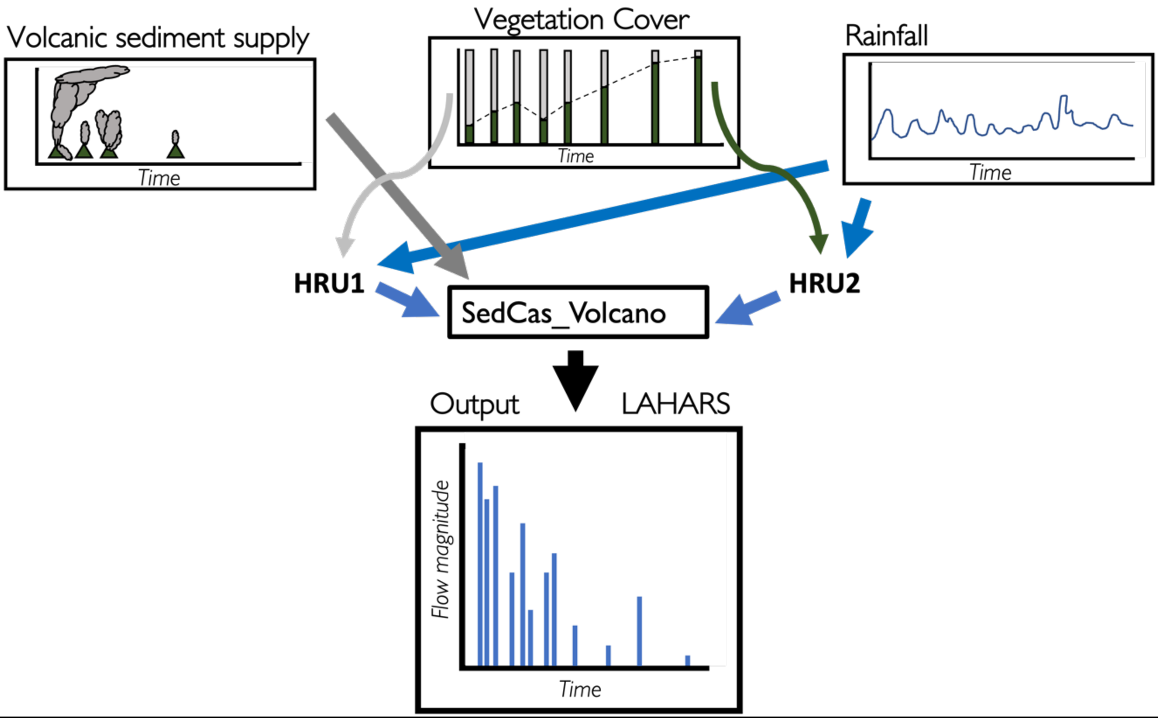


Figure 4.3: Schematic of SedCas_Volcano.

Below I give more detail on these changes to the model structure to produce SedCas_Volcano. I also describe how I derived parameter/variable values from data presented in the previous chapters, other literature, or by posterior calibration, as detailed in Table 4.1. Calibration of unconstrained parameters (all sets of W_{scap} and k_s, R_{dep}) involved an iterative process of least 200 trial-and-error runs with different combinations of input parameters. I evaluated model output against observations to progressively reduce apparent residuals with respect to: 1) the overall/agregate magnitude-frequency distribution of lahars, 2) the frequency of lahars for each year of the study period, 3) the aggregate frequency of lahars for each month, 4) specific sediment yield variation over the study period, and 5) periods of transport vs supply limited flow.

Sediment supply

For SedCas_Illgraben (Bennett et al., 2014; Hirschberg et al., 2021), sediment supply was generated stochastically from a probability distribution of landslides, based upon DEM differencing estimates of total erosion over a 20–30-year period. In my case, estimates of daily sediment supply volumes are available (provided by Chapter 3), so a stochastic approach is not needed and sediment supply to SedCas_Volcano is supplied as an input timeseries (s_{in}).

The retransfer parameter (R_{dep}) within SedCas causes a proportion of sediment input to be deposited onto the hillslope, rather than into the channel (where it can be remobilised), rendering it stored and inaccessible to runoff. The debris fans around SHV have built up considerably over

Input Parameters	Description	Unit	Values	Source/Calibration
n_HRU	Number of hydrological response units	-	2	-
HRUs	Names of HRUs	-	'Deposit'/'Vegetation	-
A	Catchment area	km^2	6.4	Upper catchment delineation
E	Catchment elevation	m	600	Mean elevation of catchment
W_{scap}	Water capacities	mm	[r_{d1}: 4, r_{d2}: 38] [r_{v1}: 120, r_{v2}: 80]	Posterior analysis
K_s	Water residence times	hr	[r_{d1}: 1, r_{d2}: 72] [r_{v1}: 3, r_{v2}: 240]	Posterior analysis
L_{min}	Minimum volume of lahar	m^3	1000	Order of magnitude of small flows based on Darnell et al. (2012)
L_{vols}	Lahar volume thresholds	m^3	1000; 10000; 100000	Orders of magnitude for small, medium and large flows based on Darnell et al. (2012)
Q_L	Critical discharge for lahar initiation	mm	0.093	Derived from integrating L_{min} over catchment area.
S_{max}	Maximum sediment content of lahar	-	0.6	Upper limit for hyper-concentrated flow
S_{max_nL}	Maximum sediment content of non-lahar stream flow (supply-limited)	-	0.2	Upper-limit of normal stream flow
R_{dep}	Redeposition rate: proportion of sediment input placed into storage on hillslope/debris fans.	-	*	Posterior analysis
h_{cap}	Hillslope capacity, upper limit of hillslope sediment storage. Redundant in this iteration of SedCas; value set above maximum possible sediment accumulation.	m^3	35 x10^6	***
Input variables				
Pr	Precipitation	mm	*	***
S_{in}	Sediment input	mm	*	***
v_{share}	Vegetation cover share	-	*	***
Model outputs				
$\mathbf{S_o}$	**Sediment output**	**mm**	*	-
$\mathbf{S_{pot}}$	**Potential sediment output (in case of supply limitation)**	**mm**	*	-
$\mathbf{L_o}$	**Lahars**	$\mathbf{m^3}$	*	-
$\mathbf{L_{pot}}$	**Potential lahars (i.e., floods, supply-limited flows)**	$\mathbf{m^3}$	*	-

Table 4.1: Parameters, input variables and outputs of SedCas_Volcano, and their source or means of calibration where appropriate. * indicates variable timeseries data. ** indicates value calculated from other known values. *** indicates uncalibrated, based on measured/estimated timeseries.

the course of the eruption (Figure 2.12), so this is a relevant parameter for SedCas_Volcano. Owing to the inconsistent ways in which estimates of sediment supply were made in Chapter 3 (i.e., via catchment-scale DSM analysis vs measurement of valley/channel fill within individual reaches), the proportion of material that has been deposited permanently is difficult to assess. The former measurement will capture deposition of hillslope-stored sediment, whereas, owing to its spatially restricted nature, the latter measurement only includes material deposited in active channels and will miss a (potentially large) portion of sediment deposited on the debris fan. Thus, a single R_{dep} is inappropriate. I decided to introduce R_{dep} as a variable parameter ranging between 0.63 and 0.8 (this involved only a simple edit to the code). This parameter was calibrated responsively after the hydrological parameters had been chosen (see below) by comparing modelled and observed periods of sediment yield and supply vs transport limited activity (i.e., informed by observations of aggrading/degrading LDR).

SedCas has two initial conditions available for channel (sc_{init}) and hillslope (sh_{init}) sediment storage. For SedCas_Volcano, I kept these as their default of 0 due to: 1) evidence presented in Chapter 2 indicates that in 2001 the system had already switched into a sediment-deprived, supply-limited and low-yield state, suggestive of very low sediment availability in the channel network; and 2) because in SedCas_Volcano, hillslope storage only acts to emulate the building of the debris fans. No evidence suggests the collapse of these fans into channels upon reaching a capacity, so this initial condition is irrelevant.

Hydrological module

Montserrat has a fully humid tropical climate (temperatures do not reach below 0ºC), snow accumulation and melt is not a consideration in this context. Thus, I removed all the parameters and model code related to snow. Similar to SedCas (Hirschberg et al., 2021), SedCas_Volcano requires two separate HRUs, one to represent vegetated surfaces and one to represent devegetated surfaces (i.e., deposits). There are two crucial hydrological differences between the Illgraben and the Belham Valley:

1) Unlike bedrock, the volcanic deposit is poorly consolidated and permeable, and thus, has some storage capacity, though this storage capacity is not known. Both infiltration excess and antecedent wetness over a number of days are important considerations as shown by Chapter 3.
2) Vegetation cover has varied considerably as a result of volcanic perturbations with important hydrological implications (e.g., Alexander et al., 2010).

Figure 4.1b shows a schematic of the updated hydrological module configuration. To address the first issue, I have included an additional reservoir to the top of the deposit HRU (r_{d1}) with a residence time of 1 hr, the minimum time step of the model. It is important to note that this minimum timestep is a potential limitation of the model, given the prevalence of short-lived (minutes – tens of minutes) high intensity rainfall in Montserrat known to initiate runoff; these events will not be captured. Nonetheless, decreasing the size of the time step would increase computational expense and potentially require a different source of rainfall data. Infiltration is not simulated by SedCas. However, by including a small capacity reservoir to represent the surface, infiltration exceedance can be emulated to produce discharge more readily during high intensity rainfall events, while also allowing some water to infiltrate into the lower reservoir.

A summary of infiltration rates measured on Montserrat is available from Barclay et al. (2007); the lowest rate measured on a volcanic deposit was 0.75 mm min^{-1}, equating to 45 mm hr^{-1}. This is relatively high compared to other volcanic deposits (Major and Yamakoshi 2005; Barclay et al., 2007; Jones et al., 2017), and does not account for reduction in infiltration induced by fresh tephra, or potentially increased runoff generated over the steepest slopes within the UTR (e.g., Morbidelli et al., 2018). Nonetheless, this value of 45 mm provided a preliminary estimate for capacity for r_{d1} and served as the first step for the calibration of the hydrological module. It was ruled out early in the process owing to highly restricted modelled discharge generation and lahar initiation. Smaller values were iteratively tested, and a capacity of 4 mm was eventually selected; coincidentally, the same value was used for bedrock by Hirschberg et al. (2021). With a residence time of one hour, any rainfall exceeding 4 mm hr^{-1} generates discharge from this HRU. This is consistent with the infiltration rates of between 2 – 7 mm hr^{-1} noted by Major and Yamakoshi (2005) in the 1-2 years following the eruption of Mt St Helens 1980. The second reservoir (r_{d2}) accounts for water that is stored in the permeable upper subsurface of the deposit. This has been assigned a residence time of 72 hours, following findings by Jones et al. (2017) which indicate 3-day antecedent rainfall as most important for lahar initiation in the BRV between 2010-2012 (i.e., relatively limited vegetation cover). A capacity of 38 mm was set via posterior calibration.

To address variation in vegetation cover, the model code has been modified to account for a timeseries-supplied HRU ratio (V_{share}) derived from the measurements of vegetation cover presented in Chapter 2. The 'vegetation' HRU has remained in the same configuration. The top reservoir (r_{v1}) represents the canopy and topsoil, from which surface runoff is generated, and the second represents a deeper layer of soil (r_{v2}). Vegetation is widely considered as an important control on runoff due to the interception of rainfall and the attenuating effect this has on subcanopy rainfall intensity. Vegetated surfaces also tend to encourage infiltration. Vegetation therefore influences subsequent surface accumulation of water, runoff and discharge generation (Alexander et al., 2010, results in Chapter 3 also suggest its importance). Studies of rainfall interception in tropical forests are very limited, however, evidence suggests that 1) interception delays water delivery to the ground by minutes to hours; and 2) a percentage of water may not reach the surface altogether (i.e., interception loss), depending on species composition (e.g., Calvo-Alvarado et al., 2018; Brasil et al., 2020; Cleophas et al., 2022*).* I assigned the upper vegetation reservoir (r_{v1}) parameters as W_{scap} = 120 mm and k_s = 3 hr to account for: 1) the high surface area of leaves and their temporary storage capacity, 2) the observed short timescales of precipitation attenuation by interception, and 3) the typically high rate of infiltration and storage capacity of forest soils. These values were informed by evidence from aforementioned studies and results from Chapter 3, but were chosen arbitrarily to be larger than values for the deposit; final values were refined via posterior calibration. Interception loss is not accounted for. For the deeper soil (r_{v2}), antecedent rainfall is accounted for by assigning a residence time of 240 hour (10 days), in keeping with findings of Chapter 3, which suggest that 7–14-day antecedent rainfall has the largest impact on lahar likelihood over the period 2001 - 2019. Finally, I set W_{scap} of r_{v2} as 145 mm via posterior calibration.

The hydrological model operates by first calculating the hydrological parameters for each HRU by assuming that the respective HRUs cover the entire catchment area. This produces a surface discharge for each HRU (Q_{s_v}/Q_{s_d}). Each Q_s is then multiplied by land cover ratio (V_{share} or 1-V_{share} for deposit), and the two outputs are then summed to produce a total output discharge (Q_s).

Sediment transfer model

The sediment transfer model controls the initiation of lahars and the removal of sediment from the HDR. There are four user-defined parameters involved with the control of lahar triggering: the minimum volume of a lahar (L_{min}, in m^3), the critical discharge for lahar generation (Q_L, considered as a flow depth distributed over the catchment in mm), the maximum sediment concentration for a lahar (s_{max}), and the minimum sediment concentration for a flow to be considered a lahar (s_{min}).

The Belham Valley is not monitored specifically (e.g., with stream gauge, force plate, near-field geophones) so it is not possible to measure the volume of individual flows, nor their sediment contents. Instead, events have been assigned a generalised magnitude according to a series of criteria set out by Froude, 2015: small (duration of a few hours, limited spatial extent, does not reach the sea), medium (duration may exceed 12h, flow occupies ~50% of the valley floor, reaches Belham crossing, may reach the sea), or large (duration may exceed 24h, flow occupies majority of valley floor, reaches the sea). Modelling approaches by Darnell et al. (2012) suggest appropriate volumes for these categories may be around 5.0 x 10^3 m^3, 2.5 – 5.0 x 10^4 m^3, and of the order of 1.0 x 10^5 m^3 and 1.0 x 10^6 m^3 for small, medium, large and extreme respectively. I have set the minimum volume for a lahar as 1 x 10^3 m^3, the lower bound of the order of magnitude for small lahars.

I have inferred the critical flow depth for lahar initiation, Q_L, by estimating the volume of water in the smallest lahars. Lack of direct monitoring has precluded the estimation of sediment content of lahars in the BRV, however, evidence from deposits suggests that non-Newtonian debris flow activity (i.e., sediment contents in excess of approx. 60%) is rare. The majority of lahars have behaved like hyper-concentrated or sediment-laden normal stream flows, thereby having a sediment content between ≥20 – <60 %. By assuming the average BRV lahar has a mid-range hyper-concentrated flow sediment concentration of 0.4, a 1 x 10^3 m^3 lahar will have a water discharge volume of 0.6 x$10^3$$m^3$. Distributed over the whole catchment (6.4 km^2), this equates to a minimum required flow depth of 0.093 mm. I have set s_{max} as 0.6, the upper bound of hyper-concentrated stream flow, owing to the rarity of observed non-newtonian/debris flow activity (Carn et al., 2001; Barclay et al., 2007; Froude, 2015). I have set s_{min} as 0.2, the upper bound of normal stream flow. To align with the small, medium and large categories of the observed record, I have set 3 volume thresholds (L_{vols}) to categorise model output, 1 x 10^3 m^3 (small), 1 x 10^4 m^3 (medium) and 1 x 10^5 m^3 (large).

Model outputs

There are four model outputs L_o (lahars, m^3, sediment concentration between 0.2 and 0.6), L_{pot} (potential lahars, m^3, i.e., supply-limited stream flows/floods with sediment content less than s_{max_nL} = 0.2), s_o (sediment output, mm), s_{opot} (potential sediment output, mm, based upon the capacity of supply-limited flows if sediment supply was unlimited). Lahars and potential lahars are both considered as important model outputs as the sediment content or supply-/transport-limited state of lahars observed in the BRV is not recorded – all flows are relevant hazards with potential impacts. s_o and s_{pot} are used to calculate the specific sediment yield (m^3 km^{-2} yr^{-1}) and the potential specific sediment yield (i.e., if flows were at capacity). The latter represents the potential for sediment to be removed from downstream. I resampled both over the same windows of time for which observed specific sediment yields were calculated in Chapter 2 to enable comparison.

4.2.2 General data acquisition

Data used in this chapter have predominantly been derived from the dataset compiled and presented in Chapter 2. These will be briefly described again here, with some additions specific to SedCas_Volcano, please consult sections relevant to SedCas_Volcano for more information.

Observed sediment input and availability

Sediment has been supplied to the upper catchment by volcanic activity of varying types and magnitude, from high-magnitude PDCs (10^5-10^6 m^3) generated by dome collapses and vulcanian explosions, to frequent (at times daily) low-magnitude tephra fall and rockfall events driven by progressive dome degradation. The previous chapter presented a timeseries comprising of PDC activity feeding Tyer's Ghaut/Farrell's Plain and the North Gage's fan, and tephra fall incident over the entire catchment. For the purposes of this chapter, I have produced an

timeseries of all forms of sediment input. Sediment availability has been assessed directly and by proxy, by accounting for periods of upper catchment sediment depletion and downstream degradation as presented in Chapter 2.

Vegetation cover

Chapter 2 demonstrated that volcanic activity has repeatedly caused damage or destruction of vegetation over the catchment. Estimates of vegetation cover throughout the study period are available on a quasi-annual basis, derived from a combination of classified satellite (Normalised Difference Vegetation Index; NDVI), aerial imagery, and literature sources. I have linearly interpolated this dataset to produce a continuous daily record of vegetation cover over the study period; this is not a true representation of changes occurring between observations, however it serves as a best available estimate for use with SedCas_Volcano.

Climatic variables

Five climatic variables are utilised by the original iteration of SedCas: hourly rainfall, as well as measures of temperature, incident shortwave radiation (SW; insolation), albedo and cloud cover. The latter four are required specifically for the Priestley-Taylor method for estimating potential evapotranspiration (PT-PET). Limited ground observations necessitated the acquisition of entirely remotely sensed data. As with Chapter 2, I acquired 30-minute estimates of rainfall rate (mm hr^{-1}) dating back to January 2001 from the joint NASA/JAXA Integrated Multi-satellitE Retrievals for GPM (IMERG) mission. I resampled this data to produce a timeseries of hourly estimates of rainfall rate in mm hr^{-1}, to be consistent with data requirements of SedCas. I was able to source land surface temperature (LST) data from the Moderate Resolution Imaging Spectrometer (MODIS; MOD11A1-061). Data availability is relatively sparse over Montserrat due to cloud cover – estimates of day time LST are available approximately every 3 days since February 2000 (linearly interpolated to fill gaps). I was able to source daily estimates of incident short wave downward irradiance (SW) from NASA's Clouds and the Earth's Radiant Energy System (CERES) project for the whole study period at a resolution of 1ºx1º, i.e., the whole island. However, no data was available for cloud cover or albedo, which precluded the use of PT-PET (see section). Instead, another means of approximating PET, Hamon PET (based on Hamon, 1961), is available in the model which requires temperature (i.e., MODIS LST), Julian day and latitude as inputs (SW data not used).

Lahars and sediment yield

As Chapter 2 details, lahars have been recorded in Montserrat Volcano Observatory activity logs since the onset of the eruption. Chapter 2 produced estimates of sediment yield over the study period, this record is used here to help calibrate SedCas_Volcano. The records of lahar activity and sediment yield are used to calibrate and validate the model. It should be noted up front that some inconsistency exists between the available definitions of lahar magnitude, namely that Darnell et al.'s (2012) model outputs suggest that it would require a large flow ($\geq 1.25 \times 10^5$ m^3) to reach the sea, whereas in the Froude (2015) record, reaching the sea is a possibility for medium flows. This presents a potential challenge for comparing model outputs and observations which will be discussed further later.

4.3 Results

Figures 4.4 a-f present the 'best fit' output from SedCas_Volcano, as acquired by iterative/trial-and-error calibration, which sought to progressively reduce apparent residuals between first-order (magnitude-frequency) model outputs and observations. The first clear finding (Figure 4.4a) is that the model performs well when simulating the *aggregate* magnitude frequency of medium and large lahars over the whole study period. This model configuration simulates 31/31 of the recorded large lahars, and modestly over predicts the frequency of medium lahars (71/64). However, it severely underperforms when generating small flows (31/171; figures 4.4 a and b); 140 small flows are not accounted for. Assuming a sediment concentration of 0.4, and an average bulk volume of 5000 m^3, this equates to approximately 2.8 x 10^5 m^3 of sediment yield unaccounted for over the period. This is the equivalent of a specific sediment yield of approx. 2.5 x 10^3 m^3 km^{-2} yr^{-1} over the whole period, a relatively small ~2% of the total average observed specific sediment yield, 108 x 10^3 m^3 km^{-2} yr^{-1}. Even under altered parameter settings which would be expected to produce runoff more readily (i.e., reduction of water capacities and increased residence times to encourage reservoir filling), the frequency of small flows was under estimated and medium/large flows subsequently overestimated. These runoff-enhancing conditions also lead to unrealistic flow discharges for extreme lahars of 2010, i.e., exceeding 1.5 x 10^6 m^3 (although volumes of observed flows are not known; Froude, 2015) and cause the model to lose further skill when reproducing sediment yield patterns.

Figures 4.4c and 4.4d subsequently only consider only medium and large flows, i.e., the most relevant hazards and those responsible for most sediment transport and geomorphic changes. On monthly and annual timescales, differences between model output and observations become more apparent. The aggregate seasonal signal produced by the model is bimodal compared with the observed tri-modality; the model fails to capture the peak in April. As such, the model subsequently under and over-estimates the frequency of lahars during and between the apparent seasonal peaks. Similarly, some of the interannual variability is captured, however, again, peaks and troughs in inter-annual lahar frequency are not captured, again resulting in over and under estimation of frequency. The most notable over/under estimation occurs in 2005 (when very few lahars were observed), 2008 (the model forecasts < 50% of observed flows), and 2013-owards (observed reduction in lahar frequency is not captured by the model).

With regards to modelled flow volume, supply and transport limitation, and resultant sediment yield, results produced by the model have some merit. In general, the volumes of modelled flows are within reasonable bounds, as set out by model results by Darnell et al. (2012). While the model does simulate extreme lahars in 2010 (Froude, 2015), it fails to simulate the other observed case of extreme lahar activity in May 2006 (Alexander et al., 2010, Darnell et al., 2012), though a large lahar is simulated around this time. Switches between transport and supply-limited flow are captured with this configuration of model parameters and appear to be in line with the general timing of observations, inferred from evidence in the BRV. Namely, transport-limited flow dominates in years of coincident or recent eruptive activity (much of 2001-2011), whereas supply-limited flow becomes prevalent during 2005-6 and 2012-owards, consistent with evidence of a switch to a degrading channel regime around these times. The observed cycles/fluctuations of sediment yield are also reasonably well simulated with respect to timing and order of magnitude. This said, the magnitude of the 2003 and 2007 peaks are both approximately 30% below observations, and the large, modelled peak 2010-2011 is a considerable departure from observations (350% greater) and difficult to reconcile.

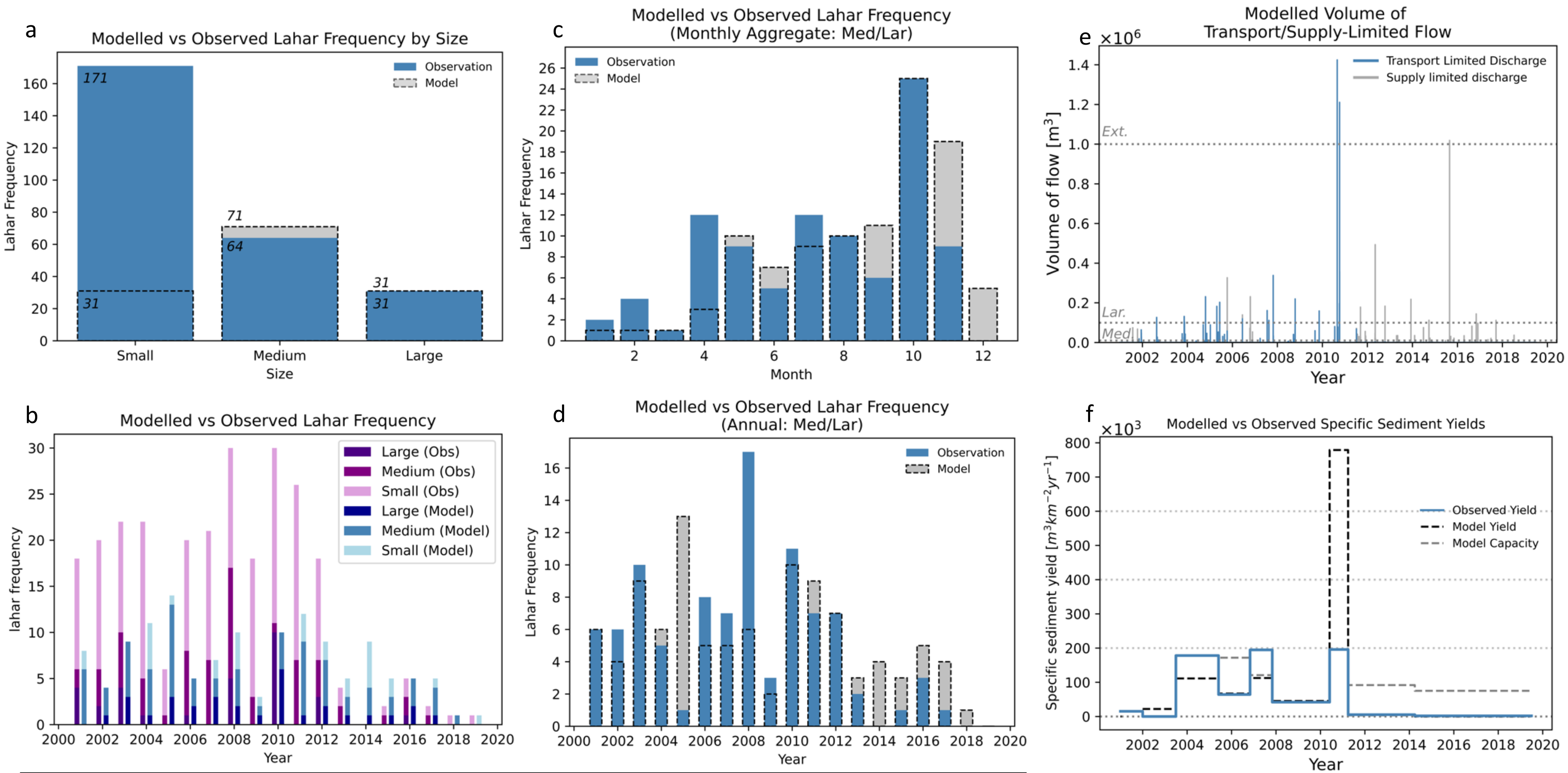


Figure 4.4: a) magnitude-frequency comparison between modelled and observed lahars, clearly demonstrating the under forecasting of small flows; b) break down of modelled and observed lahar magnitude by year; c) comparison of modelled and observed monthly aggregate frequency of medium and large lahars; d) comparison of modelled and observed annual frequency of medium and large lahars; e) volume of modelled transport and supply-limited flows; f) comparison of modelled and observed sediment yield variation over the study period, also showing the specific sediment yield capacity of modelled supply-limited flow.

Forecasting of individual lahars:

SedCas, in its original form, was not designed specifically to act as a predictive/forecasting model owing to the stochastic nature of sediment supply. By contrast, with SedCas_Volcano, all input variables are measured timeseries data (i.e., none are stochastic). Thus, there is an opportunity to explore the model's ability to forecast individual lahar events. Owing to the evident under-forecasting of small flows, I neglected small flows and compared the days on which medium and large lahars were observed versus those on which they were forecast to occur. Figure 4.5 shows a confusion matrix of this comparison, comprising of True Positives ('TP', i.e., hits, where the model correctly forecasts a lahar), True Negatives ('TN', i.e., also a hit, whereby the model correctly forecasts non-occurrences), False Positives ('FP', i.e., false alarms, where the model predicts a lahar but no lahar was observed), and False Negatives ('FN', i.e., misses, where the model fails to forecast an observed lahar). This confusion matrix is accompanied by Table 4.2, which contains scores for commonly adopted categorical forecast skill metrics (e.g., Sohn and Park 2006).

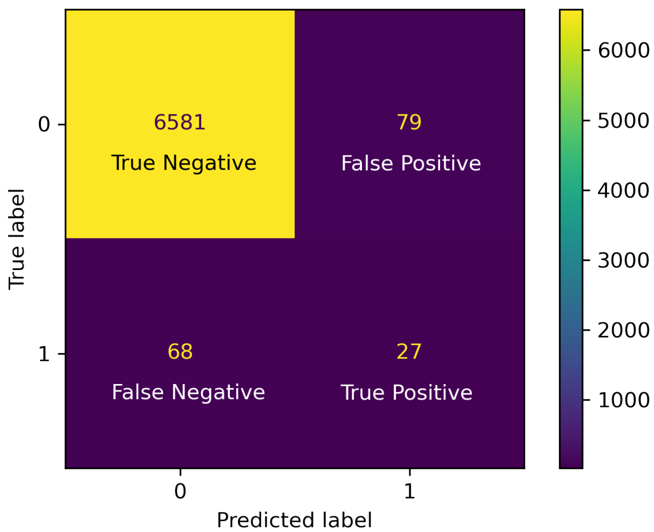


Figure 4.5: Graphical confusion matrix of model-predicted days with medium and large lahars compared to observed days with medium or large lahars. 1 = lahar, 0 = no lahar.

These results indicate that the model is, overall, very accurate (A = 0.97). However, this stems from the model's ability to forecast when a lahar *will not* occur (PoFD = 0.01, i.e., 1% probability that the model will falsely forecast a lahar when no lahar occurs). Forecasting when a lahar *does* occur is of most interest for hazard management. In this respect, it is clear that the model performs rather poorly. SedCas_Volcano achieves a low Hit Rate (0.28) and a high False Alarm Rate (0.74), which means that its Critical Success Index is a very low 0.16. The Heidke Skill Score. (0.26) indicates that the model has a degree of skill compared to chance but that this is low.

Skill test	Score	Description
Accuracy (A)	0.97	$$A = \frac{TP + TN}{ALL}$$ Overall accuracy of model in terms of the proportion of occurrences/non-occurrences that are correctly forecast. Score range: 0 – 1, best score: 1 (does not indicate perfect forecast).
Hit Rate (HR)/ Probability of Detection (PoD)	0.28	$$HR = \frac{TP}{TP + FN}$$ The proportion of observed occurrences correctly forecast. Score range: 0 – 1; best score: 1 (does not indicate perfect forecast).
False Alarm Ratio (FAR)	0.74	$$FAR = \frac{FP}{TP + FP}$$ Proportion of incorrectly forecast occurrences that were observed as non-occurrences. Score range: 0 – 1; best score: 0 (does not indicate perfect forecast).
Probability of False Detection (PoFD)	0.01	$$POFD = \frac{FP}{FP + TN}$$ Proportion of all observed non-occurrences that were incorrectly forecast as occurrences. Score range: 0 – 1; best score: 0 (does not indicate perfect forecast).
Critical Success Index (CSI)	0.16	$$CSI = \frac{TP}{TP + FP + FN}$$ Proportion of all observed and forecasted events that were correctly forecast. Score range: 0 – 1; best score: 1 (indicates perfect forecast).
Heidke Skill Score (HSS)	0.26	$$HSS = \frac{TP \times TN - FP \times FN}{((TP + FP)(TN + FP) + (TP + FN)(TN + FP))/2}$$ Provides an assessment of a forecast's improvement over random chance. Score range: -∞ – 1; best score: 1. Score below 0 indicates no skill.

Table 4.2: Categorical forecast skill metrics (Sohn and Park 2006), scores achieved by SedCas_Volcano when forecasting medium or large lahars, and a brief explanation of each metric.

4.4 Discussion

The performance of SedCas_Volcano is challenging to assess given the nature of its development. There are ways in which the model roughly succeeds in its current configuration: 1) modelled flows are of realistic volumes, consistent with the volumes modelled by Darnell et al. (2012); 2) it approximately reproduces the first-order/aggregate magnitude frequency of *medium and large* lahars over the study period; 3) it is able to approximately reproduce switches between transport- and supply-limited flows (supply limitation in 2005-6 and 2012 onwards); which subsequently allows it to, 4) reproduce the observed fluctuations of sediment yields over the period, at least with respect to timing and relative order of magnitude. It is important to make clear again that these are principal means by which I calibrated the model, so they may be overfitted, and thus are not appropriately diagnostic of its performance. Nonetheless, it is positive that, by accounting for incident and antecedent rainfall, sediment availability, and vegetation cover, these patterns are reproducible by the model, and it demonstrates the *potential* there is for further development to achieve more accurate simulation of the behaviour observed in the Belham River Valley via improved calibration/constraint of parameters.

There are four important ways in which the model does not perform so well: 1) it underestimates the number of small flows; 2) it does not fully capture inter-annual and inter-seasonal patterns; 3) modelled sediment yields, particularly in 2010, are some way from observations; and 4) it performs poorly when forecasting individual medium and large lahars. These shortfalls can be related to limitations of the model (processes accounted for within it, or not), data (its composition and accuracy) and the challenges associated with model development. Crucially, SedCas_Volcano is simple. It does not set out to simulate the complex array of physical processes involved with lahar generation and sediment transport. Ultimately, this exercise serves as an interesting experiment to establish to what degree such a complex system might be simulated within this kind of computationally inexpensive and highly simplified modelling framework.

Firstly, to discuss the model's inability to model small flows, despite steps taken to address this issue (e.g., parameter modifications to encourage discharge generation), and its limited performance when forecasting the timing of medium and large flows. There are four plausible reasons for these shortfalls, all of which may apply to some degree: 1) the existing model parameter values may be inappropriate; 2) the GPM data is not fully representative of the rainfall occurring on the ground; 3) there are additional processes that are unaccounted for in the model; and 4) there may be a problem within the model that I have been unable to identify via troubleshooting which inhibits the generation of small flows in particular. With regards to 1) this is very likely owing to some of these parameters being effectively totally unconstrained and the trial-and-error means of calibration I have used. This could be addressed by having better constraints on the hydrological parameters, either by using more robust calibration methods (e.g., Monte Carlo simulations, Hirschberg et al., 2021), or ideally by acquiring empirical constraints by making observations on the ground (neither of which were possible during the course of this PhD). Regarding 2), this is inevitable and not resolvable, as it is a function of the nature of the data; GPM is spatio-temporally averaged and thus will necessarily not be entirely representative. Crucially, a) it will likely fail to detect the true intensity of short-lived high-intensity rainfall events associated with common meso-scale weather systems (Matthews et al., 2002; Barclay et al., 2007) a problem also observed elsewhere (e.g., Pradhan et al., 2022, and references therein), and b) will inevitably include rainfall that may not be occurring within the catchment (much of the cell covers the east of the island and the ocean). Again, lahars have been observed on days with very low, or no recorded rainfall, and not on days on which high rainfall has occurred (please refer to figure 3.6). This will explain some of the false positives/negatives of the model forecasting, and indeed will have an important control of modelled sediment transport. An alternative source of rainfall data would be required to make improvements on this. It would be interesting to use the available rain gauge data instead, or, alternatively, access to radar data that is able to capture summit/source area rainfall would be ideal for other studies (Dinku et al., 2002; Froude, 2015). This was not available for this study, though Meteo France operate a weather radar in Guadeloupe which covers Montserrat which could be used in future work (Froude, 2015). Difficulty capturing rainfall over mountainous or complex terrain is a common problem owing to inaccessibility for rain gauge installation, inhospitable conditions for rain gauge installation (e.g., risk of destruction by volcanic activity), lack of spatial resolution of data (e.g., satellite-derived estimates), and topography induced errors (e.g., radar) (Dinku et al., 2002, 2009; Matthews et al., 2002; Mashingia et al., 2014; Gilewsky and Nawalany, 2018; Gilewsky, 2021). Thus, until improvements are made, fluvial and geomorphic modelling efforts will always be limited by this problem (Pradhan et al., 2022).

The third point above, regarding additional processes that are unaccounted for in the model, is also likely to be key in understanding other shortfalls, namely the inability to fully capture inter-annual and inter-seasonal patterns. Two processes are missing from the model structure. Of greatest pertinence is that modifications to the surface and general character of deposits, and the subsequent impact this has on hydraulic response, are not accounted for by SedCas_Volcano. This is potentially important on two counts. Firstly, the multi-modal seasonal variation of lahar activity recorded in the BRV has been observed previously by Barclay et al. (2007) and has been postulated to be related to changes in hydraulic response of deposits driven by evolving antecedent conditions, including prolonged dry periods (i.e., the dry season, ~Dec-Mar). Prolonged dry periods have a mixed effect on runoff response from land surfaces. In some cases, it appears that dry periods encourage runoff, likely due to surface crusting/sealing (Doerr et al., 2000; Cerdà and Doerr 2007), in other cases runoff decreases owing to increased infiltration driven by moisture deficit or surface cracking (Penna et al., 2011; dos Santos et al., 2016; Shoener and Stone 2019). On volcanic surfaces, again, similar disparity exists in findings; Jones et al. (2017) find that dry periods encourage infiltration into deposit surfaces, whereas Capra et al. (2010, 2018) find that hydrorepellency caused by deposit dryness encourages runoff generation. Indeed, Capra (2010, 2018) find that lahars become more likely at lower rainfall intensities when preceded by dryness and observe a similar early rainy season peak in lahar activity. It may be that deposits on Montserrat undergo sealing during dry periods which encourages higher runoff rates in response to rainfall in the early rainy season (Barclay et al., 2007). This is not accounted for in SedCas_Volcano and may explain the model's inability to capture the early peak in lahar activity in the early wet season (April, Figure 4.4c).

Secondly, though the model accounts for the availability of sediment, this only considers the bulk volume of sediment, not the nature (e.g., grain size) of the available sediment, nor the degree of channelisation of deposits. Sediment grain size distribution of volcanic deposits is known to be an important control on runoff. The presence of finer tephra grains inhibits infiltration and encourage greater rates of runoff (Pierson and Major 2014; Jones et al., 2017). Sediment is removed from deposits preferentially according to grain size. Small grains are more readily eroded by streamflow, with larger grains, such as boulders, only being mobilised by rarer, high discharge flows which have sufficient competence to displace them (Alexander and Cooker 2016). Thus, winnowing (the preferential removal of fine grains) progressively occurs on the surface of deposits and channel beds. This can increase the infiltration capacity of the deposit and thereby restrict the magnitude of generated runoff (Major and Yamakoshi 2005; Pierson and Major 2014). By having a single parameter to represent the hydraulic response of the deposit through time, SedCas_Volcano will not capture this effect. Thus, the failure of the model to capture the decrease in flow activity in periods of limited sediment supply with relatively high rainfall (2005/2006, 2013 onwards) may be caused by this. The unchanging hydrological parameters representing the deposit may therefore be causing underestimation of the amount of runoff generated in periods of high sediment availability; conversely, in periods of low sediment availability, runoff generation may be overestimated. Modification to the structure of the deposit HRU to enable variable hydrological parameters could account for this.

Speculatively, the second missing process is potential impacts from hydrothermal activity. Montserrat's subterranean hydrology is complex; around SHV this likely (using the Centre Hills as an analogue) consists of a combination of perched aquifers as well as an active hydrothermal system, with approximately 20% of annual rainfall contributing to aquifer recharge (Hemmings et al., 2015). Ground water-driven spring activity is to some extent a determinant of ephemeral flow in some ghauts of the Centre Hills (Hemmings et al., 2015). While evidence of changes to ground water and spring activity is not available for the surrounds of SHV (2 springs were identified in the BR catchment by Walker (1965), one now buried beneath the Farrell's Plain debris fan), interaction of magma with groundwater is known and/or inferred to have occurred at SHV (phreatic explosions preceded eruption of juvenile magma in 1995, Sparks et al., 2002; Hautmann et al., 2010, have inferred volcano-induced ground water movements). Magma-induced changes to ground water and spring activity have also been observed or inferred at other volcanic systems (Shibata and Akita, 2001; Hurwitz and Johnston, 2003; Kopylova and Boldina, 2012; Jasim et al., 2018). It may be that there is some influence of spring-derived water availability associated with magma-induced alteration to groundwater during periods of heightened volcanic activity, and less so during quiescent periods. This is entirely speculative, but it could explain some of the missing inter-annual variability in model output.

With respect to the modelling of sediment yields, all the limitations noted above impact on this as lahars are the principal agents of yield. The below-observation yields modelled in 2003/4 and 2006/7 are caused by insufficient transport capacity of modelled flows occurring during these windows of time and could be better matched by increasing water availability by altering the hydrological parameters. However, making these adjustments further increases the discharge modelled for 2010/11, generating yield values that are even more unrealistic than they already are. Unfortunately, it is not clear why the 2010/11 discharge, transport capacity, and thus yield, are so much higher than observed. It may be due to an overestimation of rainfall for the large hurricane-related rainfall events observed in 2010 (Froude, 2015). Alternatively, perhaps the model overestimates the impact of vegetation on runoff dynamics, and this becomes most apparent when vegetation is most depleted, combined with the most intense rainfall activity, as was the case in 2010. Part of this may be related to deposit channelisation not being incorporated into the model. Channel confinement reduces the quantity of sediment available for flows, as flows become spatially more focussed, thereby accessing less sediment (Pierson and Major 2014). It may be that in reality the development of channels reduced the quantity of sediment available to the large flows in 2010, thereby exerting a limit on sediment yield. Along a similar vein, this discrepancy may also be related to the alteration in drainage structure that occurred between 2009-2010. This led to the diversion of a portion of summit runoff via Hussey Ghaut rather than Tyer's Ghaut. It is possible that this loss of discharge inhibited erosion of sediments in Tyer's Ghaut, thereby reducing the yield from this reach compared to previous periods despite the large quantity of available sediment. In future applications of this model framework, it might be possible to introduce a number of reservoirs to represent the upper catchment, one for each sub-catchment. These could each have their own water and sediment storage, as well as a variable area. This could enable the simulation of discharge from sub-catchments as they change in size.

A further limitation of this modelling exercise, as with Chapter 3, is the detection of and designation of the size of observed lahars; this is a very important consideration as they form a key part of the calibration process. Firstly, it is noted in the literature that monitoring of lahars has not occurred systematically, and many events may not be included in the record owing to monitoring attention being focussed elsewhere (Barclay et al., 2007; Darnell et al., 2012; Froude, 2015). This prevents the establishment of a full picture of the activity in the BRV and therefore makes comparison with the model more challenging. For example, on some days on which high rainfall has been recorded but no lahar recorded, this may be due to the lahar being missed, rather than no lahar actually happening. Secondly, the categorical, but mostly unknown volume of observed flows is a challenge as the volumetric thresholds for these categories are not defined and thus may not align with the assigned L_{vols} thresholds applied to the model output. Further, the lahar record considers lahars occurring along the *entire* Belham River channel; this includes any flow emanating from the UTR, as well as *additional* discharge emanating from hillslopes surrounding the LDR, via, for example, the Sappit River. Additional discharge from outside the UTR complicates the comparison of modelled vs observed flows. For example, a small lahar (as defined by L_{vols}) may emerge from the UTR, but be enlarged/bulked by the additional discharge from slopes draining into the LDR, and thus increase in magnitude and may in theory be registered as medium. In addition, the extra water discharge will dilute the flow, thereby altering its sediment concentration and transport capacity, influencing the channel bed response. Thus, there is a lot of uncertainty in the comparison of the model output and observations. A future iteration of the model could include the LDR, model this additional discharge, as well as aggradation and degradational behaviour.

Overall, this experiment with SedCas_Volcano has garnered some valuable insights. It has demonstrated that with approximate measures of sediment input and availability, rainfall, and vegetation cover it is possible to broadly capture some of the first-order patterns of lahar incidence and sediment transfer in the Belham River Valley. It also demonstrates that fluvio-sedimentary systems impacted by volcanic eruptions are highly complex and dynamic systems. By demonstrating the latter, it clearly shows the need for more research, particularly in terms of parameterisation and consideration of more processes to improve the efficacy and potential utility of this type of modelling framework. Ultimately, the accuracy and value of the output of any model is dependent on the accuracy of its inputs.

With further development, SedCas_Volcano has the potential to provide a useful means of estimating the possible variation in lahar magnitude within the context of evolving catchment conditions. The original iteration of SedCas (Bennett et al., 2014; Hirschberg 2021) has been used to model produce forecasts of debris flows and sediment yield based upon climate change scenarios. With improved calibration, SedCas_Volcano could be applied in a similar forecasting manner, based upon eruption scenarios. Such a capability could potentially serve hazard management in the event of renewed activity at SHV. However, this estimation of flow magnitude is its limit; it is spatially lumped and therefore does not provide information relating to the spatial threat of flows. With this in mind, SedCas_Volcano instead has the potential to form the first part of a modelling chain (Figure 4.6): 1) observations of the catchment and climatic variables are supplied to SedCas_Volcano, which 2) produces an output of estimated flow volumes, which 3) may then be fed into a spatially integrated mass-flow model, such as LAHARZ (though it is important to note that LAHARZ has been calibrated specifically for a set flow type). In theory, such a process chain could enable the relation of measurable conditions in lahar source areas to potential inundation zones (if adequate topographic data is available) which could then inform hazard/risk assessments.

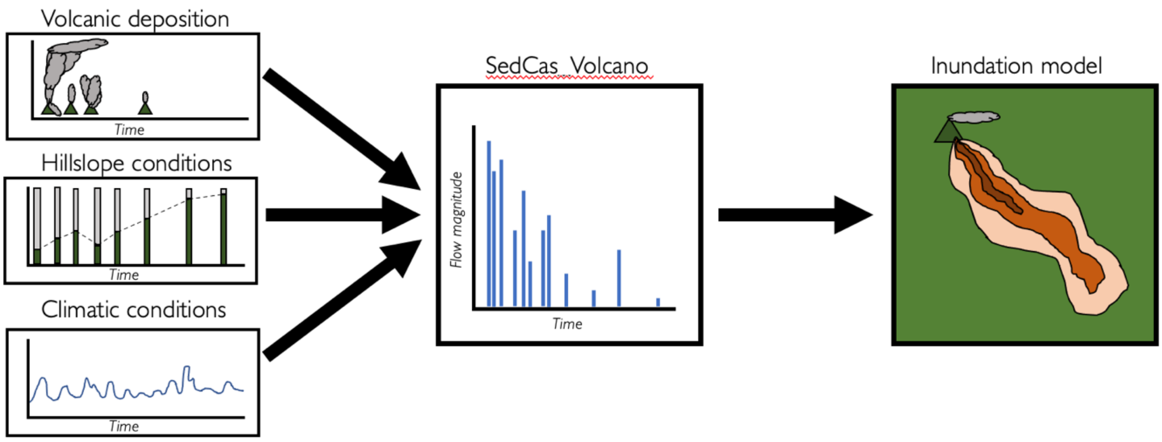


Figure 4.6: Schematic example of a potential modelling chain relating catchment/ environmental conditions to mass-flow inundation models (e.g., LAHARZ), via the use of SedCas_Volcano.

4.5 Conclusions

In this chapter I have adapted SedCas (Bennett et al., 2014; Hirschberg et al., 2021) to suit a volcanic disturbance setting to simulate multi-decadal lahar activity, in what I believe is a first of its kind study. This simple numerical model was designed to simulate the first-order patterns of debris flow activity and sediment yield from the Illgraben, Switzerland, in response to episodic sediment supply from seasonal landsliding. I have modified this model framework to produce SedCas_Volcano by making modifications to: 1) enable sediment supply by timeseries (to allow use of the sediment supply time series provided by Chapter 2; allow emulation of both infiltration excess and short-term (3 day) storage of antecedent rainfall within volcanic deposits; and 3) account for changing vegetation cover observed in the Belham River Valley (Chapter 2). Parameterisation of the model was completed in part with guidance from published findings and results from earlier in this thesis, as well as by iterative/trial-and-error calibration by comparing model outputs with observations. I have presented the best fit model outputs. The results show that by accounting for sediment supply, rainfall patterns and vegetation cover change, SedCas_Volcano is able to 1) simulate flows with realistic volumes; 2) broadly capture the first-order patterns of medium and large lahars (i.e., those that are most hazardous); and 3) is able to simulate the timing and relative order of magnitude of rises and falls in sediment yield over the study period. However, shortfalls have been identified, namely: 1) small lahars are severely under forecast (though this accounts for a very small amount of total sediment yield); 2) seasonal and inter-annual patterns are not fully simulated; 3) simulated sediment yields, while within the same order of magnitude, were at one point 350% higher than observed; and 4) the model performs poorly when forecasting the occurrence of individual flows. I have discussed these shortfalls with respect to inherent limitations of the model framework, namely that it is a simple model and there are processes unaccounted for within it (e.g., changes to deposit hydrology), and limitations of the data (e.g., GPM rainfall, limitations of the lahar record). Overall, this exercise has proved as a valuable experiment and has demonstrated that this form of simple, computationally inexpensive numerical model has promise for modelling decadal-scale evolution of volcanically-disturbed watersheds, but that improvements are needed with respect to the processes considered and the nature of parameterisation/calibration.

Chapter 5: 'Mountain Aglow'- Evaluating the merits of co-creation in disaster risk management practices on the island of Montserrat

The previous chapters of this thesis have explored the legacies of the eruption of Soufrière Hills Volcano that remain within the landscape of the Belham River Valley, Montserrat. This chapter diverges from this and considers how the cultural legacies of the eruption – the songs, poems, and stories, all based on the lived experience of the eruption – might be used as a means of raising awareness, learning how to live with volcanic risk, and how to cope with the impacts of volcanic eruption, if surface activity were to resume at SHV. This step away from the physical impacts of eruptions on landscapes and their response is relevant to this thesis because of my role as a Research Assistant in the Mountain Aglow project. My involvement in this was a major part of my development as a researcher over the course of this PhD and presented an invaluable opportunity to build interdisciplinary skills. My supervisors and I agreed that it would be of benefit to gain some research output related to the work I had done on the project. A full introduction to the relevant fields of research is provided in Section 1.3; in this introductory section I will reintroduce the general rationale, describe Mountain Aglow and detail my involvement in the project.

5.1 Introduction

Community preparedness is an essential component of effective Disaster Risk Reduction (DRR) and key for bolstering community capacity and resilience in the face of disaster (Paton and Johnson 2001; Kitagawa 2016). Awareness is considered an essential prerequisite for improved preparedness (e.g., Paton and Johnston 2001; Eisenman et al., 2009; Shaw et al., 2009; Lindell and Perry 2012; UNDRR 2015). Effectively engaging and educating the public to build their awareness of environmental hazards and how to respond to them (Disaster Risk Education; DRE) is thus a primary focus for Disaster Risk Management (DRM; the implementation of policies and strategies to reduce and prevent risk) (UNDRR 2015). Traditionally, a wide range of active and passive (e.g., evacuation orders and signage) macro-level, top-down approaches may be employed, whereby experts and authorities work together to assess the risk and provide advisories for the public to act upon (e.g., Glik 2007; Cadag and Gaillard 2012; Gaillard et al., 2013). However, despite this broad array of means to communicate disaster risk at their disposal, disaster managers are still regularly confronted by disasters brought about by preparatory or responsive action not being taken by affected individuals (Gaillard et al., 2013; Sufri et al., 2020; Dallo et al., 2022). Inaction may be a result of competing priorities (e.g., relating to wellbeing or actions to secure livelihoods), alternate beliefs (e.g., religious attitudes), and an incomplete understanding of hazard impacts and timescales given the inherently complex and uncertainty-laden nature of environmental risks (Barclay et al., 2019; Sufri et al., 2020; Bankoff 2021; Lejano et al., 2021; Dallo et al. 2022).

Alternate knowledges of hazards, with local/contextual, experiential, or traditional bases, which are not solely grounded in the timescales or causal sequencing associated with scientific analysis, are increasingly recognised as an important consideration for DRM (Parker and Handmer 1998; Gaillard et al., 2013; Whitman et al., 2015; Kitagawa 2016; Lejano et al., 2021). Indeed, previous research based on volcanoes (e.g., Cronin et al., 2004; Armijos et al., 2017; Joseph et al., 2022), and within a wider risk context (e.g., Eisenman et al., 2009; Walshe and Nunn 2012, Uekusa et al., 2020 and references therein, Lejano et al., 2021), have demonstrated that community-level understandings are beneficial to improving community resilience and response to disaster risk.

The intertwining of scientific and alternate/experiential knowledges, though relatively novel as a concept, is thus increasingly viewed as beneficial for the development of locally and culturally appropriate Disaster Risk Reduction strategies (UNISDR 2015, Lejano et al., 2021, Sevilla et al., in review). Co-creation frameworks, whereby different forms of knowledge and perspectives from a range of stakeholders (scientists, DRR practitioners, public bodies, communities and individuals) are given parity of respect, are encouraged in order to combine these knowledges (e.g., Cronin et al., 2004; Lejano et al., 2021; Vargas et al., 2022; Sevilla et al., in review). On one hand, the inclusion of culturally-relevant information/knowledge increases the potential relevance of communicated material; on the other, co-creation frameworks provide an opportunity for co-learning, a means to improve our understanding, as scientists, of the local and cultural context into which we are communicating. Thus, co-creation not only enables the incorporation and dissemination of numerous knowledges, but also helps scientists to situate their scientific knowledge within the local cultural context and reframe their communications to better suit and complement the needs and knowledge of the communities they work with. To date, limited research has quantified and demonstrated the positive impact of co-created initiatives in a DRR context (Cadag and Gaillard, 2013; Lejano et al., 2021; Sevilla et al., 2022).

Mountain Aglow

This chapter presents and evaluates ‘Mountain Aglow’, an innovative co-created multi-media DRR initiative for communicating volcanic risk and sharing eruption experiences to inform coping with volcanic risk in Montserrat. This initiative sought to broaden the scope and reach of disaster risk education practices on Montserrat by introducing alternate, i.e., not solely scientific disaster knowledges (e.g., individual/local disaster experience, portrayed by imagery, songs, poetry, story-telling), as important means of engaging at-risk populations and situating scientific communications within the local/cultural context. In doing so, its goal was to enhance DRR activities by widening their reach/outcomes and deepening their impact. This section explains the initiative, its background, and provides details of the stages of its development.

The Mountain Aglow (MA) exhibit (Figure 5.1) was produced in 2019 as part of the Arts and Humanities Research Council (AHRC) and Global Challenges Research Fund-funded (GCRF) '*Disasters Passed*' project. Disasters Passed drew upon findings from previous research in Dominica, St Vincent and the Grenadines, and Montserrat. In particular, it built upon insights gained from an antecedent project 'Explosive Transformations', which was based on St Vincent. This research established three fundamental findings: (1) cultural responses to hazardous events in the Caribbean contain powerful knowledge about impacts, response, and recovery; (2) their transmission provides a strong mechanism to include communities in their own preparedness and recovery; (3) both the historical and recent past contain important knowledge that deepens understanding of how and why people place themselves in areas of high risk. A co-created arts/science exhibit, 'Soufrière Blow', was produced as part of this research, centred on the experience of the 1902 and 1979 eruptions of La Soufrière Volcano, St Vincent and the Grenadines. It was designed to complement the formal volcanic risk messaging on the island by encouraging the sharing of experiences and bolster community resilience in this multi-hazard environment.

Figure 5.1: a) (left) the Mountain Aglow exhibit with the Soufrière Hills Volcano in the background, and b) (right): the Mountain Aglow exhibit lit up by FLOW performing its 'magma and rockfalls' simulation.

Disaster Passed sought to build upon this to improve how we, as scientists, share and engage with volcano-impacted communities by: 1) sharing the importance of cultural and historical knowledge in disaster risk reduction in the Caribbean; 2) engaging in a process of collaborative learning with DRR partners to develop the vehicles for how we share this information; in order to 3) develop of a deeper understanding of how cultural and natural histories can be effectively integrated and celebrated, and how this can inform and shape strategies for disaster risk reduction. The aim was to develop two co-created (i.e., involving the participation of scientists, civil authorities, and members of the public) exhibits and a website (https://www.mountainaglow.com) combining personal perspectives and insights of the lived experience of environmental disasters in the Caribbean, in the form of arts/cultural products/narratives, with scientific/risk information. One of these exhibits, Mountain Aglow, was based on Montserratian experiences and intended for use in Montserrat. A second exhibit was to draw upon experience and research from Montserrat, St Vincent and Dominica and be designed for use in the UK to open a dialogue with government and policymakers with respect to aid and international development.

In this work I focus only on Mountain Aglow, the Montserrat-centred part of the project. The overall aim of Mountain Aglow was to collate artistic and scientific material specific to Montserrat and subsequently curate innovative exhibits/communication tools that would encourage engagement from a wide range of end users in Montserrat. The desired outcomes were: 1) the enhancement of the repertoire of communication tools available to risk managers; 2) the encouragement of inter-demographic and inter-generational story-sharing related to experiences of the eruption; 3) an increase in the perceived relevance of DRR communications within a larger portion of the community and subsequently greater engagement with DRR.

The MA exhibit itself centres on the eruption of the Soufrière Hills Volcano, contextualising it within social and geological histories of Montserrat. It consists of 1) an aluminium square-based pyramidal frame with information panels suspended off it (Figure 5.1a/b), and 2) 'FLOW', a 3m LED tower with attached lights and speakers. It was co-created via consultation with and discussion between UK and Caribbean scientists, DRR practitioners, public organisations, and individuals from a variety of societal sectors. The following subsections will detail each stage of the project. Figure 5.2 shows the timeline of the project, broken down into four stages. 5.3 shows network diagrams of the involvement of, and interaction between, stakeholders in each stage of the project. Table 5.1 provides details of the institutions involved, including acronyms used to represent them.

Institution	*Role and contribution to the project*
DRR	
Montserrat Volcano Observatory (MVO)	*Role:* Monitor and document the activity of the volcano in real-time; provide advisories to/collaborate with government/government bodies (e.g., DMCA, see below) and communicate with general public (e.g., weekly/annual reports, setting of hazard level system to control exclusion zone access, outreach); scientific staff also undertake their own research and facilitate research by external scientists. *Project contribution:* Integral to Stages 1-3, contributed to stage 4 (three staff were interviewed and 1 provided essential logistical support).
Disaster Management Coordination Agency (DMCA)	*Role:* Government branch responsible for issuing warnings and leading response to any kind of natural phenomena that may induce disaster on the island (includes volcano, hurricanes, flash floods, earthquakes, tsunamis); control the access to the Exclusion Zone (in coordination with the MVO and the Royal Montserrat Police Service (RMPS)); educate the local population about the natural hazards affecting Montserrat. *Project contribution:* Contributed to Stage 1 and Stage 4 (two staff members were interviewed, provided exhibit materials), integral to Stage 3 (coordination of workshops and launch).
Montserrat Red Cross (MRC)	*Role:* Provide day-to-day support for those in need on the island (primarily the elderly) as well as humanitarian assistance in the event of a disaster (e.g., provision of supplies, emergency shelter); disaster response activity coordinated by the DMCA. *Project Contribution:* Contributed to Stage 1 (three members of staff/volunteers interviewed) and Stage 4 (two staff members/volunteers interviewed).
Non-DRR	
Ministry of Education, Youth Affairs and Sport (MoE, includes schools)	*Role:* government department charged with the establishment and maintenance of the national curriculum and the support of the three primary schools and one secondary school on Montserrat: *Brades Primary School (BPS), Lookout Primary School (LPS), St Augustine Primary School (SAPS; private school with slightly different funding/curriculum)* and *Montserrat Secondary School (MSS).* *Project Contribution: Integral to Stage 3 (workshops and activities run via schools) and contributed to Stage 4 (one interview and three focus groups).*
Government of Montserrat/Office of the Governor (GoM)	*Role:* governing powers of Montserrat, includes the locally elected parliament and the UK-representing Governor's Office. *Project Contribution:* Contributed to Stages 1 (consultation) and 3 (logistic support for launch).
Montserrat National Trust (MNT)	*Role:* Responsible for the documentation, archiving and preservation of Montserratian history and culture; educate the public; tourism. *Project Contribution: Contributed to all stages (Stage 1: one member of staff interviewed, provided access to exhibit materials; Stage 2: hosted the exhibit; Stage 3: logistic support; Stage 4: one member of staff interviewed).*
Montserrat Arts Council (MAC)	*Role:* celebrate and promote the continuation of Montserratian culture, particularly with regards to the arts. *Project Contribution: Contributed to Stages 1 (one member of staff interviewed, logistic support for MA launch), 3 (logistic support for MAJ launch) and 4 (one member of staff interviewed).*
Montserrat Public Library (MPL)	*Role:* serves as an educational and community hub. *Project Contribution: Contributed to Stages 1 (one member of staff interviewed) and 4 (logistic support and one member of staff interviewed).*
Montserrat Farmers' Association (MFA)	*Role:* professional association of Montserratian small-holding farmers. *Project Contribution: Contributed to Stage 1 (focus group).*
Montserrat Tourist Board (MTB)	*Role:* official tourism office of Montserrat, responsible for designing and implementing tourism-related initiatives. *Project Contribution: Contributed to Stage 1 (focus group).*
Montserrat Tour Guides Association (MTGA)	*Role:* professional association of tour guides. *Project Contribution: Contributed to Stages 1 (group discussion) and 4 (one member interviewed, informal conversation with another).*

Table 5.1: List of organisations involved with the Mountain Aglow Initiative

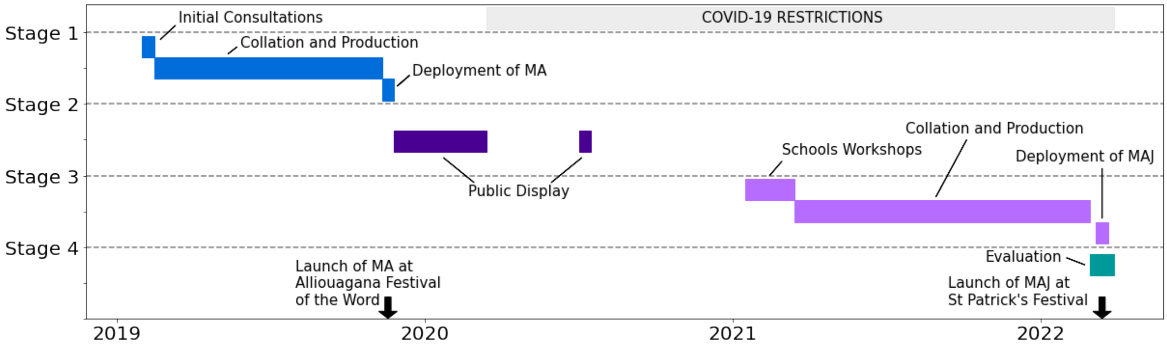


Figure 5.2: Timeline of the Mountain Aglow initiative

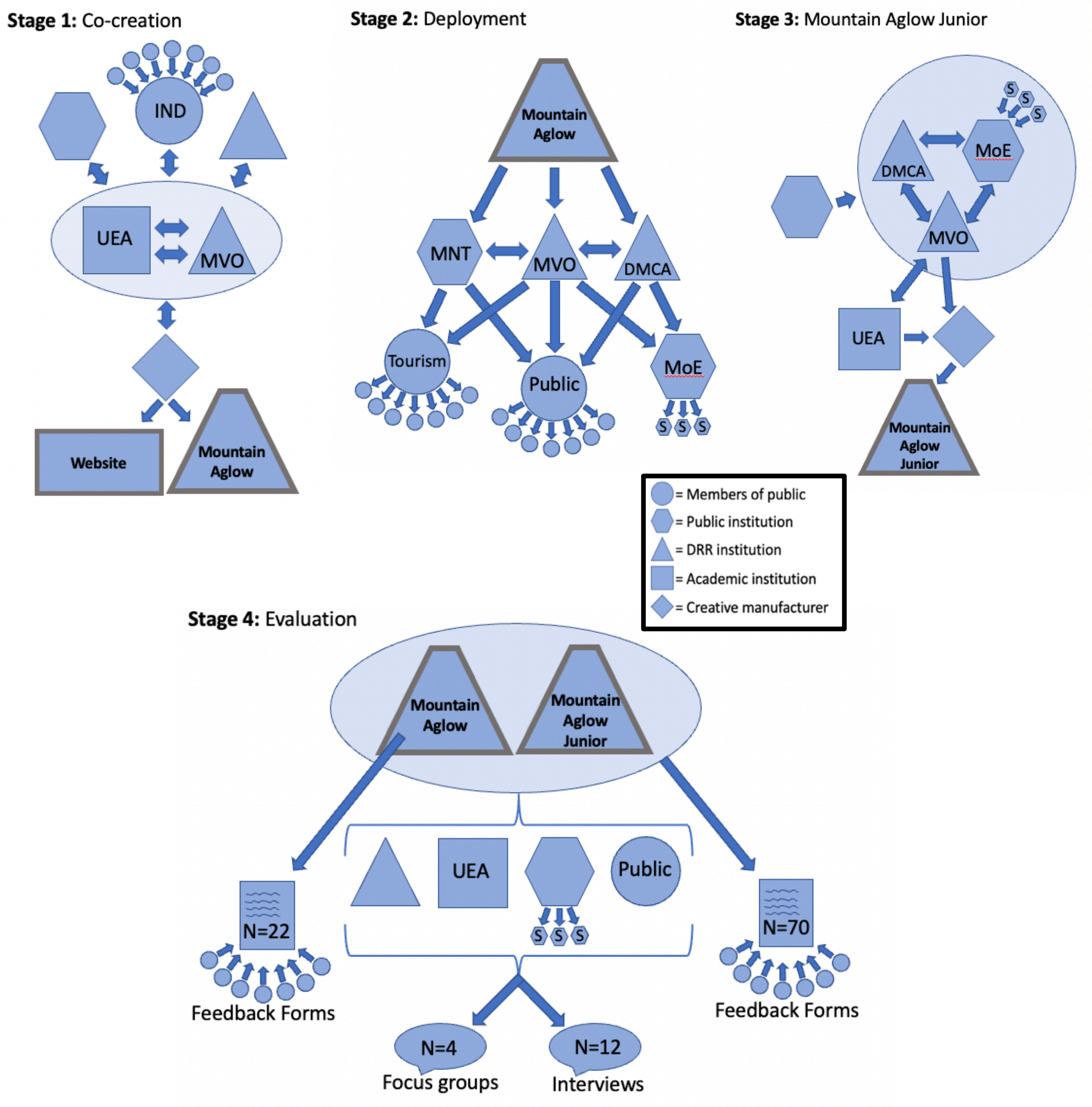


Figure 5.3: Network diagrams of each stage of Mountain Aglow, showing the involvement of key organisations.

Stage 1: co-creation, production, and delivery

The concept of Mountain Aglow was first conceived by UK and Caribbean scientists following the success of Soufrière Blow. Discussions held among these scientists identified potential limitations of existing volcanic risk communication strategies in Montserrat. MVO and DMCA communications to the public consisted of: social media posting; a semi-regular radio show on national radio featuring MVO scientists; visits to MVO by school groups; visits predominantly by tourists to MVO view a video documentary about the eruption; an MVO creative writing competition for children. These discussions among scientists also established the key scientific concepts that needed to be conveyed, e.g., the geological history of the island, subsurface processes, and key methods of monitoring. Initial consultations with wider Montserrat project partners took place during a two-week field campaign in February 2019, which consisted of a series of interviews and focus groups. Further discussions with other non-scientist stakeholders steered/informed the choice of themes for each exhibit panel which were as follows:

- *'Before and After'*, exploring how the island had changed as a result of the eruption;
- *'Volcano Island'*, describing the geologic and social/historical context of the eruption, including timelines of the last 1000 years, and of the eruption itself;
- *'Falling Ash and Stones'*, describing the experience of living with ash fall during the eruption;
- *'Volcano Guts/Watching the Volcano'*, including brief descriptions of the ways in which scientists monitor the volcano;
- *'Moving, Crossing and Leaving'*, capturing the experience of evacuations from the south to the north, or eventually overseas;
- *'Moments of Light and Laughter'*, capturing the brighter, more beautiful side of living with an erupting volcano.

Between March and September 2019, following the establishment of themes, UEA/MVO acquired access and reproduction permissions for photographs, music, art, poetry via contact with stakeholders, or direct contact with individual Montserratians or members of the diaspora via radio appearances and social media. UEA/MVO partners then selected the visual/text materials for exhibit panels, which were designed in partnership with RockSolid Graphics (UK). The unused material was then included on the website. Ongoing discussions with stakeholders spurred the development of an audio-visual component of the exhibit to enhance its sensory impact and broaden types of information the exhibit could convey. MVO subsequently held recorded story-telling interviews with Montserratians about their experiences of the eruptions. Meanwhile, UEA worked with OutPut Arts (UK) to produce 'FLOW', a 3m LED column, with attached speakers and LED strings, able to: 1) perform programmed light sequences to convey aspects of the themes (e.g., rising magma, falling ash), 2) play music and audio recordings from interviews with participants, and 3) simulate the glowing rock falls from the lava dome that so many participants spoke of. Stakeholders in Montserrat were kept updated and asked for feedback by email as the process went along throughout 2019.

Mountain Aglow was initially launched in October 2019 at Norwich Science Festival in the UK, before being unveiled in Montserrat at the Alliouagana Festival of the Word, in early November 2019. The UEA/MVO team hosted the exhibit at both launches and kept reflective diaries to evaluate engagement with, and perceptions of, the exhibits.

Stage 2: Deployment and public display

Mountain Aglow was initially launched in October 2019 at Norwich Science Festival in the UK, before being unveiled in Montserrat at the Alliouagana Festival of the Word, in early November 2019. The UEA/MVO team hosted the exhibit at both launches and kept reflective diaries to evaluate engagement with, and perceptions of, the exhibits.

Following delivery and launch, the MA exhibit was left with Montserratian project partners to use as they saw fit. The exhibit was hosted at the Montserrat National Trust/National Museum between November 2019 and March 2020 (MVO staff assisted some hosting). Public display was inevitably curtailed by the onset of COVID-19 restrictions. In July 2020 the exhibit was on display for three weeks to mark 25th anniversary of the eruption. During these periods, the exhibit was visited by Montserratians and tourists, some of whom completed feedback forms.

Stage 3: Mountain Aglow Junior

In January 2021 MVO and DMCA joined forces to instigate Mountain Aglow Junior (MAJ), an initiative designed specifically to engage primary school children. Between January and March 2021 the Mountain Aglow Exhibit installed at each of the primary schools for one week. Several workshops given to Grade 5 and 6 students (ages 9-10) by MVO, DMCA, former government (in office during the onset of eruption), musicians/Calypsonians, and other members of the public, offering various perspectives of the eruption. These workshops were led by MVO/DMCA and held in classrooms aside from one session which was a field trip to Plymouth. The children were tasked with creating artistic products (e.g., paintings, poems) based on what they had learned and/or experienced during workshops and encouraged to hold their own story-telling interviews with members of their family or wider community. Each of the six classes was assigned with a theme from the original exhibit to focus on.

Once the children's material had been collected, MVO led the design of new exhibit panels in collaboration with teachers from the schools between March 2021 and January 2022. Production of panels completed by RockSolid Graphics (UK), mediated by UK project partners. The finished MAJ Exhibit launched at a special launch night as part of the annual national St Patrick's festival in March 2022, hosted by MVO, DMCA, the schools and GoM. Both exhibits (MA and MAJ) were installed at the Montserrat Cultural Centre throughout much of St Patrick's festival, and thereby formed a peripheral part of many other events. Representatives of the MVO and UEA were present at all events to host the exhibits to encourage engagement, assist completion of feedback forms and make observations which were recorded in reflective diaries.

Stage 4: Evaluation

I was involved in Mountain Aglow between February and November 2019, i.e., Stage 1, while employed as a research assistant by the Disasters Passed project. I assisted in most aspects of the work carried out by the project during this period. In this role, I:

- Attended and led interviews and focus groups with project partners/stakeholders in Montserrat during the consultation phase in February 2019;
- Held responsibility for assisting the collation of materials (pictures, songs, poems) by approaching our Montserratian project partners and members of the public in Montserrat or the Montserratian diaspora in the UK;
- Assisted and at times oversaw the design and manufacturing process by working with UK project partners Rock Solid Graphics;
- Helped lead the unveiling of the exhibit in Norwich in October 2019;
- Took charge of the logistics involved with the deployment of the exhibit to Montserrat in November 2019;
- Formed part of the team of UK and MVO scientists who hosted events during its unveiling.

Given my extensive involvement in the first stage of the project, and my deep enjoyment of it, I was in a good position to conduct an evaluative study to assess its impact. Progress towards the completion of this PhD was delayed by the COVID-19 Pandemic and my subsequent shift to part-time to manage some health issues. Fortuitously, the subsequent delay to the end of my studentship aligned with the reopening of the borders and reduction of public health restrictions in Montserrat and the St Patrick's festival. I therefore found myself with a short notice opportunity to carry out this evaluative analysis. As I have stated, this has been an important part of my development as a researcher and thus warrants inclusion in this thesis.

This chapter is the product of *Stage 4* (Evaluation) which draws upon reflections and feedback (e.g., visitor feedback forms and reflections by the UK/MVO team) from throughout each stage of the project, as well as via interviews/focus groups held with stakeholders/exhibit visitors during a field campaign in March 2022. Evaluation of engagement projects is essential to 1) reflect upon the process of their development, 2) assess how well they perform in terms of achieving their stated goals by measuring their outcomes, and 3) elucidate potential longer-term impacts (Wilkinson and Weitkamp, 2020). This in turn enables an assessment of how worthwhile and beneficial they are to recipient communities, and the identification of potential points of improvement for subsequent iterations or similar projects (Hagemeier-Lose and Wagner 2009; Henstra et al., 2019; Wilkinson and Weitkamp, 2020). Through this evaluation I seek to assess the outcomes and impacts of this initiative on DRR activities and community capacity on Montserrat and reflect upon the co-creation process it was built upon.

I address four main research questions:

1) Has the Mountain Aglow initiative expanded the repertoire/reach of, and engagement with, DRR activities on Montserrat when compared to before?
2) Has the Mountain Aglow initiative engaged the younger generation in Montserrat, specifically, and made DRR activities more relevant to them when compared to before?
3) Has the inclusion of story-telling and artistic expression, based on individual lived experiences of the eruption and their associated emotive impact, successfully encouraged experience sharing within and across generations and demographics? And finally,
4) What insights can be gathered about the benefits and challenges of the co-creation process involved in this initiative? For the latter, while it is not possible to make a direct comparison to a non-co-created initiative, participants were asked to reflect on the process.

5.2 Methods

I adopted a mixed methods approach to capture as broad a range of feedback as possible. Mixed methods approaches, whereby qualitative and quantitative data are used in a complementary manner, are frequently adopted in social research to expand the breadth of investigations (Johnson et al., 2007, and references therein, Creswell and Creswell 2017). This approach also facilitates a combination of pre-determined lines of questioning/investigation, while allowing room for the emergence of unexpected topics/points of discussion (Creswell and Creswell 2017) . Specifically, I have adopted a convergent parallel mixed methods approach, whereby qualitative and quantitative data has been collected in parallel (i.e., over a similar time frame) and have been used to complement one another (e.g., Tomasi et al., 2018; Akash and Aram, 2022; Areia et al., 2023). This approach is appropriate in this case as I am interested in understanding perceptions of, and engagement with, the exhibits and initiative as a whole; data pertaining to this can be gathered both qualitatively, via written feedback or in interview, or quantitatively, via Likert scales on a feedback form. Further, use of both long-form (interviews/focus groups) and short-form (feedback forms) also permits both in-depth and focussed investigation with a small number of individuals, while simultaneously gathering more limited data from a broader portion of the population (Wilkinson and Weitkamp, 2020; Creswell and Creswell 2017).

Table 5.2 provides a summary of the different data collection methods that I adopted, together with the respective number of participants. In this study most data are qualitative, acquired by interviews and focus groups held with project stakeholders involved with various parts of the process, as well as a number of individuals not previously involved. Interviews and focus groups followed the same protocols which can be found with a list of participants can be found in Appendix 3.1. Interviewees were recruited either via their previous involvement in the project, or by invitation upon in person encounter. I was unable to meet with some prospective participants (e.g., Montserrat Tourism Division) owing to their limited availability.

Method	Participants	Structure	Consent
Interview	MVO (n=2) DMCA (n=2) MRC (n=2) MoE (n=1) MNT (n=1) MAC (n=1) MPL (n=1) MTGA (n=1)	Semi-structured, tailored according to participant's background.	Written/signed (including audio option)
Focus Groups	Members of public (n=2) BPS (n=3) LPS (n=3) SAPS (n=3)	Semi-structured, tailored according to participants' background.	Written/signed (including audio option)
Informal anonymous discussion	n=6	Unstructured	Verbal
Feedback form	n=92	n/a	Implicit
Reflective diaries	UEA/MVO team n=6	n/a	Implicit

Table 5.2: Summary of methods used in this study, participant counts and consent types.

I also made use of anonymous informal conversations with individuals at public events, and reflective reports made by members the scientific team (UEA/MVO) involved in the conception and management of all stages of the project. This was supplemented by anonymous feedback forms filled out by visitors of the exhibit(s). The feedback form consisted of two open ended questions (qualitative): *'What kind of reflections did the exhibits prompt and how did you feel?'* , and *'In what ways do you think the exhibits could benefit Montserrat, now and in the future?'*. It also included two 5-point Likert scale questions (quantitative) to score levels of interest in, or perceived importance of, aspects of the exhibit(s). These were: *'Please rate how interesting/informative you found each panel'*, and *'Please rate how important the following aspects of the exhibit were to you'*. These scales ranged from 1 – 5; 1 meaning *'Not Interesting/Important'*, 3 meaning neutral, and 5 meaning *'Very Interesting/Important'*. The feedback form can be found in Appendix 3.2. For each question, respectively, 8% and 10% of respondents returned the same score across all aspects. It is not possible to discern whether this reflects a true attitude or a limited engagement with the exercise.

The feedback gathering process involved participation of some description by at least 100 unique individuals, constituting ~2% of the Montserratian population. Interview and focus group participants were all adults of working age (8 male, 14 female); all were Montserratian natives except for one teacher and one scientist; 18 had experienced volcanic activity in some way (i.e., ash fall through to evacuation), 4 had not. Interviews/focus groups were not arranged to occur in any specific order, rather they were conducted when participant availability allowed. The demographic characteristics of those completing feedback forms were not collected as they were anonymous; it is possible that interview/focus group participants also completed a feedback form prior to interview, this is not something I controlled.

My ethics and consent framework was drawn up under supervision from Dr Teresa Armijos formerly of the School of International Development, University of East Anglia (since moved to School of Geosciences, University of Edinburgh). I submitted this project to the UEA Faculty of Science Research Ethics Subcommittee for approval as a follow-on project from the previously approved Explosive Transformations project, a predecessor of Disasters Passed and Mountain Aglow. My approved ethics application can be found in Appendix 3.3. I acquired written, verbal and implicit consent depending on the type of interaction I had with participants as shown in Table 5.3. All interview and focus group participants were given consent forms to sign, indicating their consent to interview and consent to audio recording; the consent form can be found in Appendix 3.4. Where consent was not acquired for audio recording (one instance), verbal consent was subsequently requested for note taking and then granted. Verbal consent was also obtained for after-the-fact notetaking during any informal conversations following an introduction and explanation of the purpose of my work.

I manually entered feedback form responses into Microsoft Excel where I coded responses based on key words relating to the feelings/reflections induced for visitors and the perceived benefits of the exhibits. I both manually and semi-automatically transcribed 9.5 hours of audio recordings of interviews and focus groups either using a limited free trial of OtterAI transcription software for about a third of the recordings, or Microsoft Word, with manual checking for errors (background noise and Caribbean regional accents were at times problematic for the software). I then imported these transcriptions into NVivo, where I coded them according to themes based on my lines of questioning (guided by my four key research questions; interview protocols can be found in Appendix 3.2), or those that became apparent during the semi-structured interviews. A list of the identified codes and the frequency of reference to them can be found in Appendix 3.5.

This work was opportunistic and rapidly developed due to unexpected favourable circumstances. As a result, my analysis has been based on the retrospective application of a logic model approach. Logic models are frequently used to facilitate the evaluation of initiatives/programs that seek to lead to change or improvement (e.g., Helitzer et al. 2010; McLaughlin and Jordan 2015). In simple terms, through a series of steps (Figure 5.4), logic models relate an initiative's initial aims to available/required materials/resources, and proposed interventions, through to the proposed approaches of evaluation, and then to evidence of its outcomes (usually short-term instances or observations e.g., positive feedback, high interest, observations of story-telling) and observed or inferred impacts (i.e., long term changes to practice, e.g., an improved capacity for hazard education, changes to school curriculum, improved community capacity). It is important to note from the outset that given time restrictions it was not possible to conduct pre- and post-exhibit interaction surveys to specifically assess baseline conditions and subsequent change. Consequently, this work is primarily reliant on qualitative evidence from testimonial.

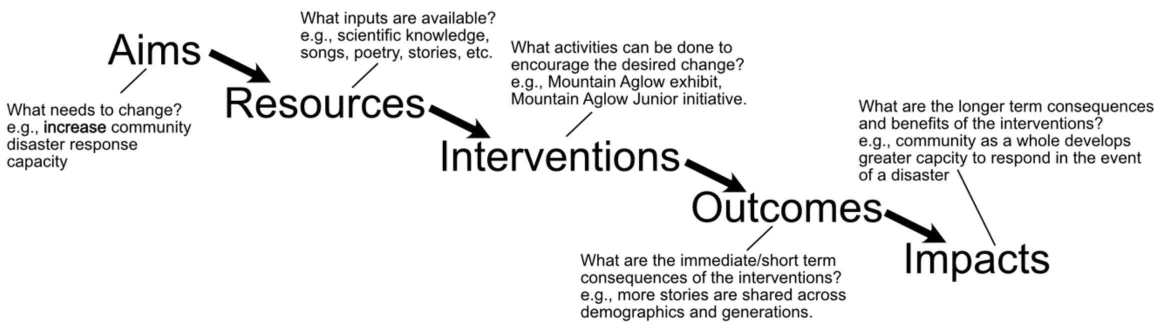


Figure 5.4: Flow chart demonstrating the structure of a logic model.

5.3 Results/Findings

In this section I explore evidence relating to each of the 4 research questions of this study, as outlined in section 5.1. A full summary of individual findings is provided in Table 5.3; these are then explored more generally in the main text. I begin by exploring evidence of engagement with MA and any subsequent enhanced reach of DRR activities, before presenting evidence relating to youth engagement, experience sharing, and then insights related to the co-creation process. It is important to note that the research questions are not necessarily mutually-exclusive and that evidence may therefore relate to more than one question. I provide example quotes from interviews and focus groups to demonstrate some of the types of responses given. These are the opinions/perspectives of these individuals, not the departments or organisations they work for.

5.3.1 Disaster Risk Reduction activities

This subsection explores evidence relating to research question 1, *'Has the Mountain Aglow initiative expanded the repertoire/reach of, and engagement with, DRR activities on Montserrat?'*. I first detail evidence about any perceived purpose that the MA initiative fulfils with respect to DRM, and then present evidence relating to the contribution of MA to DRR activities on Montserrat.

5.3.1.1 An identified purpose

> *'There's been no surface activity for a long time, so a lot of people on the island don't have any experience of that, so something like this is a good tool to humanise what surface eruptive activity is like and what it means. It's not just, abstractly, ash fall and fragmentation, it's 'this is what people felt… you're coated in ash the whole time, you're sleeping in it, you're eating it.' – Director of MVO*

All interview and focus group participants spoke in some way of the purpose, or even 'need', for an initiative such as Mountain Aglow; this was mentioned a total of 37 times across all interview files. The majority spoke of the fact that now, almost 30 years on, a much of the population does not have experience or memory of the early stages of the eruption, and that, crucially, much of the population aged 15 and under may have no memory at all of surface activity at the volcano (the last eruptive activity occurred in February 2010).

a) Engagement with Mountain Aglow – Research Question 1	***b) Youth engagement – Research Question 2***

- MA/MAJ seen by MVO and DMCA as a new, meaningful, and engaging tool for disaster risk education.
  - Crucially seen as one of the only resources available that incorporates the lived experience of the eruption.
- Engagement with the exhibits has been positive.
- MAJ constitutes an entirely unprecedented schools-based DRE activity.
- Enables engagement with wider audience:
  - Cultural/artistic leaning of MA/MAJ has enabled its presence at cultural events/festivals; MVO/DMCA would not have been in attendance otherwise.
  - Cultural/artistic leaning seen by some as making interaction with MVO/DMCA communications more accessible and relevant; it appeals more to people who are not necessarily scientifically minded.
  - Pyramid structure, brightly coloured panels, and the lights and sounds of FLOW all seen as attractive/eye catching/attention-drawing.
- Stakeholders believe engagement with the exhibits has not reached its potential owing to COVID restrictions and a mixed perception within the population.
	- Teachers report excitement from children to be interacting with and learning from workshops (particularly for trip to Plymouth) and being involved in the process of making Mountain Aglow Junior.
	  - Large quantities of material produced by the children.
	- Teachers report greater interest, curiosity and understanding about volcano-related curriculum; report un-guided discussions of volcano in and out of class; discussions of the experience of people living through the eruption of La Soufrière, St Vincent, April 2021.
	- Numerous contributors to MAJ workshops describe curiosity from children outside of workshops.
	- Teachers and MoE call for more activities like this in the future.
	- MoE praise success of project, and:
	  - Raise possibility of curriculum changes to align with material from Mountain Aglow; run their own trip to Plymouth in July 2022 which is now intended to be part of standard Grade 5 curriculum.
	  - Raise possibility for annual or biannual events based around MA/MAJ.

c) Story sharing – Research Question 3	

- Stories shared directly to UEA/MVO team while hosting exhibit.
- Observations made by UEA/MVO team, or testimony from interviewees describing stories being shared by others.
  - Experienced persons to inexperienced adults (including teachers).
    - Inexperienced persons describe gaining 'insights and perspectives' they had 'not considered or been exposed to before'.
  - Experienced persons to children.
  - Experienced persons to tourists.
- Non-experienced persons report gained insights/perspectives into eruption experience that they had not considered/been exposed to; felt the story of the volcano more real and less removed from their lives.
- Mountain Aglow Junior project seen as successful for portraying the experience to children.
  - Visitors 'moved' and 'proud' of how MAJ captured the essence of the experience; almost as if they had 'first-hand experience'.	

d) Co-creation benefits – Research Question 4	***e) Co-creation challenges – Research Question 4***

- Contributors feel their perspectives and stories have been heard and acknowledged.
  - *'Their experiences and what they have to say has been given weight and visibility.'*
- People from a range of backgrounds from across the community were brought together to make the exhibits.
- Scientific team report the process enabled them to:
  - Learn more about the experience of the eruption and what people went through.
  - Contextualise the work that they do within the history and culture of Montserrat.
  - Relate more to members of the public with whom they communicate and better appreciate what information is most relevant/important/valuable to them.
  - Garner important ethical insights about the effects of gathering information and stories from affected populations.
  - Develop wider professional skills outside of their scientific and risk communication work.
- Improved Institutional Cooperation
  - MVO and DMCA report improved communication between them as a result of their cooperation during the MAJ project; plans for more co-led outreach events; both sides expressed the importance of the working relationship for effective DRR - particularly important at the time of writing due to potential of renewed surface activity.
  - Schools view both DMCA and MVO as more approachable following MAJ; has helped DRR institutions understand resource limitations/needs and an easier means to communicate with young people.
  - MNT and MVO reported enhanced working relationship due to shared responsibilities for transport and hosting of exhibits; has implications for future joint education projects.
	- Complex array of interacting factors that caused conflict/inefficiency (see Section 5.3.3.3)
	- Inherent challenges of carrying out a truly representative co-creation process:
	  - Short consultation phase, relatively small and self-selecting number of people involved in initial stages of project.
	  - Higher vested interest from certain partners encouraged an imbalance of time and resources spent on the project.
	- Conflict arising from:
	  - Perceived siloing, imbalance of power over the project or lack of sharing of responsibility/involvement.
	  - Perceived imbalance of benefits offered between stakeholders.
	- Increased workload of stakeholders as work on project was unpaid and additional to other work/duties

Table 5.3: Synopsis of evidence/findings.

Reference was also made to the demographic shifts that have occurred over the last two decades; by most recent estimates, 56% of the population are Montserrat-born (down from 61% in 2011), with the remainder from overseas, including the Caribbean nations of Guyana (10.7%), Jamaica (8.3%) and Dominica (3.4%) (SDM, 2018). This has a compounding effect on the reduction of volcano-experience level within the population.

> *'Life has to go on, yes, and you have to get back to some sort of normalcy, but is it that we disregard [the volcano]? No, 'cause it could decide tomorrow, 'hey hey… you've forgotten I'm here… I think I might just remind you'.' – MAC Member of Staff (Interview)*

Further, given the decade-long quiescence, there is reportedly some perception that SHV is now inactive, perpetuated by recent (at the time of writing) comments made by Montserrat's Premier (head of local government). This is a misconception; according to the most recent MVO Open File Report from February 2022 (MVO, 2022), SHV *'continues to exhibit unambiguous signs of unrest and a future restart of magma extrusion remains a possibility'*. Some participants who lived through the eruption reflected that they had now abandoned preparedness measures that they previously would have adopted on a daily basis (e.g., carrying a dust mask, keeping and emergency kit in their cars, etc.) owing to a lack of perceived risk.

Specific to DRR organisations, particularly with regards to MVO, there is perception that due to the '*abstract*' and '*esoteric*' nature of scientific reports and advisories, the accessibility, reach and perceived relevance of their public communications is limited; they estimated that >90% of their interaction was with tourists, rather than people living on Montserrat. They further reflected on the MVO's lack of integration into the community (one MVO staff member described a perception of them as '*just scientists up on the hill'*) and their perception that much of the population did not understand their continued presence and purpose. Consequently, there was general concern regarding potential renewed surface activity related to the apparent 30-year cyclicity of unrest at SHV and the fact that readiness for such an outcome is not sufficient. Thus, MVO and DMCA stated that they felt the MA initiative was *'timely'* and '*really appreciated*' with respect to their outreach activities.

5.3.1.2 Engagement with Mountain Aglow (Table 5.4a)

> *'[The exhibit] speaks to me. I'm not a science person…. So the fact that you can use the arts to convey that [scientific] message … Everybody is drawn to music in some sort - it's relatable - and from there then your interest can grow into science… that kind of introduction gets them more interested in the happenings, the scientific happenings of it… Even if you're not a child, as an adult it draws you in… the whole pyramid shape of it… it's really cool... it catches the eye… it's not just a poster on the wall, it's interactive, you're caught in and you're not just reading a poem, you can hear it. You can hear the sounds. You can hear a song playing while you're reading… It makes it more interesting and it captures your attention.'*
>
> *– MAC Member of Staff (Interview)*

Evidence from across the feedback forms and interviews/focus groups indicates that the exhibits were engaging, of high interest and, crucially, appealed to persons who would not normally engage with volcano/hazards-related material, having previously perceived this type of material as only relevant to science-oriented people. 11 interviews/focus groups referred to the exhibits working to increase the reach of discussion of Disaster Risk. Figure 5.5 shows word clouds of the contrasting emotions and reflections reported following interaction with the exhibits; feelings elicited by the exhibits were also mentioned 34 times across 11 interviews/focus groups. Information pertaining to the age of respondents and whether or not they had experienced the eruption was not collected on the anonymous feedback forms – this is a potential oversight in survey design. However, it could be argued that the tone and content of responses to the question *'What kind of reflections did the exhibits prompt and how did you feel?'* imply whether

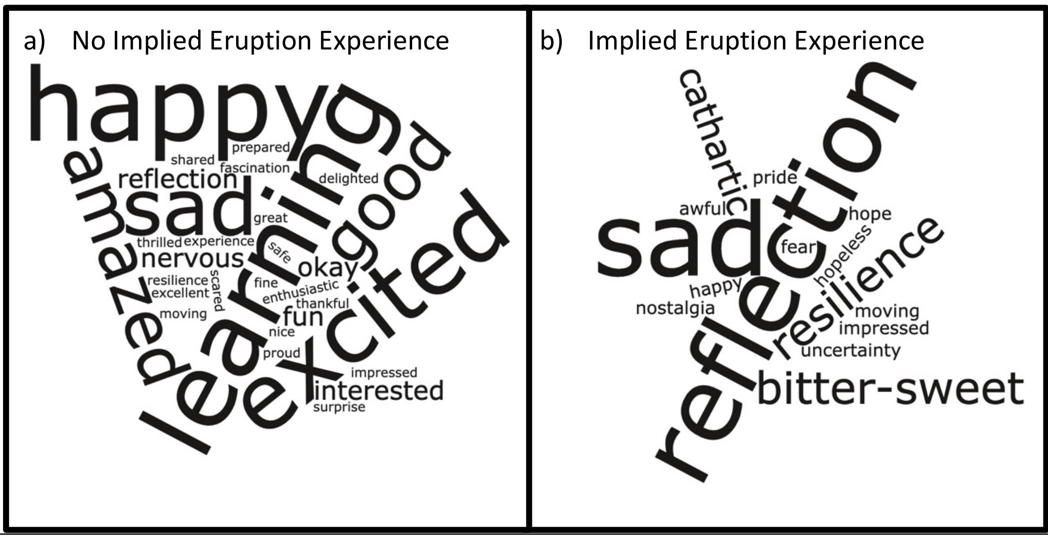


Figure 5.5: Word cloud of emotional and reflective responses to the exhibits as captured by feedback forms (in response to *'What kind of reflections did the exhibits prompt and how did you feel?'*) and interviews from non-experienced (left) and experienced (right) participants.

respondents had lived through the eruption. Specifically, there appears to be a split between responses that primarily refer to learning, implying no experience of the eruption, and those that refer to reflecting on or remembering the past, which implies, but does not guarantee, that they went through the events. This split in the type of reflections prompted by the exhibits was corroborated by responses from interview/focus group participants based upon whether they had lived through the events themselves or not. Importantly, Figure 5.5 demonstrates that interaction with the exhibits elicited positive engagement (positive emotions and learning) from those assumed to not have experience of the eruption. Conversely for those with implied experience, there more negative or mixed emotions were expressed. Sadness was the most frequently expressed emotion, and followed by 'bitter-sweet', which for some reflected their pain of the losses incurred, but also the pride in the resilience of the country and its people. Figure 5.6 shows the aggregation of scores provided by the feedback forms. The 'Volcano Island' theme was rated most interesting (Figure 5.6a) of all with a mean rating of 4.3, closely followed by 'Before and After' (4.0). This concurs with observations reported by exhibit hosts who noted that the timelines and images of Plymouth were particular points of interest for many visitors; many also expressed surprise and reported that they had not known that Montserrat was made up of 4 volcanoes of varying age.

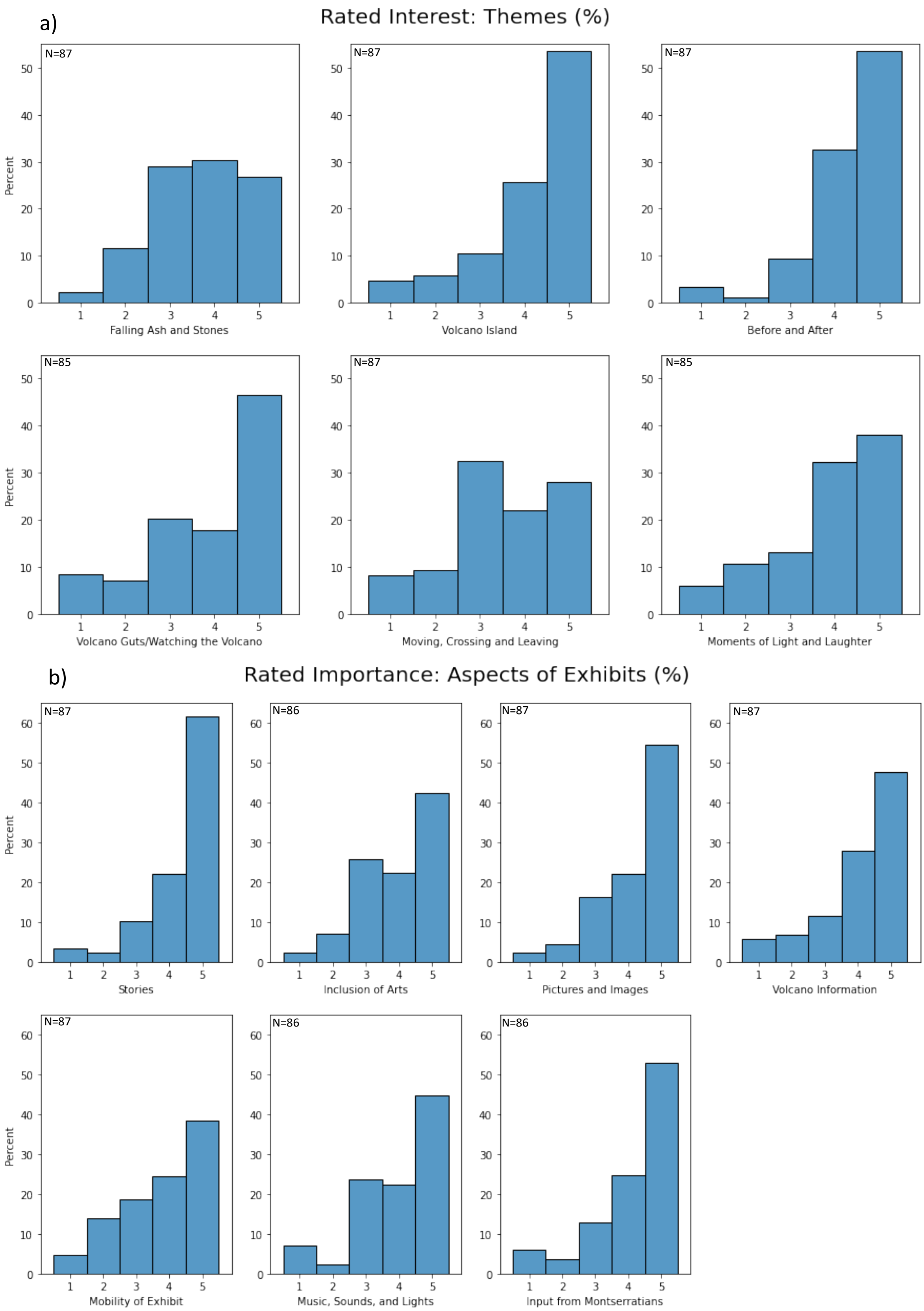


Figure 5.6: Percentage distributions of feedback scores supplied by returned feedback forms (Appendix 3.2), in response to questions a) *'Please rate how interesting/informative you found each panel'*, and b) *'Please rate how important the following aspects of the exhibit were to you'*. 1 is the lowest score (*'Not Interesting/Important'*) and 5 the highest (*'Very Interesting/Important'*).

In general, the MA initiative was perceived as highly valuable having provided a means to engage with a wider section of the population, by:

- Being more engaging than pre-existing DRE activities due to, for example, its multi-media nature or the '*captivating*' lights and sounds of FLOW. It also increases the relevance and accessibility of DRE activities to a wider range of individuals by incorporating the human experience, via stories and the Calypsos/music/arts, as told by other Montserratians (see also section 5.3.3).
- Being culturally leaning, which has enabled, and will continue to enable (more events are planned), the presence of the exhibit and DRR practitioners at national festivals (e.g., Alliouagana Festival of the Word, St Patrick's Festival).
- Serving as the basis for an unprecedented schools outreach program and contributing to the education of young people with respect to the volcano (i.e., Mountain Aglow Junior; Table 5.4, see section 5.3.2).

It was also viewed as an important means to contextualise the eruption within Montserrat's 'disaster past' and contribute to wider hazards education; for example, the timelines on the Volcano Island panels provide a segue to discuss earthquake and hurricane hazard, both of which have impacted Montserrat in the past.

A key motivator of this initiative was to contribute towards increasing the preparedness of communities and individuals in Montserrat. When approached on this topic, participants provided a mixed, but consistently positive, response, and, overall, it was felt that the MA initiative contributes positively to general awareness and preparedness on Montserrat (see also Table 5.4).

Benefit	**Count**
Education	47
Education (youth)	27
Education (general)	9
Education (history)	7
Education (volcano)	4
Experience Sharing	20
Awareness	16
Preparedness	16
Tourism	13

Table 5.4: Frequency count of perceived benefits of the exhibits as provided by feedback forms in response to question 2, 'In what ways do you think the exhibits could benefit Montserrat, now and in the future?'

The improvement of general awareness was raised 56 times across 16 interviews/focus groups; the perception that preparedness had been improved was shared in 11 interviews/focus groups, the perception that it had not was shared in 1. The perspectives offered included:

- The exhibits contribute directly to preparedness simply by increasing awareness, informing what could happen in the event of renewed surface activity and providing some detail about what that experience might be like.
- The exhibits themselves do not address preparedness measures (e.g., carrying a mask in case of ash fall) and thus do not directly impact preparedness. Instead, they are a valuable means of increasing awareness and improving contextual/background knowledge and improving rates of engagement with DRR-related activities, which would in turn encourage preparedness measures.
- In reality, nothing can prepare you for the experience of a volcanic eruption. It is impossible to convey the experience of '*day turning to night'* as the '*ash obliterated the sun'*, or the sound of '*hailing on the roof'* and realisation that it is '*stones falling from the sky'*. One cannot be prepared for such an experience, but by telling the story, people are at least made aware of the events and might be encouraged to seek advice about preparatory measures.

These are positive outcomes; however, it was felt by MVO, DMCA, and MNT that engagement with the exhibits had not yet met its potential, citing the following reasons/evidence:

- COVID restrictions: COVID lockdowns/gathering restrictions prevented/limited visits to the MA exhibit.
- Insufficient interest: The MAJ initiative did not elicit the anticipated degree of interest/engagement, in that only a small proportion of parents and invited guests attended the launch events. MVO staff reported that this may come from a negative perception that the project was primarily an MVO initiative.
- Mixed perception: the exhibits could induce a mixed response among the 'experienced' population because the materials have the potential to bring up '*bitter-sweet*' and '*painful*' memories. There is also a degree of fatigue with regards to discussion of the volcano and its impacts; some members of the community perceive the volcano to be '*asleep*' and that continued discussion of the volcano amounts to '*scare-mongery'*.

Despite this, both members of DMCA staff stated that they believed it was unlikely that any particular sector of the population would necessarily respond negatively to the exhibit. Instead, opportunities had to be more carefully considered/targeted in order to reach groups of people who have so far not engaged. They felt that on the whole the initiative at large was achieving its aims despite the limitations imposed by COVID restrictions.

5.3.2 Youth Engagement

In this subsection I summarise evidence pertaining to the second research question, *'Has the Mountain Aglow initiative engaged the younger generation in Montserrat, specifically, and made DRR activities more relevant to them?'* (See Table 5.3b)

The Mountain Aglow Junior initiative was conceived specifically to boost engagement with young people, by taking the MA exhibit to schools and running a series of classroom- and field-based volcano-related workshops. Across the board, teachers and DRR practitioners reported their perception that Grade 5 and 6 pupils:

- Exhibited a high level of excitement and enthusiasm during the undertaking of the MAJ campaign;
- Were now more engaged with hazards/volcano-related topics/curricula, having learned from the MAJ experience, and maintained their curiosity about it;
- Had engaged in unguided discussions about the volcano both inside and out of class;
- Had approached workshop leaders outside of school to learn more.

The trip to Plymouth was seen to be particularly engaging for the children, with teachers reporting that the experience had caused a combination of great interest, excitement and shock; the vast majority of the children had never been to Plymouth and many had heard very little about it until the trip. Further, the workshops preceded the paroxysmal explosive phase of the eruption on the nearby island of St. Vincent in April 2021. Some teachers were enthusiastic to report that there were lively discussions in class of what the people in St Vincent might be experiencing and going through (e.g., ash falling, shovelling ash). The teachers believed that much of this discussion was inspired and informed by what the MAJ initiative imparted to the children as it had enhanced their awareness of the volcano and what it had done in Montserrat.

Representatives of the Ministry of Education and the three primary schools, staff of the MVO and DMCA, as well as other organisations such as MAC and MPL, all remarked about how beneficial they perceived the Mountain Aglow Junior initiative had been for the children involved. Furthermore, schoolteachers noted great interest from younger year groups who were inspired and excited by the work the older children had done and wished to be involved in projects of their own in future. On these grounds, all relevant participants expressed interest in further MA/MAJ-oriented schools-based activities so that more children could be involved and learn in future. A representative of MoE stated that the MA initiative was an effective and beneficial 'one-off project', one that they would like to continue and saw potential for being developed into a 'program' (i.e., a long-lived initiative), provided funds could be found; they expressed desire for interaction with the exhibits and related activities to be incorporated into the hazards-related curriculum, and that there was potential for the exhibit materials to be used to inform the curriculum in future. Subsequently, in July 2022, MoE took charge of organising a Grade 5 trip to Plymouth in partnership with MVO and DMCA. This was regarded as a success, with the MoE expressing their desire for such trips to become part of the standard Grade 5 curriculum in future.

5.3.3 Conveying the Lived Experience

> *'We still live with an active volcano and it's only through shared experience people understand the power of the volcano… it's critical to always tell the story, no matter how painful it is… especially when it comes to disasters.' – DMCA Member of Staff (Interview)*

This subsection relates to research question 3, *'Has the inclusion of story-telling and artistic expression based on individual experiences of the eruption successfully encouraged experience sharing within and across generations and demographics?'* (See Table 5.3c)

Portraying the experience:

An important reflection for this evaluation is whether the volcano-experienced end users of the exhibit materials feel that the end results are representative of their experiences that they wish to convey. All relevant participants (i.e., those with eruption experience) responded positively when questioned; on aggregate, the overall perception was that the original MA exhibit effectively portrayed a generally representative '*snapshot*' of the experience and the associated challenges, and that it was documented, presented, and retold accurately and in *'the right way'*. This is further reflected implicitly by the number of interview participants and feedback forms noting that the MA exhibit brought back memories of the time, elicited an accompanying (and often complex, bitter-sweet) emotional response, and caused them to reflect on their own experiences (Figure 5.5).

A conduit for cross-demographic sharing of stories and experience:

Evidence from observations made by myself, the MVO/UEA team members, and interviewees, indicates that the exhibit(s) regularly elicited both prompted (i.e., when questioned by a host) and spontaneous story sharing by visitors to a range of audiences (i.e., experienced persons sharing with other experienced adults, non-experienced adults, children, and tourists). Benefits of the experience sharing aspect of the exhibits were raised and discussed in 57 individual instances across all interviews/focus groups. Some participants explained that reading or hearing the stories presented in the exhibits inspired them to reflect on their own experience and share their stories. In most observed cases, story sharing was prompted by the materials relating to 'Before and After', which triggered descriptions of life in Plymouth, such as where people used to live and go to work; 'Falling Ash and Stones', which prompted stories of how '*day turned to night'* and hearing the sound of hailing on the roof when actually it was falling rocks); 'Moving, Crossing and Leaving', which caused persons to recall the turmoil of evacuations referred to in one of the included songs, 'One More River to Cross'; 'Moments of Light and Laughter,' which brought on retellings of the common experience of going to watch the mountain glow at night. Crucially, several non-experienced interviewees reflected that they had learned from hearing the stories and that they had gained insights and perspectives into the eruption experience that they had not considered or been exposed to before; this made the story of the volcano *'more real'* and less removed from their lives. Some of these people were teachers who are involved with teaching the hazards curriculum in Montserrat. Story and experience sharing was further noted as a benefit offered by the exhibits on 20 feedback forms in response to *'In what ways do you think the exhibits could benefit Montserrat, now and in the future?'*; the inclusion of *'Stories about the experience of the eruption'* is also identified as the most important aspect of the exhibit, with more than 60% rating this as 'Very Important' (Figure 5.6b).

> *'I liked telling my stories… the children [ask me], 'How old are you?', and I say I'm as old as the mountain, because I've seen mountains grow, and I've seen them tumble.'*
>
> *– Teacher (Focus Group)*

The clearest material evidence of the effectiveness of experience sharing is the materials produced for the Mountain Aglow Junior exhibit. The responses by interviewees are suggestive of the high degree to which the children were able to capture the experience in their creative products. Some participants described themselves as being '*moved*' and '*proud'* of how the

Mountain Aglow Junior exhibit materials were able to capture the essence of the experience of the eruption; a number of these participants remarked that it was as if some of the materials were produced by people who had '*first-hand experience*' of the events.

> *'The children's exhibit I found was particularly interesting because they were not around during the time, they had no idea, but they were still able to bring that to life, so that the ordinary man or the visitor can understand it… that would have crossed from the parents or the adults to the children, so you have that cross-generational experience [sharing] happening there… it's not just hearing it, the kids have documented it.'*
> *– MNT Director (Interview)*

Potential for community catharsis

> *'I think one of the things we haven't dealt with in Montserrat is the trauma - the trauma we encountered with the volcano - I don't think we have dealt with it in a real way.'*
>
> *– Teacher (Focus Group)*

Six interviewees indicated that they believed the exhibit could potentially form a means for community healing, suggesting that the exhibits could form the basis of community meetings with specific intention to encourage individuals to share their experience for cathartic purposes. Indeed, two participants referred to the fact that they had not spoken about their experiences for many years, if at all, up until their involvement with the MA initiative; both expressed that this had been helpful and cathartic for them. Another two participants within one focus group raised specifically that they felt the loss caused by the eruption had not been fully acknowledged, both within the Montserratian community and externally (e.g., in terms of monetary value, an estimated loss of economy, and human/social capital) and other felt that many people had not had a chance to properly grieve. They believed that the exhibits may offer a more 'friendly' way of approaching the subject and could form a focal point for community meetings aimed at addressing this.

5.3.4 Reflections on the co-creation process (Table 5.3d and e)

This section now relates to the fourth research question, *'What insights can be gathered about the benefits and challenges of the co-creation process involved in this initiative?'*

5.3.4.1 Perceived benefits of co-creation:

> *'I just found that it was a well thought out, well put together production that had the heart of the people in Montserrat in mind. You didn't come along with elephant feet, trampling over everything and saying, 'this is what you want'. You allowed the people to be a part of it. You asked questions and you didn't just ask questions, you got down to the heart of the story. What does this mean to you? What does the volcano mean to you? How did you come through? You cared. The project actually cared about the people, and this is what is important to me.'* - *Librarian (Interview)*

> *'I think it's good that different people in Montserrat were able to contribute to a single project. I think the wide-reaching contributors; Musicians/songwriters/Calypsonians, children, artists, the ordinary people whose quotations were used and so on. I think that the wide range of people contributing to a single project can only be positive because it shows that people can work together.' – Musician (Interview)*

The fact that the exhibits were in part *'made by and for the people of Montserrat'* was rated as 'Very Important' by more than 50% of feedback form respondents (Figure 5.6b). Furthermore, the primary benefit of the co-creation process noted by interview participants was the respect the process had for the stories and experiences of Montserratians. It made these individuals feel included, and that '*their experiences and what they have to say has been given weight and visibility'*. One participant remarked that they were surprised to be asked about it as no one had asked before, and that it had been important for them personally to feel recognised. It was widely felt that the reason the original MA exhibit captured the story correctly and effectively was that it was informed by members of the Montserratian community themselves, brought together from a range of backgrounds and with a range of experiences. This was further suggested to have encouraged wider engagement with the exhibits; anecdotally, people with family members or friends involved were more likely to take an interest. For some, the process has contributed to a sense of pride and shared ownership of the exhibits and the story portrayed. This was especially so with the MAJ exhibit; one teacher specifically stated that the children of their class felt a sense of great pride in the exhibits, that they felt they owned the story and felt part of the history.

Participants further reported that the MAJ exhibit felt more co-owned than the original MA exhibit owing to the extent of the children's involvement in the production of the materials and that this had led to the indirect involvement of parents/other members of the community via the children's interviews.

Benefits of the co-creation process have also been felt by the scientific stakeholders at MVO and UEA. Their reflections indicated that being involved in the co-creation process:

- Helped them to learn more about the experience of the eruption and what people went through (e.g., learning the extent to which it is debilitating to have to deal with daily ash fall).
- Helped to contextualise the work that they do within the history and culture of Montserrat.
- Enabled them to relate more to members of the public with whom they communicate and better appreciate what information is most relevant/important/valuable to them.
- Allowed them to garner important ethical insights about the effects of gathering information and stories from affected populations.
- Had contributed to the development of wider professional skills outside of their scientific and risk communication work.

5.3.3.2 Enhancement of inter-institutional cooperation

Feedback from the majority of relevant interviewees revealed some level of enhanced cooperation between institutions or community entities as a result of the co-creation process. Figure 5.7 summarises these outcomes.

MVO – DMCA

Most evidence of improved cooperation between DRR organisations relates to the relationship between MVO and DMCA; MRC's involvement in the project was limited to Stage 1 owing to prioritisation of other commitments on their part. The importance of maintaining an effective working relationship between these two organisations was cited on both sides for general volcanic risk management purposes, but particularly with respect to the approaching 30 year anniversary of the onset of eruption. Interviewees from both institutions expressed concern of the approximately 30-year cyclicity (1890s, 1930s, 1960s, 1990s) of volcanoseismic crises in the ~100 years leading up to the eruption. All subsequently stated the necessity for effective cross-institutional communication in case another cycle of volcanoseismicity were to occur in the

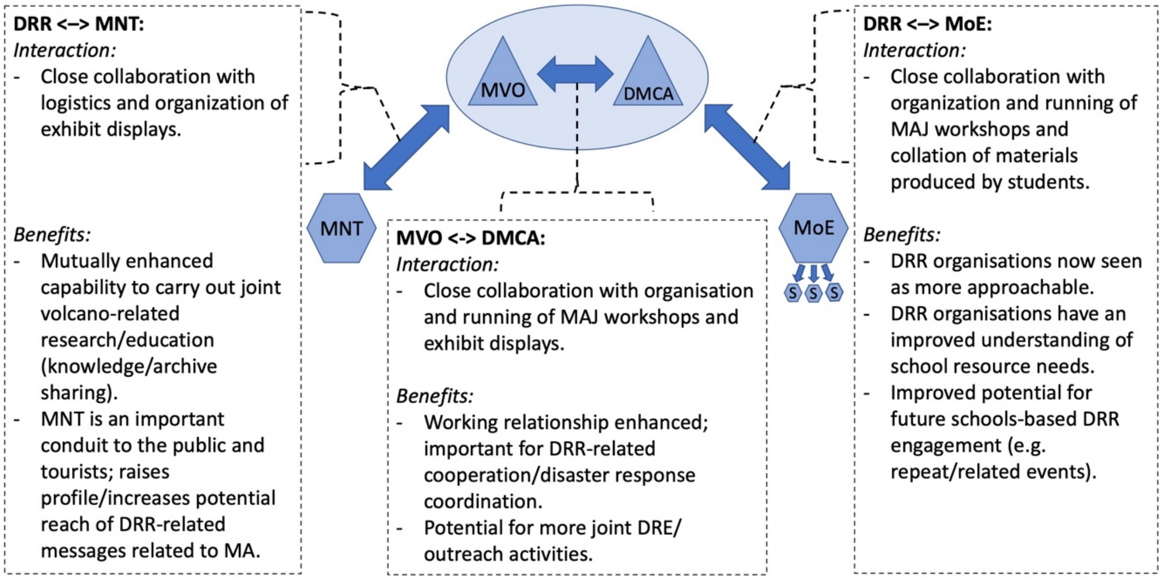


Figure 5.7: Schematic of reported enhanced cooperation between institutions and the perceived benefits.

next few years, particularly if it were to result in renewed surface activity. It was felt that the improved cooperation of the two organisations will enable MVO and DMCA to work more closely together/in partnership behind for general DRR purposes and for outreach-related events in future.

DRM institutions – Schools/Ministry of Education

Schools were identified by DRR practitioners, MoE, MNT and MPL, as an important conduit for DRE efforts because they provide access to young people en-masse in an educational setting. Representatives of MoE expressed that the project (MAJ in particular) had made the MVO/DMCA more approachable and that this had encouraged and eased communication; both sides perceived that this would help facilitate collaboration with future volcano/general disaster-related educational activities (including the aforementioned potential adaptations to the curriculum) and enable ongoing sharing of ideas and expertise (scientific/risk-related vs pedagogical) and enhancement of activities. Interviewees from the MVO cited that working so closely with the schools during MAJ helped them to understand resource limitations at the schools, which helped/will help them design activities with the schools more effectively/appropriately.

DRM - National Trust

MVO and MNT both mutually reported that their communication and cooperation had been enhanced as a result of the MA initiative, particularly as a result of sharing the use of the exhibit and management of logistics, with important implications. MVO identified the MNT as an important conduit for access to tourists and the general public owing to their mandate to document, preserve and share the history and culture of Montserrat; the MNT serves as a useful potential conduit for disseminating information and jointly organising outreach activities. Similarly, the MVO, as a scientific institution is a valuable source of knowledge and information about the volcano for MNT. This enhanced cooperation between the two organisations was seen on both sides as potentially beneficial for future educational projects.

5.3.3.3 Reported challenges and limitations of the co-creation process

Interviews with key stakeholders revealed a complex interplay of factors that lead to challenges and inefficiency within the co-creation process; this primarily centred around an imbalance of workload and involvement between stakeholders. Figure 5.8 shows a schematic of the range of interplaying challenges identified during interview analysis. The key issue is that there were multiple stakeholders, each with their own interests, resources, perceptions and expectations to

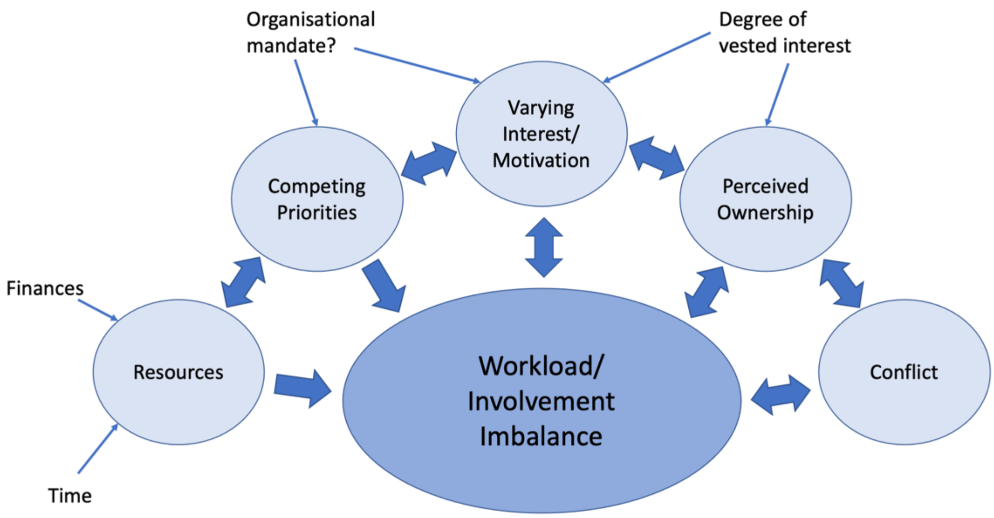


Figure 5.8: Schematic of factors reported to have contributed to a perceived imbalance of workload and/or involvement of stakeholders within the co-creation process.

be taken into account. Though the MA project was intended to be widely inclusive from the outset, some natural biases were recognised by stakeholders in terms of control over/leading activities. The concept of the initiative and its funding came from academics based at UEA in the UK, and the main institutional link in Montserrat was MVO. For practical reasons, this ultimately formed the key partnership of the early stages of the project; potential project partners were subsequently consulted and invited to be involved. Over the course of the development of MA, owing to higher vested interest (i.e., financial investment and the project's focus on volcanic risk communication) in the project, more willingness to spend time on the project, and access to production/manufacturing resources, UEA and MVO maintained this lead role, providing updates and requesting feedback as the process went along. Representatives of MNT and MRC indicated that their involvement and engagement with the project declined following the initial consultations due to evolving competing priorities of their institutions and the need to focus resources elsewhere. DMCA representatives indicated that they felt that there was an imbalance of control over the project in UEA/MVO's favour from the outset, stating that they felt that work on the project quickly appeared to become siloed, and that sharing of progress/information felt as though it was on a 'need to know' basis, which discouraged deeper involvement in the project from them. In addition, during the deployment of MA, conflict was reported between stakeholders when certain benefits (e.g., UK visit for exhibit launch, and training for staff to set up and use the exhibit) were seen/interpreted to have been afforded to some institution staff (MVO, MNT) but not others (principally DMCA).

Though the conflict and imbalance between MVO and DMCA was seen to be resolved and cooperation improved during the course of MAJ, MVO reported a similar imbalance of workload with respect to the later stages of the development of MAJ. From their perspective, involvement was well balanced for the organisation and leading of workshops, however, despite the intended shared responsibility of design of the MAJ exhibit, the majority of the selection of materials and the design of panels was done by them, due to a perceived lack of interest/willingness from other parties. In general, a key issue highlighted by all key proponents of the MAJ project (i.e., MVO, DMCA, teachers) was the additional workload; for all, the project was outside of their job descriptions and unpaid/voluntary which meant that the project was naturally not prioritised by some.

The inclusivity of the project was widely praised by those involved, however, some (particularly MVO) noted that only a small portion of the population were involved, either by circumstance or choice on their part, and that the means of recruitment was necessarily self-selecting. The initial consultation phase was relatively short (lasting ~2 weeks) and predominantly made use of contacts already known to UEA/MVO; subsequent recommendations of other individuals to approach were followed (snowballing). MVO staff expressed that this may explain part of the limited engagement with the exhibits so far. They further indicated that while materials (e.g., recordings of stories) were being collated, some individuals refused to interview upon approach because of 1) a lack of interest, and/or 2) a perception that their input would not be respected or acknowledged in the final product. Conjecturally, this latter perception stems from previous incidences of non-Montserratian researchers having allegedly failed to acknowledge contributions (this issue was raised in 2 interviews). For whatever cause, a wide swathe of the population in Montserrat was not included in discussions and therefore their experiences were not necessarily represented within the project.

5.3.5 Additional findings of note

Interviews and focus groups were semi-structured, geared towards addressing certain points, but allowing room for discussion of other topics. Three topics in particular were spontaneously raised by some participants: cultural and historical continuance; development of wider skills for young people; potential avenues of further development of the project. Table 5.5 synopsises these findings.

Topic	*Description*
Cultural/historical continuance	*'It helps keep the memory alive' – MAC Member of Staff (Interview)* - Exhibits help to highlight the role of the volcano in Montserratian history and culture. - MAJ perceived to have produced '*young cultural ambassadors*' who can continue to uphold Montserratian culture and share its history. - MA initiative as a whole contributes to MNT mandate to document and archive historically and culturally important materials, particularly in light of Montserrat's traditionally very oral culture. - Cultural/historical/human experience aspect of exhibit seen as a very valuable tourism resource.
Development of wider skills for young people	- MAJ project perceived as an excellent and unique opportunity for pupils to develop transferable skills that are important for them as members of the community: o Interpersonal Skills (holding their own interviews) o Team Working (MAJ activities required group working) o Synthesis and Creativity (creative material produced from what they had learned during workshops/ interviews).
Avenues for further development	- Produce materials in Spanish/Haitian creole to increase accessibility to ethnic minorities. - Audio/video walk throughs to help explain the background of panels to non-experienced persons with limited background knowledge. - QR codes to link the exhibit to the website for people to learn more. - Expansion of exhibit materials to cover other hazards, e.g., hurricanes.

Table 5.5: Summary of additional findings.

5.4 Discussion

5.4.1 From Outcomes to Impacts

The evidence above reveals a broad range of valuable immediate *outcomes* of the Mountain Aglow initiative. From here it is important to further consider these outcomes to elucidate the *impacts*, i.e., the ways in which the MA initiative has induced potentially meaningful longer-term change for the future (Wilkinson and Weitkamp, 2020). It is possible to outline and discuss 3 key impacts: 1) an enhanced DRE and DRR capacity; 2) capacity building by specifically engaging the young people of Montserrat; and 3) community capacity sharing and the enhancement of social capital via the sharing of experience; each of which relate to the first 3 research questions of this analysis. Figure 5.9 summarises how these impacts are related to the measured outcomes.

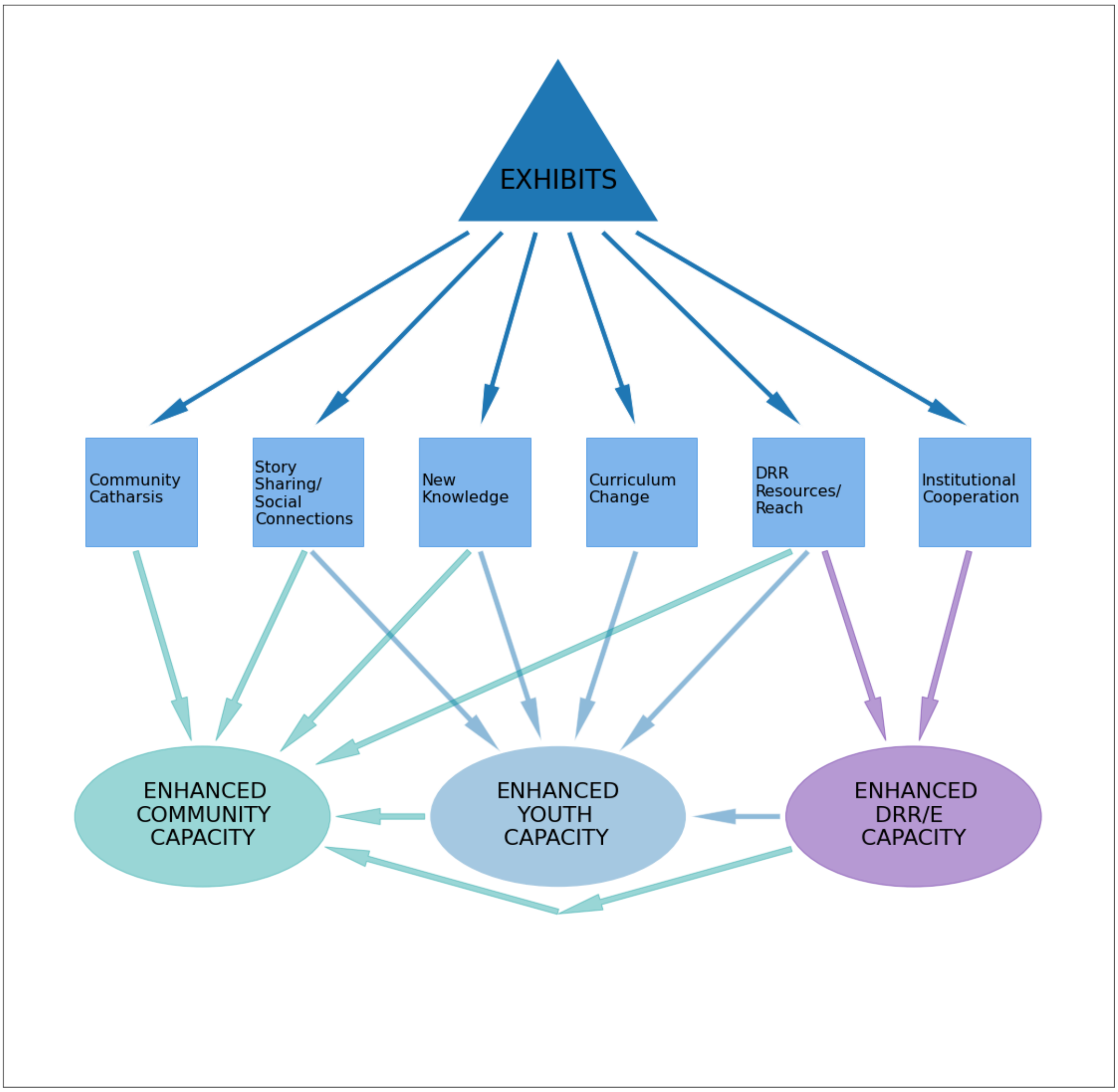


Figure 5.9: Network diagram showing key outcomes identified by this analysis, and the identified impacts of the initiative.

5.4.1.1 An Enhanced DRM Capacity

Research Question 1: '*Has the Mountain Aglow initiative expanded the repertoire/reach of, and engagement with, DRR activities on Montserrat?*' Answer: Yes.

The Sendai Framework sets an objective to 'promote strategies to strengthen public education and awareness in disaster risk reduction, including disaster risk information and knowledge, through campaigns, social media and community mobilization, taking into account specific audiences and their needs' (UNDRR, 2015). The MA initiative sought to particularly take into account 'specific audiences and their needs', i.e., in this case, persons for whom DRE practices are less relevant or accessible to improve engagement. Testimonial from numerous interviewees outlined above clearly demonstrates that Mountain Aglow has expanded the repertoire, the reach and engagement with DRE practices on Montserrat. Further, the evidence offered by: feedback forms (e.g., indications of learning; perception of the exhibits as valuable educational resources; ubiquitously high ratings of interest in each of the themes); testimonials stating that the exhibits had made learning about the volcano more relevant; the undertaking of the unprecedented Mountain Aglow Junior project; teachers detailing the school children's enthusiasm to be involved and their subsequent engagement with MAJ; and the fact that the exhibits have been hosted at public events/museums and visited by a range of individuals; all suggest that the exhibits have already expanded the repertoire and reach of, and engagement with, DRE-related activities. Primarily, MA has provided a conduit for the transference and conveyance of alternate, non-scientific, volcano knowledges (e.g., experiences, see also section 4.1.2), which are widely seen as valuable contributions to disaster risk reduction alongside scientific information (e.g., Lejano et al., 2021). This is significant for two key reasons, 1) it has widened range the of knowledges from which understanding about the volcano can be obtained, and 2) it has increased the accessibility and apparent relevance of volcano-related communications to members of the population who are not necessarily scientifically-inclined or may not have previously engaged. The heightened relevance and cultural leaning of the exhibit also broadens the range of scenarios in which DRR practitioners can engage with the public in future (e.g., national festivals). This has important implications for expanding future/ongoing DRE/outreach activities, by heightening the visibility of DRR-related discussion within the community, and thereby contribute to greater awareness and preparedness.

Public awareness building is widely recognised as a keystone and prerequisite for building community preparedness and disaster resilience (Ardalan et al., 2008; Shaw et al., 2009; Gaillard and Pangilinan, 2010; UNDRR, 2015) Both DMCA and MVO identified that awareness within the community is low owing to the prolonged quiescence and limited experience of the population, and that this was a key concern. There is good evidence that the MA initiative has made a positive contribution towards efforts to improve general awareness of the volcano and the experiences of it, both within the younger generations and more widely. Feedback scores indicate engagement with the exhibits has been positive and the materials have generated interest; the written reflections about learning from the exhibits are important in this regard too, being suggestive of an improved awareness. Importantly, awareness building was widely reported in interviews, particularly with regards to school-aged children, but also from reports from DRR-practitioners, teachers (some indicated their own improved awareness) and other community members, with many others stating their belief that the exhibits have the potential to contribute to general awareness building. Within the current context of Montserrat's post-disaster recovery, and with the potential of renewed activity at the volcano, general awareness building is significant also by being in line with another Sendai Framework guideline. This states that 'in the post-disaster recovery, rehabilitation and reconstruction phase, it is critical to prevent the creation of and to reduce disaster risk by "Building Back Better*" and increasing public education and awareness of disaster risk' (UNDRR, 2015).

Effective collaboration between stakeholders, be they governments, DRR-practitioners, public institutions, or communities, is known to be essential for sustainable disaster risk reduction; it enables the sharing of knowledge and expertise between entities which in turn increases the collective capacity to effectively prepare and respond to disasters when they occur (Cadag and Gaillard, 2011; Marfai et al., 2015; Karali et al., 2020). Again, the Sendai Framework calls for the promotion and improvement of 'dialogue and cooperation among scientific and technological communities, other relevant stakeholders and policymakers for effective decision-making in disaster risk management'. With respect to volcanic disaster response, the eruption of La Soufrière, St Vincent and the Grenadines, late 2020-April 2021 provides a particularly salient example of how effective institutional cooperation enables the implementation of robust preparedness measures and a rapid and tightly orchestrated disaster response which ultimately prevents any loss of life (Joseph et al., 2022). The enhancement of DRR - DRR and DRR - non-DRR institutional relationships reported during this evaluation is therefore an important impact with implications for both ongoing disaster risk education and disaster response in the potential event of renewed surface activity at the Soufrière Hills Volcano. Continued collaboration via the use of the exhibits for joint public outreach events, as well as the potential opportunity for more activities related to Mountain Aglow Junior, serve as opportunities to continue to reinforce cooperation between these entities involved in the MA initiative at large.

5.4.1.2 Towards an engaged, curious, and informed youth

Research Question 2: '*Has the Mountain Aglow initiative engaged the younger generation in Montserrat, specifically, and made DRR activities more relevant to them?*' Answer: Yes.

Children and young people are increasingly regarded as an essential consideration in disaster risk reduction, largely due to their higher vulnerability (a disproportionate number of disaster victims are children; Gaillard et al., 2010), but also due to their potential to act as proponents of disaster risk reduction by influencing action and decisions within their families and communities (Mitchell et al., 2008; Tanner, 2010; Burrows 2017; Williams et al., 2017; Mort et al., 2018; Ronan et al., 2022). Indeed the Sendai Framework recognises that '*children and youth are agents of change and should be given the space and modalities to contribute to disaster risk reduction, in accordance with legislation, national practice and educational curricula*' (UNDRR, 2015). Such is the increase in attention on children and youth impacts in disaster, a relatively new subsection of DRR practice has been established, Child-Centred DRR (CC-DRR), which seeks to account for the specific needs of children, and encourage their participation in DRR (Amri et al., 2015; Ronan et al., 2016). By educating and building the awareness of young people, they are able to develop their own ability to prepare and respond to adverse events. With this, they themselves can become active contributors to the adaptive and responsive capacity of their communities at large (Tanner 2010; Gaillard et al., 2010; Ronan et al., 2016; Goto et al., 2022).

Mountain Aglow Junior sought to enable the targeted education and active participation (e.g., Gaillard et al., 2010; Goto et al., 2022) of children in the discussion about volcanic risk in Montserrat to raise their awareness by improving their engagement with and understanding of disaster risk material. The Mountain Aglow Junior exhibit itself, and the testimony from volcano-experienced members of the community indicating that it captures the essence of parts of the experience of the eruption, are clear indications that stories relating to the eruption have been transferred to the young people involved and that they have developed an understanding of the experience. Beyond this, testimony detailing the excitement to be involved exhibited by the children is a promising indication of engagement, awareness and learning outcome. Though inconclusive, some literature suggests positive emotion, such as excitement, may enhance learning and memory retention (Um et al., 2012, Tyng et al., 2017). This is further supported by statements by teachers which indicate the children's greater interest in hazards curriculum and their curiosity and discussions of the experiences of those living through the eruption of La Soufrière, St Vincent. Crucially, the above examples demonstrate the acquisition of new knowledge within this sector of the population, which has important implications for their awareness and the development of their own capacity to respond to disaster.

Furthermore, the uptake (e.g., the Plymouth trip), or desire for uptake (e.g., consideration of potential funding of future related activities), of MA-related activities into the curriculum is an important outcome as it demonstrates that the educational authorities on Montserrat have observed benefits of enough significance to warrant their repeat. It indicates the beginnings of a tangible modification to educational practice in Montserrat to include more DRR-related material. Furthermore, the reported learning done by teachers, many of whom are non-experienced, is additionally important for the implementation of this curriculum (teachers are the first/most immediate credible source of information about hazards; Gaillard et al., 2010). This is salient as it has positive implications for the continued disaster risk education of children into the future.

5.4.1.3 Sharing and building community capacity through cross-generational and cross-demographic knowledge and experience exchange

Research question 3: '*Has the inclusion of story-telling and artistic expression, based on individual lived experiences of the eruption and their associated emotive impact, successfully encouraged experience sharing within and across generations and demographics?*' Answer: Yes.

Evidence of story sharing related to the MA initiative, and engagement with these stories (e.g., learning, emotional responses), is widespread within this analysis, and has been observed occurring between experienced adults, and non-experienced adults, children (particularly evident in MAJ) and tourists. This is an important outcome as the sharing of stories and experiences of hazard events, and social learning in general, are widely recognised as essential components of improving awareness, increasing preparedness, and enhancing resilience of at-risk populations (e.g. Hicks et al., 2017; Kato and Endo 2020; Prawoto and Octavia 2021). Every individual's memory or story contains knowledge about the experience and impacts of hazards and how one might respond to their occurrence (Garde-Hansen et al., 2017); each one constitutes part of a collective memory situated within the local cultural context (Lejano et al., 2021). Thus, sharing these experiences enables the utilisation of this collective memory and the transfer of knowledge in a manner that is culturally appropriate for recipients. Transference of knowledge requires social connections (i.e., social capital) and the sharing of this knowledge may in turn enhance the depth and breadth of social connections available to individuals, either by enhancing the value of pre-existing connections (i.e., these connections develop and become a resource of hazard knowledge) or by the establishment of new connections (Chamlee-Wright and Storr, 2011; Bihari and Ryan, 2012; Uekusa et al., 2022). The acquisition of new hazard knowledge, and the access to and/or awareness of social connections with relevant hazard knowledge, enhances the resources available to an individual to build a picture of how a hazard event might affect them, and thus build their capacity to prepare or respond if such an event occurs. While this analysis has not specifically controlled for the capacity of individuals, the wide evidence of experience sharing serves as a proxy indicator of a positive impact to capacity building within the community.

The notion of the exhibits potentially contributing to catharsis and healing within the community was to some degree unexpected, but also salient within the context of capacity building. Following the Indonesian tsunami of 2004, the principle of 'Build Back Better' began to take hold in post-disaster recovery, and was ultimately adopted into the Sendai Framework (Kennedy et al., 2008; WHO 2013; UNDRR 2015). The principle is that post-disaster recovery should serve to not only enable communities to recover to a pre-disaster baseline, but instead leave them in a better position to cope with potential future disasters; many at-risk communities reside in areas that may be prone to repeat or multiple hazards (Perry and Lindell 2008; Sullivan-Wiley and Gionotti 2017). A part of this effort attends to the psychosocial recovery of disaster survivors, for whom impacts may be devastating and complex (Norris 2006). Within this context, building back better incorporates psychological recovery and the promotion of wellness (Norris et al., 2008; Gil-Rivas and Kilmer 2016; Fernandez and Ahmad 2019). It is notable that after 25 years there appears (anecdotally) to be a significant portion of the volcano-experienced population who have not yet been able to properly grieve, come to terms, and recover psychologically, an essential part of post-disaster recovery (WHO 2013; Gil-Rivas and Kilmer 2016). This proposed use of the exhibits as a catalyst for cathartic story sharing within this section of the population is hypothetical; however, it is worth recognition as a potentially important impact due to the possibility for it to improve the capacity of individuals by themselves (i.e., by helping them to recover psychologically) and the community at large (e.g., the sharing of stories, experiences and insights, i.e., knowledges, and thus expanding or strengthening social connections within this group).

5.4.2 Co-creation: worth it?

The Mountain Aglow initiative was based upon a process of co-creation to intertwine local, experiential knowledge with formal, volcanic risk communication, to enhance DRE effectiveness by enabling both the community and disaster risk scientists to learn. It is pertinent to reflect upon this approach, assess its overall merits and consider the fourth and final research question, '*What insights can be gathered about the benefits and challenges of the co-creation process involved in this initiative?*'

It is this process - based upon cooperation between scientists, government bodies and members of the public - that enabled the sharing, collation and presentation of stories and materials related to the lived experience of the eruption. Firstly, it is salient that individuals involved felt that the approach 1) respected and gave weight to their perspectives and experiences, and that others in the community could learn from them, and 2) that it brought people together from across the community with varied perspectives; these are important for individuals on a personal level, as well as the wider community with regards to social capital and capacity building. Indeed, the respect paid to these experiences and points of view was posited as a driver for some of the engagement with the exhibits. The analysis presented in this chapter has already demonstrated the beneficial *impacts* that the Mountain Aglow initiative has had for volcanic disaster risk reduction activities and potential capacity building on Montserrat. These successes are all attributable to the process of co-creation, and in themselves serve as praise for the approach (see also examples presented by Gaillard et al., 2010, Goto et al., 2020, Lejano et al., 2021, Huthoff et al., 2022).

Beyond this, an additional key aspect of co-creation is co-learning (e.g., Cronin et al., 2004, Shaw et al., 2009, Lejano et al., 2021), whereby learning occurs bi/multi-laterally (as opposed to a traditional unidirectional approach), i.e., in this case, scientists also learning from communities. Through the co-creation process, via interviews, focus groups, informal discussions, and interaction with artistic materials, the scientific stakeholders in this project were able to learn from members of the community with respect to: individual experiences of the eruption; what individuals learned from their experiences; the role that the volcano plays within everyday life/the culture of Montserrat; what members of the community feel is most important to share with others about the volcano and its hazards; and the perspectives that the community have towards the scientists. The insights gained from this learning on one hand steered the design of the exhibits (e.g., ash being a key theme, the development of FLOW), but on the other enabled the scientific team to reflect upon their position in the community, the work they do and how to situate their science/risk communication efforts in a more culturally, locally, and even ethically, appropriate manner. This has important potential implications for increasing the effectiveness of their scientific/risk communication into the future by enabling them to better understand the perspectives and needs of those with whom they communicate (e.g., Cronin et al., 2004, Bankoff 2015, Lejano et al., 2021).

Overall, this analysis demonstrates that the benefits offered by co-creation are plentiful and wide-reaching. On this basis, this chapter is intended to serve as evidence to encourage the adoption of this type of co-creation approach within other risk communication contexts. Nonetheless, this analysis has also identified some difficulties associated with the process which warrant recognition. Firstly, relative to unidirectional communication techniques, co-created initiatives require additional work and resources, and are more prone to challenges owing to their multi-lateral nature (e.g., Kelman et al., 2012). The MA initiative has been no exception, with the sustainability of the initiative at times being questioned as a result of workload imbalance (work was voluntary/outside job descriptions; varying interest and involvement between stakeholders), and transient conflict arising from perceived miscommunications. Secondly, DRR practitioners reported concern that the exhibits had not generated the interest and reach they had expected given their co-created nature and wish to explore how this could be addressed by future projects. These provide opportunities for future learning, and, thus, two key questions emerge: 1) how can a project like this be made more sustainable? 2) How could the impacts be expanded?

With respect to question 1, '*How can a project like this be more sustainable?*', the main routes towards improvement are financial and related to degree of vested interest. Firstly, aside from members of the UEA team, none of the stakeholders were paid for their work on the project, all time gifted to the project was voluntary. This inevitably meant that priorities of paid work took precedent for other stakeholders. Financially, two options are apparent; one would be to provide monetary compensation to a range of key stakeholders and establish clear agreed roles and expectations from the outset, another might be to provide funding for one (or more) individual(s) to oversee and manage the project. With respect to question 2, '*How can the impacts be expanded?*', in the immediate term, it is likely that more opportunites for display in light of reduced COVID restrictions and visibility at national festivals will improve this. Further, targeted activities in certain areas or communities of the island may encourage people to visit. Beyond this, similar projects in future could consider expanding the extent and depth of co-creation. In this case, the initial consultation phase was short, and thus necessarily limited in reach, and was led by the UEA/MVO team, all of whom were non-Montserratian. Similarly the production of materials was dominated by this group. Thus, while this was not captured in this analysis, it may be that the exhibits are perceived as an MVO production, rather than a Montserrat production, per se, which may limit interest (given perceptions of the MVO). In future, expanding the opportunity for more control from local stakeholders may build the sense of ownership and thereby encourage more engagement within the community.

5.4.3 Limitations of this evaluative work

It is important to acknowledge the context within which this research was conducted. Due to, 1) an extension to my funding in early 2022, in combination with 2) a change in the border restrictions in Montserrat related to the COVID-19 pandemic and 3) the coincident launch of the Mountain Aglow Junior project, I found myself with a unique and very time-limited opportunity to carry out this research. I have been able to draw upon additional material (i.e., data collected prior to my fieldwork), but the research plan and ethics framework for the necessary field season were consequently put together with haste. In hindsight, the resulting framework was not optimal and this has meant gaps in the research approach have been identified - I'd like to discuss these here.

Measuring changes in understanding/attitudes: It has not been possible to collect data that specifically captures changes in understanding/perceptions/attitudes of those visiting the exhibits or taking part in the project. Rather, I have captured only perceptions after interaction, and then did not specifically assess *changes* to attitudes. Other evaluative exercises are likely to benefit from this sort of approach to clearly demonstrate the influence of, or changes instigated by, interaction with exhibits. This would require a pre- and post-interaction survey, specifically approaching perceptions/understanding of various aspects covered by the exhibits. However, there are limitations to this, too, particularly in terms of the time required from participants to complete such a survey.

Sample size and breadth: Had more time been available, I would have liked to hold more interviews with persons interacting with the exhibits who were *not* involved in the deployment of the project. It would also be valuable to seek perspectives of persons who had not interacted with the exhibits at all to ascertain levels of interest/perspectives more widely within the population; this could contribute towards understanding *why* interaction with the exhibits has been limited. My approach to interviewing was to prioritise people who were involved in the co-creation/MAJ stages of the project, as they may be 1) involved in disaster management and thus have important DRR perspectives, 2) involved with teaching, and thus have important insights into the engagement of young people, or 3) have valuable general insights related to the use of the exhibit and the process of co-creation. The findings presented in this chapter are further biased by the inherently self-selecting participation of interaction with the exhibit, i.e., interaction with the exhibit requires a pre-existing interest and openness to the experience. The sample measured by feedback forms is therefore not representative of the population of Montserrat as a whole. There are large portions of the population who have not interacted with the exhibits at all and for whom nothing has changed. This has to some degree been due to the restricted level of access to the MA exhibit due to COVID-19; it has only been hosted in either public institutions or during events, all subject to gathering size limits. In light of the above, results presented must be taken with caution. Under non-COVID-restricted conditions, there is potential for the exhibit to be displayed more openly as part of national festivals (such as St Patrick's which often occupies streets) and therefore allow interaction from members of the public who are not typical invitees to MCC events or visit MNT sites. Thus, further evaluation may be beneficial in future.

5.5 Conclusions

This chapter has argued that the Mountain Aglow initiative has made a meaningful contribution to DRR practices on Montserrat by identifying three principal impacts:

- 1) Mountain Aglow has enhanced DRE and DRR capacity in Montserrat by adding to the repertoire of resources available to DRR practitioners, by improving the relevance of DRE communications by incorporating the lived experience, as well as by enhancing inter-institutional ties between DRR and non-DRR institutions.
- 2) I argue that it has enhanced, and may continue to enhance (by means of modified curriculum and DRE activities), capacity within the younger generation in particular, which has important implications for the capacity of the community at large, as the young people are now more aware and more engaged with risk messages related to the volcano. This increases their capacity to make informed decisions and actively participate in community level DRR responses in the future. particularly noticeable within the younger generation.
- 3) Finally, the initiative has enhanced the development of social capital and capacity sharing within the community by encouraging the sharing of stories of the lived experience of the eruption within and across generations and demographics.

In combination, these impacts work in parallel to enhance the building of disaster risk awareness within the Montserrat population by rendering the communicated messages more relevant and situating them within the local cultural context. This chapter also reflected upon the co-creation process on which this initiative was built, with the following key findings/insights:

- 1) Co-creation is a highly valuable approach for intertwining alternate, experiential knowledges and scientific messages. The impacts of Mountain Aglow are demonstrative of the value added by the approach.
- 2) The co-creation of Mountain Aglow has enabled scientists to learn more about the lived experience of the eruption of Soufrière Hills Volcano and the cultural context within which they are communicating. This provides an opportunity for tailoring communications to better suit the needs and complement the understanding of the public.
- 3) Co-creation is a complex process, involving numerous stakeholders, each with their own perceptions, expectations, and resources. This can present challenges, however, this chapter argues that the benefits offered by the process far outweigh these challenges, and with due consideration, they may be mitigated in future initiatives.

In all, this evaluative analysis has demonstrated the benefits of co-created risk communication initiatives built upon the incorporation of both scientific and experiential knowledges of volcanic risk. Consequently, it is likely that this type of approach could be successfully applied to other contexts. This type of project could be designed to focussed other historically active volcanoes which have inspired a cultural response. Additionally, it may be that experiences depicted in an exhibit of this kind about one volcano could be shared with culturally similar population living near a volcano that has not erupted in historical times (e.g., in this case, another Caribbean island). Finally there is scope for this type of communication tool to be applied to other forms of hazards, such as hurricanes. Indeed, a hurricane-focussed set of exhibit materials would also be beneficial in Montserrat. It is hoped that the insights gained from this evaluation can help inform the design of any future initiative of a similar nature.

Chapter 6: Conclusions and Outlook

This thesis has set out to examine a range of aspects relating to both the physical and social/human legacies of the eruption of the Soufrière Hills Volcano. In doing so, it has sought to develop greater understanding of how the geomorphic and socio-cultural readjustment to the eruption can provide insights for the management of longer-term risk posed by episodic eruptions. On one hand it has explored the multi-decadal impact that this eruption has had on a small river system, the Belham River Valley. Chapters 2, 3 and 4 have:

1) Examined this in terms of the broad scale hydrogeomorphic changes that have occurred within the catchment in response to disturbance.
2) Examined how catchment-scale changes appear to mediate the likelihood of lahar hazard.
3) Attempted to reproduce the observed patterns of lahar activity and sediment yield using a simple spatially lumped sediment cascade model, SedCas_Volcano.

On the other hand, Chapter 5 has explored the outcomes and impacts of the Mountain Aglow initiative: a novel, co-created and arts-based disaster risk reduction tool. This initiative utilised the cultural legacies of the eruption as a keystone for situating volcanic risk within everyday life on the island and increasing the relevance of volcanic risk communications. In this concluding chapter, I summarise the key findings of this thesis, consider potential improvements and discuss routes for further research.

6.1 Monitoring long term geomorphic change and lahar hazard

Chapter 2 has presented a detailed synthesis of the volcanic disturbance of the Belham River Valley, Montserrat. The Belham Valley provides a unique opportunity to examine the multi-decadal response of a river system to prolonged episodic disturbance by volcanic eruption, thanks to the existence of a rich body of literature and data pertaining to its evolution (Barclay et al., 2007; Susnik et al., 2009; Alexander et al., 2010; Darnell et al., 2010; Froude, 2015). This chapter has demonstrated that the valley has undergone net aggradation by means of numerous (>250) lahars in response to significant and repeat sediment loading and the disruption of hillslope processes induced by the eruptive activity. This aggradational response has occurred at varying rates, at times acutely as a result of large or extreme lahar events, otherwise cumulatively via small-moderate lahars. It has also been punctuated by periods of relative channel stability or minor degradation in response to upstream sediment depletion and the transition to conditions dominated by supply-limited flow. With this, I presented a conceptual model for the evolution of this valley to serve as a model of fluvial response to episodic explosive eruptions which could be applicable elsewhere. This model ties together the catchment-scale conditions (volcanic sediment input, vegetation cover, rainfall) to the downstream response (lahar activity, channel aggradation/degradation). I then situated this response within the context of other disturbance-recovery pathways induced by varying types of volcanic disturbance (large transient disturbance – persistent eruptions). I concluded by positing that episodic eruptions induce a fluvial response which is, in effect, a hybrid between those generated by small transient eruptions and persistent eruptions. In common with river systems impacted by persistent eruptions (Thouret et al., 2014), sediment yields are elevated over more prolonged periods. However, the induced cycles of disturbance-recovery/aggradation-degradation are more dynamic between episodes of activity, which are effectively repeat small disturbances. Uniquely, episodic eruptions, particularly those involving multi-directional dome growth, render affected catchments additionally prone to extreme events, induced by tephra fall or anomalous damage to vegetation, which may buck channel recovery trends in periods of limited sediment availability. This results in transient aggradational or degradational events.

This work makes a valuable contribution to a body of other detailed studies pertaining to the hydrogeomorphic consequences of volcanic eruptions on fluvial systems (e.g., Mt St Helens, Major et al., 2000, 2018, 2019; Mt Pinatubo, Gran and Montgomery, 2005, Gran et al., 2011; Semeru, Thouret et al., 2014; Mt Hood, Pierson et al., 2013). It is valuable principally because it has specifically assessed the multidecadal impact of *episodic* eruptive activity on fluvial systems which has not been done in this detail before. It has also situated this response within the context of fluvial recovery pathways in response to a spectrum of disturbance types. However, despite these positive outcomes, it is pertinent to consider the ways in which studies of this type could be improved in future.

6.1.1 Improvements to catchment-scale monitoring

The dataset presented in Chapter 2 is extensive and comprehensive; it incorporates sediment supply, changes to source deposits, variation in vegetation cover, rainfall, lahar activity, sediment yields from the upper catchment, and downstream geomorphic changes. However, there are a number of ways in which the dataset could be made more robust and informative. In this subsection I discuss the limitations of the dataset and the means by which improvements could be made for similar studies in future.

6.1.1.1 Evolution of source areas and downstream channel change:

One key challenge of this study was the assessment of the changing conditions in the source areas (Tyer's/Farrell's Plain and Gage's Fan). The limited record of observations in the source regions of the Belham Valley precludes the acquisition of a full picture of deposition and erosion through time. The quasi-annual photography of Tyer's Ghaut compiled by Froude (2015) has allowed the assessment of general trends in deposition and erosion, sufficient to generate tentative estimates of yield over roughly annual time spans, but it lacks temporal detail and wider spatial coverage. In some cases, as with Gage's Fan, the very limited observational record more or less precludes analysis of geomorphic change over large expanses of time (e.g., between 1999 – 2010). This is a major limitation which generates a large degree of uncertainty in the estimation of the magnitude and timing of sediment yields from the upper catchment.

A similar problem applies to downstream evolution. Owing to their proximity to inhabited areas, the Middle and Lower reaches of the Belham Valley have fortunately been examined in more detail by previous authors and the MVO (Barclay et al., 2007; Susnik et al., 2009; Alexander 2010; Darnell 2010; Darnell et al., 2012, 2013; Froude, 2015). The photographic and observational record of these areas is the richest. However, these observations are still relatively limited and exist only on a quasi-annual basis owing to the timing of field investigations. The available observations therefore provide snapshots within a dynamically evolving system. These are highly valuable; however, their snapshot nature precludes higher resolution assessments of relative rates of change. The ability to assess rates of change would be valuable, particularly in a system where geomorphic change is dominated by individual large events.

Modern topographic analysis techniques, such as systematic and regular repeat photogrammetric or structure from motion (SfM) surveys, e.g., by unmanned aerial vehicles (UAVs), offer an exciting means of solving this problem (Dietrich, 2014; Abancó and Hürlimann 2014; Cook, 2017; Cucchiaro et al., 2019; Laporte-Fauret et al., 2019; Andaru et al., 2021, 2022). UAVs equipped with high resolution cameras are now inexpensive and their operation is relatively simple, as survey flight paths are programmable. Adoption of this sort of low-cost approach would allow for systematic analysis of changes resulting from deposition and erosion; with regular repeat surveys the effects of individual flow events could routinely be assessed. These types of DSM are often much higher resolution and lower vertical error than those used in this thesis; often of the order of centimetres, compared to up to 10 m spatial resolution and 5 m error. This would enable much higher precision geomorphic change detection (Clapuyt et al., 2016; James et al., 2017; Andaru et al., 2021). Conjecturally, regular and systematically updated high-resolution DSMs of the valley floor would also allow for rapid adjustments to flow routing models for lahar hazard assessment (e.g., Darnell et al., 2012, 2013; Franco-Ramos et al., 2020; Andaru et al., 2021, 2022).

A secondary difficulty with assessing the sediment transfer through the Belham Valley is the inability to ascertain how much sediment is transported into the ocean. Apart from the observations of coastal progradation in Chapter 2, no data exists pertaining to offshore deposition from the BRV. Offshore deposition elsewhere has been quantified, e.g., by le Friant et al. (2009, 2010), Tromifovs et al. (2012) and Karstens et al. (2013). With improvements to upper catchment monitoring, this may not be such an essential line of research. However, repeat measurement of near-shore bathymetry, using the same workflow as I adopted for geomorphic change detection in the upstream catchment, would provide a more complete picture of source to sink transfer of sediment. This method has been used to examine near-shore deposition in other fluvial systems (Browning et al., 2019; Zhou et al., 2020; Guo et al., 2021), including in response to disturbance (Gelfenbaum et al., 2015) and volcanic sedimentation (Di Traglia et al., 2022). Furthermore, offshore measurement negates the need for measurements to be made near to the volcano and is thus a lower-risk approach.

6.1.1.2 Vegetation:

I have been fortunate to acquire quasi-annual satellite data to analyse vegetation cover change over the study period - this has provided a key data timeseries for this work. Nonetheless, this data is limited due to its temporal sparseness. The eruption of SHV coincided with the earlier stages of development of multi-spectral satellite imagery and its usage for monitoring land cover change. The first use of satellite imagery to map changes in vegetation cover following eruption was performed to capture recovery after the eruption of Mt St Helens, 1980 (Lawrence and Ripple, 1999). Given the nature of return periods of individual satellites at these times, and the regular presence of cloud cover over Montserrat, there is only a limited amount of data available for the first 10 – 15 years of the eruption. It was not possible to find any satellite data prior to 2000, which means satellite observations of the initial disturbance are non-existent. Modern studies will now benefit from access to a wealth of high resolution and short return time satellite data, from numerous state-of-the-art sensors (Fathoni et al., 2021; Lazzeri et al., 2021; Teodoro and Duarte 2022).

It is important to acknowledge also that my NDVI validation process was limited, though fortunately it was sufficient for the purposes of this study. This was a function of data availability and could not be rectified during the undertaking of this work. Future studies would benefit from having the capability to directly validate and calibrate multispectral satellite data, for example by conducting ground-truthing surveys using UAVs equipped with multispectral sensors (e.g., Di Gennaro et al., 2019; Mazzia et al., 2020; Sotille et al., 2020; Tang et al., 2020). This would enable the comparison of spatially constrained NDVI values from both UAVs and satellites to ensure that remotely sensed data from satellites is indeed representing what is on the ground.

6.1.1.3 Rainfall:

This work has outlined the utility of remotely sensed rainfall data for the purposes of lahar incidence analysis. I opted to use the IMERG GPM data product owing to previously noted limitations of the existing rain gauge network. Namely, that:

1) Owing to rain gauge malfunction, or a lack of any rain gauge being installed, there are windows of time over the study period when no data has been available.
2) Rain gauges produce point data, i.e., they are representative of rainfall at a single point in space. This therefore does not capture the high spatial variability of rainfall over the catchment (Matthews et al., 2002; Barclay et al., 2007; Hemmings et al., 2015).
3) Crucially there are no gauges on the volcano, and therefore no coverage of the volcano summit and lahar source areas (e.g., Matthews et al., 2002; Barclay et al., 2007; Froude, 2015).

GPM is an alternative which provides a continuous and uninterrupted dataset as well as coverage of the volcano summit. However, this dataset is not without its own limitations which have been referred to on occasion in previous chapters. Figure 2.6 showed the spatial footprint of the GPM cell used for this analysis. Importantly the cell does cover the volcano summit, and, crucially, Farrell's Plain and Gage's Fan, the two key source areas for lahars. However, a large portion of the cell (~50%) covers the sea, and 45% of the cell covers the eastern half of the island; the Upper Catchment of the BRV occupies only about 5% of the cell area. It is therefore likely that some rainfall detected by GPM is *not* actually occurring within the Belham watershed. Furthermore, the spatial and temporal averaging (30 mins) will mean that this data does not fully capture the full magnitude of common short-lived mesoscale convective weather systems.

There is thus still room for improvement with regards to the acquisition of rainfall data over lahar source regions. Some form of weather radar which can resolve rainfall occurring specifically over lahar source areas could offer a solution this issue given its use in other mass-flow studies (e.g., Froude, 2015; Idanza et al., 2016; Hapsari et al., 2020). This would negate the need for installation of rain gauges on the volcano where they have previously been destroyed (Matthews et al., 2002). That said, weather radar is also beset by limitations, especially over mountainous areas (e.g., Dinku et al., 2002; Vulpiani et al., 2012; Sokol et al., 2021). This study therefore joins a long list of studies faced with challenges when acquiring rainfall datasets in mountainous regions (Dinku et al., 2011; Mashingia et al., 2014; Gilewski and Nawalny 2018; Barros and Arulraj 2020, and references therein).

6.1.1.4 Lahar Activity:

The lahar record used in this thesis was built upon the 1995 – 2013 record compiled by Froude (2015). Now spanning 25 years, to my knowledge, this record is amongst the most comprehensive in the world. However, this record also has its limitations. Firstly, owing to a lack of volumetric estimates, the classification scheme set out by Froude (2015) and adopted here designates lahars as ‘small’, ‘medium’, and ‘large’. This is based upon criteria relating to valley occupation, entry to the sea and roughly how long the flow lasted. While more specific volume estimates have been suggested for small, medium, and large lahars by Darnell et al. (2012) via modelling studies, the Froude (2015) and Darnell et al. (2012) studies had distinct contexts and aims, so their respective magnitude classifications were not designed in tandem. Therefore, it is uncertain to what degree they align with one another. In addition, the hazardous nature of lahars and their high variability along stream renders the measurement of sediment concentration highly impractical; information regarding sediment concentration is very sparse. Furthermore, the seismic detection of lahars in the Belham Valley is limited by the reliance upon the far-field seismic network utilised for volcano monitoring. Previous authors have speculated that the far field nature of the seismic network has 1) missed lahar events owing to their cooccurrence with other volcanic phenomena and the signals are lost; 2) missed lahar events owing to the similar seismic signal generated by quarrying in the valley; or 3) limits confidence in observations due to lahars signals potentially being generated in valleys other than the BRV (Barclay et al., 2007; Darnell et al., 2012; Froude, 2015). Unfortunately, the record does not contain start/finish times which precludes the calculation of rainfall intensity-duration thresholds for lahar triggering. Re-evaluation of seismic data could solve this in future.

Improvements to lahar detection could be made by the establishment of a dedicated near-field system of seismometers/geophones along the channel or the installation of a force plate. These instruments can be calibrated to provide insights into mass flow characteristics including their volume and sediment load (van Westen and Daag, 2005; Davilla et al., 2007; Berger et al.,2011; Abancó et al., 2012, 2013; Vasquez et al., 2014, 2016; Aratanno et al., 2016; Hürlimann et al., 2019; Bosa et al., 2021). In theory, this could enable a higher-confidence record of lahar activity that includes information on sediment concentration and start/finish times. This in turn would enable more in-depth analysis of lahar activity and its evolution within an evolving catchment.

6.1.2 Improving the analysis of lahar incidence

Within Chapter 3 I used the dataset compiled in Chapter 2 to examine in more detail the conditions associated with lahar activity. This analysis returned useful conclusions. Principally it demonstrated that lahar activity in the Belham River Valley appears to be influenced by incident rainfall magnitude, antecedent rainfall, sediment availability and vegetation cover in combination. It is thus unsurprising that over the study period there is no absolute lahar initiation threshold in terms of incident rainfall magnitude. This is a finding that is consistent with other studies (Barclay et al., 2007; Froude, 2015; Jones et al., 2017). Instead, the likelihood of lahars evolves under varying prevailing catchment conditions. First of all, in general the likelihood of lahar activity increases steadily with increasing magnitude of incident rainfall. This statement is true also when considering the three catchment conditions, however the degree of likelihood varies depending on the conditions. For example, high antecedent rainfall over 7-14 days prior increased the likelihood of a lahar by up to 40% at low-moderate 1-hourly incident rainfall compared with low antecedent rainfall. Similar, though lower magnitude, variance of lahar likelihood was evident when considering sediment availability and vegetation cover. These are valuable findings. However, the insights gained from this analysis are limited by the data it is based upon and the method of analysis. In future, this type of analysis could be enhanced by making improvements to catchment monitoring, as outlined in the sections above. Improved monitoring of lahars, a more representative data source of rainfall, together with higher temporal resolution of observations in the upper catchment would provide the means for more in-depth analysis, including by using intensity-duration analysis to assess variation in triggering/sustaining rainfall (e.g., van Westen and Daag, 2005; Capra et al., 2010; Jones et al., 2017).

6.2 A statement on the efficacy of SedCas_Volcano and potential further study.

Chapter 4 presented SedCas_Volcano, an adaptation of a simple numerical sediment transfer model, SedCas (Bennett et al., 2014, Hirschberg et al., 2021), which I used to simulate lahar activity in the BRV over 2001 - 2019. This is the first time SedCas has been applied to fluvio-sedimentary processes outside of the Illgraben, Switzerland, a small alpine debris flow torrent for which it was designed. This work derived parameter values from the dataset collated in Chapter 2, from literature sources, and/or by iterative/trial-and-error posterior analysis/calibration for unconstrained parameters. Positively, the results demonstrated that some of the patterns of lahar behaviour and sediment transport in the BRV are reproduced by this simple model, e.g., volumes of modelled flows, first-order magnitude frequency of medium and large lahars, and the timing of fluctuations in sediment yield within the correct order of magnitude. There are several ways in which the model performed less well; these provide valuable insights into how model performance could be improved. SedCas_Volcano did not simulate most small flows for reasons that remain unclear at this stage; it did not capture fully the observed seasonal and inter-annual variability; and it showed a low degree of skill when back-casting the timing of medium and large lahars. These failures are related to the inherent simplicity of the model, the available observational data, as well as the means of parameterisation/calibration. Ultimately all models are data limited; the value and accuracy of a model is dependent on the detail of the processes it captures and the accuracy of the data to which it is calibrated. In this case, firstly, I have identified that accounting for hydrological evolution of volcanic deposits could be an important next step for development of the model. To address this, the model structure would need to be adjusted slightly to allow for a variable deposit water capacity that is responsive to deposition events. Secondly, due to the availability of data, some parameters are unconstrained and calibrated by trial-and-error. This could be addressed by improving calibration (e.g., via use of monte Carlo simulations; Hirschberg et al. 2021) or by collecting relevant proxy data. Thirdly, as shown in section 6.1, the available data has its own limitations which have important implications for modelling; I would seek to improve the range and frequency of data collection. Nevertheless, this experimentation with SedCas_Volcano is the first of its kind and is a valuable first step towards the modelling of evolving lahar activity in an episodic volcanic disturbance setting.

6.3 Mountain Aglow: building upon key reflections

Chapter 5 presented my evaluative analysis of Mountain Aglow, a novel, multi-media, co-created, science and arts-based exhibit initiative. This initiative brought together scientific knowledge of volcanoes and alternate knowledges derived from the lived experience of the eruption of SHV. In doing so it sought to situate volcanic risk within everyday life and encourage dialogue about it within and across generations and demographics of the population of Montserrat. My analysis aimed to assess the extent to which the initiative had achieved its goals of:

1) Making a positive contribution to the repertoire and reach of disaster risk reduction activities on the island;
2) Actively engaging Grade 5-6 pupils in conversations/discussions about the volcano;
3) Instigating the sharing of stories between persons with experience of the eruption and those without;
4) Providing scientists and DRR practitioners, via the co-creation process, with greater understanding of the socio-cultural context they work within and help them position their communication to suit the needs, background and understanding of the public more appropriately.

My findings first concur with findings of Monteil et al. (2020) that there is a perception within the community that the volcano has become less relevant as the most recent quiescent period has gone on. Stakeholders all agreed that an initiative such as MA was therefore necessary for improving readiness within the community, particularly given the potential for heightened unrest and possible renewed activity related to 30-year cycles of unrest observed before the eruption. My findings also suggest that the MA initiative has achieved its goals, with numerous observed outcomes, which together indicate positive longer-term impacts of the initiative. I identified the following impacts:

1) Enhanced Disaster Risk Education capacity within the Disaster Risk Management organisations of Montserrat.
2) Enhanced capacity (to prepare and respond to an emergency) of the young people involved in the Mountain Aglow Junior project as a result of improved engagement,

knowledge building, and social capital development via interaction with other project stakeholders/members of the community.

3) Enhanced capacity of the sections of the Montserrat population who have engaged with the Mountain Aglow initiative. This is a result of the combination of the two impacts above, as well as the encouragement of story-sharing within the population. The latter has provided an opportunity to develop or strengthen social capital within the population and has the potential to offer a means of catharsis for persons who have not come to terms with the impacts of the eruption.

Reflections from scientific stakeholders also indicate that they too had learned from the co-creative process in that it had enhanced their understanding of the experience, their ability to relate to members of the population, and establish an understanding of what is most important to members of the wider population. This is an important impact as it may influence the work of these scientists in future. There was also evidence of ways in which the project could be improved. For instance, 1) with regards to reach, stakeholders felt that the project had not yet attained its potential, and 2) throughout the project there were instances of avoidable conflict.

I believe this work makes a valuable contribution to a small but growing body of work pertaining to the use of co-created, arts-based materials for community engagement within the context of disaster risk (Gaillard et al., 2013; Lejano et al., 2021; Sevila et al., in press). It has clearly demonstrated the potential benefits of this type of approach to volcanic risk communication for both improving community engagement and enhancing the knowledge of scientific stakeholders. It shows that the intertwining of scientific facts and alternate, subjective, and experiential knowledges of hazardous events can enhance the relevance and communicability of messages related to them. This work thus serves as endorsement for this type of approach within other volcanic, or wider disaster risk reduction, contexts.

Going forward, there are abundant opportunities to expand upon this approach to DRM, both in Montserrat and elsewhere. In Montserrat, the exhibits can continue to be used for public events and as a basis for schools-based activities. There is also potential for materials to be produced about other hazard events, such as earthquakes and hurricanes; the devastating Hurricane Hugo, which occurred in living memory, in 1989, is likely to have induced a similar artistic response (Fergus, 2010). Elsewhere, this co-creation and arts- and story-based framework has the potential to bring benefits to DRM in a wide range of settings and would be in keeping with recommended DRR strategies put forward by the UNDRR (2015).

6.4 Concluding Statements

The eruption of Soufrière Hills Volcano has disturbed both the physical and human landscape of Montserrat since its onset in July 1995. Through this thesis, I have set out to explore 1) the multi-decadal patterns of geomorphic change and lahar hazard induced by the episodic eruption of SHV, and 2) Mountain Aglow, a novel arts- and science- based volcanic risk communication tool, and its impact on disaster risk management practices on Montserrat. Thus, to conclude, the key findings of this thesis are as follows:

- *Multi-decadal geomorphic evolution and lahar hazard:*
    1) The eruption of SHV has induced a complex pattern of fluvial response within the Belham River Valley.
        - The BRV has undergone net aggradation driven by acute pulses of sediment transfer via large lahars, or cumulatively via small-medium lahars. Aggradation has been punctuated by periods of channel stability or minor degradation.
        - Sediment yields from the Upper Catchment have varied by two orders of magnitude throughout the eruption, reaching a peak of 3.0 x10^5 $m^3km^{-1}yr^{-1}$ in late 1998 – early 1999. Three other peaks are identified in 2003-2004, 2007 and 2010, each with specific sediment yields of between 1.7 - 2.0 x10^5 $m^3km^{-1}yr^{-1}$. These values generally coincide with sediment supply derived from PDCs driven by north- through west-directed dome growth and are well within the range expected by small-moderate volcanic disturbances.
        - Downstream channel change is closely tied to the boundary conditions of the catchment: sediment supply, water supply and vegetation cover.
            - Acute pulses of aggradation and the highest hazard posed by lahars occur when sediment and water supply are high, and vegetation cover is low, owing to enhanced discharge and higher sediment transport capacity of flows.
            - Lack of water supply stalls sediment transport. This is important as it means that recent sediment supply via volcanic activity does not guarantee high-magnitude lahars. Sediment will remain available for remobilisation by future rainfall.

- Lack of sediment supply encourages supply-limited flows which are able to incise into the channel bed, instigating a degradational regime.

- Episodic eruptions induce a distinct fluvial response, which manifest as a hybrid between those induced by transient and persistent eruptions. In effect, given the magnitude of sediment supply events, episodic eruptions induce repeat small disturbances. Recovery begins to occur between phases of activity but is stalled by resupply of sediment from the subsequent episode of eruption.
- Episodic multi-directional dome-forming eruptions may uniquely induce extreme events which buck channel recovery trends by directly supplying tephra to lahars, or damaging vegetation.
    - Introduction of tephra (generated, e.g., by PDC or dome collapse activity directed away from catchment) directly into flows transiently provides additional sediment to the system. This drives transient aggradation when sediment in the upper catchment is already mostly depleted.
    - A reduction in vegetation cover, e.g., following damage by gas emissions or ash from explosions or dome collapse directed away from the catchment, enhances water discharge and sediment carrying capacity of flows. In sediment supply limited circumstances, this may transiently exacerbate degradational patterns (i.e., channel incision, terrace formation).
    - Extreme events may also occur as a result of anomalous rainfall, independent of volcanic activity, which are capable of inducing geomorphically significant lahars more than a decade after the most recent deposition event.

2) The likelihood of lahars is strongly influenced by both incident rainfall and prevailing/antecedent conditions within the catchment.
    - There is no absolute rainfall threshold for lahars in the BRV over the whole study period. Lahars have occurred in association with both high and low incident rainfall; 102 were recorded on days with <5 mm of rain in a 24 hour period.

- The likelihood of lahars increases with increasing incident rainfall magnitude when considering 1-, 3-, and 24-hour intensities.
- Antecedent rainfall, sediment supply and vegetation cover all appear to have a mediative influence on lahar activity in the BRV. Key findings include:
    - High antecedent rainfall over the 7-14 days prior may increase the likelihood of a lahar by up to 40% for moderate 1-hour rainfall intensities. 7-14 day antecedent rainfall has the largest impact on likelihood.
    - High sediment availability increases the likelihood of a lahar by 15-20% at low to moderate 1-hour intensities. This effect increases further with increasing intensity; 60 mm hr^{-1} appears to have guaranteed lahar activity with high sediment availability.
    - Low vegetation cover has a more modest impact on lahar likelihood but appears to have guaranteed lahar activity at rainfall intensities exceeding 40 mm hr^{-1}. This is the lowest level of rainfall intensity observed to have guaranteed lahars. The effect of vegetation cover is most apparent when considering 24-hour rainfall.

3) SedCas_Volcano represents the first attempt of its kind to reproduce decadal patterns of lahar activity in an episodically-disturbed catchment by accounting for incident and antecedent rainfall, sediment supply and vegetation cover.
    - It is able to capture the first-order patterns (aggregate magnitude/frequency over the whole study period) of medium and large lahars reasonably well but fails to simulate most small lahars.
    - It can reproduce general patterns of sediment yield in terms of the timing of fluctuations, and their general order of magnitude. Specific sediment yields are well captured in observed periods of relatively low yield. However, two peaks in sediment yield are underestimated by 30% (~130 vs. observed ~175 - 190 $x10^3$ $m^3km^{-2}yr^{-1}$), and a third is overestimated by 350% (>700 vs. observed 198 $x10^3$ $m^3km^{-2}yr^{-1}$).
    - It performs poorly when predicting the exact timing of medium and large lahars.
    - The model is limited by:

- Its simplicity and assumptions. For example, it does not account for important processes, such as the hydrological evolution of deposits. Further development is required to account for these.
- The use of unconstrained parameters, such as water capacities and residence times within the landscape. Empirical evidence related to these or improved means of calibration may assist this going forward.
- The data upon which it is built.
    - Measurements of sediment input and yield are imperfect; many of these estimates are derived from oblique photographs (Froude, 2015).
    - Measurements of vegetation cover are limited, contain gaps of no data, and have had to be linearly interpolated.
    - GPM rainfall data is not necessarily representative of what is happening over the catchment (only 5% of the GPM cell is occupied by the Upper Catchment of the BRV).
    - Observations of lahars, while expansive, are only based upon broad categories of magnitude and do not provide information of sediment content. This renders comparison with modelled output challenging.

- *Mountain Aglow and Disaster Risk Management:*
    1) The Mountain Aglow initiative has made a positive impact to Disaster Risk Management practices and community capacity on Montserrat.
    2) This initiative has demonstrated the important and useful role that the sharing of the lived experience of hazard events can play in Disaster Risk Management contexts.
    3) Co-created arts-based initiatives such as this are an effective means of enhancing engagement with disaster risk messages.
    4) Co-created initiatives such as this are a useful means of encouraging co-learning, through which scientists can also learn about the socio-cultural contexts within which they work.

To conclude, this thesis has first demonstrated the complexity of fluvio-geomorphic responses to episodic volcanic disturbance. This work makes a valuable contribution to the wider literature on the longer-term response and recovery of river systems after perturbation by explosive volcanic eruptions; importantly, this study is one of only a very few to consider episodic eruptions. Via data synthesis and conceptual model development, statistical analysis, and numerical modelling, I have outlined the importance of the interplay between sediment supply, water supply, and hillslope conditions on controlling geomorphic response downstream and the associated lahar hazard. This work has drawn upon a very rich dataset, arguably one of the richest in the world within this field. However, this thesis has shown that there remains room for improvement with respect to data collection, which would positively impact subsequent analysis and assessment of hazard. Two key means to address this would be to adopt more specific methods of monitoring lahars (e.g. near field geophones) and incorporate systematic catchment-wide observation into routine volcano monitoring procedures.

I have also explored the positive contribution of co-created and arts-inclusive volcanic risk communication tools to Disaster Risk Management practices. These initiatives are based upon the intertwining of scientific knowledge, with local and experiential knowledges of hazards, which are not solely based in scientific principles. I have demonstrated that one such initiative, Mountain Aglow, has made measurable positive impact to DRM efforts in Montserrat. The project was particularly successful with respect to encouraging intergeneration exchange of stories and experiences and the subsequent improvement of the responsive capacity of younger people. The recommendation that follows this work is that more efforts are made, both within a volcanic risk and wider environmental risk contexts, to include similar types of initiative into DRM frameworks around the world.

Appendix 1.1: Data

This appendix is digital and contains the following files and folders:

(NB: due to third-party copyright, some data has been redacted from the publicly available version of this thesis)

- Appendix 1.1 README
- 'Photos':
  - Photos of Orange House used for creation of Figure 2.16.
  - Photos at Transects B1 – 5 and the coastline, organised in folders by location and date.
  - Photos of the Upper Catchment.
- 'Satellite/Aerial Imagery':
  - [Folder] Wadge 1999 - 1999 Aerial images
  - [Folder] ASTER - ASTER images
  - [Folder] RapidEye - RapidEye images
  - [Folder] PlanetScope - PlanetScope images
  - [Folder] Pleiades - Pleiades images
- 'Data':
  - SHV_lahar.xlsx - Lahar record
  - SHV_vegetation.xlsx - Vegetation cover estimates
  - SHV_volcanic - Volcanic inputs duration (Froude 2015)
  - [Folder] GPM - GPM raw data
- 'Topographic Models':
  - dem1995.tif - Pre-eruption
  - dem1999_corrected.tif - 1999 DSM
  - dem2002.tif - 2002 DSM
  - dem2003.tif - 2003 DSM
  - dem2005.tif - 2005 DSM
  - dem2006.tif - 2006 DSM
  - dem2007.tif - 2007 DSM
  - dem2010.tif - 2010 DSM
  - dem2011.tif - 2011 DSM
  - dem2012.tif - 2012 DSM
  - dem2013.tif - 2013 DSM
  - dem2019.tif - 2019 DSM
  - ASTER_2013_GDEMV003.tif - ASTER global DEM

Appendix 1.2: Synthesis of observations

	Observation location				
Observation Date (notable events)	**Tyers/Farrel's Plain/Dyers**	**Gage's Fan**	**Centre/St George's/Garibaldi Hills and Gage's Mountain**	**Belham River**	**Source**
Pre-eruption	Forested (Mesic – Rainforest) in parts, agricultural plots cover much of Farrell's Plain	Non-existent; summit drainage is via Fort Ghaut to the west through Plymouth.	Forested (Mesic – Rainforest), agricultural land on lower slopes of Gage's Mountain	Narrow (2-3m) channel, armoured bed, densely vegetated banks, approximately annual flooding and modest overbank deposition during heaviest rainfall events. Belham Bridge (B4) had a height of 6m and valley floor width of 18m.	Barclay et al. (2007)
18/07/1995 (eruption begins)	-	-	-	-	-
08-09/1995 (El Niño passage of 3 tropical cyclones: 284mm rain in September)	-	-		Sediment laden flows (unknown origin of sediment) ~1.7m aggradation below Belham Bridge, channel occupying full 18m valley floor.	Video footage, anecdotal evidence (Froude, 2015)
Mid 1996	-	-	-	**B4**: No apparent significant changes from pre-eruption channel.	Susnik (2009)
06-09/1997 (first north and west directed volcanic activity) (El Niño)	Lava dome overtops rim of English's Crater. First northward PDCs in June, mostly limited to upper flanks/sections of ghauts. Major PDC and surge over north flanks on 25th June with significant deposition in Tyer's Ghaut and Farrell's Plain. Deposition from multiple Vulcanian explosions.	Fan development occurs during vigorous west-directed activity: dome collapse in July, periods of explosivity during August-October (75 explosions between 22/09 and 21/10)	-	25th June PDC reaches **B1** in upper Middle Belham.	Spark and Young (2002), Loughlin et al. (2002)
Early 1998	-	-	-	**B4:** 4-5m of aggradation 18 m channel beneath Belham Bridge. **B5:** Thin veneer of overbank deposits visible on golf course and near the beach.	Susnik (2009)
10-11/1998	**TG:** Dome collapse flows in October.	Dome collapse flows in October		Passage of storms brings first significant, deposit-forming lahars.	Barclay et al. (2007)

Table 1.1**:** Dates, locations and source of key observations within the Belham River Catchment. '-' indicates no observations available for a given location and date. TG = Tyer's Ghaut; FP = Farrell's Plain; HG = Hussey Ghaut; GF = Gage's Fan; SGH = St George's Hill; GH = Garibaldi Hill; CH = Centre Hills; MB = Middle Belham; LB = Lower Belham. Reference is made to transects from Figure 2.1, e.g., 'B1'.

(inter-phase dome collapses) (La Niña) (Hurricane George, 20-21 September)	40% filled with Phase 1 and post-Phase 1 deposits.			**B4:** Belham Bridge overtopped by 0.4m (total aggradation of 6.4m), boulder-sized clasts (~0.7m) deposited on bridge, channel now approx. 60m wide. **B5:** 0.5m aggradation. 125m-wide channel fully occupied by 11/1998 lahar, then splitting in to two 60m channels to form coastal sediment fans.	Froude (2015)
02/1999 (La Niña)	**TG/FP:** DSM analysis indicates that there is 8.23 +/- 3.74 x10^{6}m^3 of pyroclastic material stored in the pre-eruption landscape. **FP:** Phase 1 eastward migration of Farrell's Plain drainage divide confirmed via DSM analysis. 0.2km^2 added to catchment size; Parallel network of near-straight channels <10m wide established, draining into TG via 11 new tributaries; Much of fan remains unvegetated, northern most surge deposits washed away or revegetated. **TG:** Single channel evident along east bank. Channel widening at rate of 9.25m month^{-1} since October 1998, erosion equivalent of 8.36x10^5+/-2.8x10^{4}m^3 over 4 months. Vegetation removal evident on valley sides where valley narrows upon meeting DR. **DR:** Braiding evident on valley floor, no remnant terraces.	DSM analysis indicates 13.60 +/- 4.00 x10^{6}m^3 pyroclastic material is stored in pre-eruption landscape, most resides within and fills the upper reaches of Fort Ghaut. Subsequent watershed delineation confirms stream capture via formation of North Gage's Fan in 1997. Catchment size increased to 15.4km^2. ~400m long, 15-10m wide channel running along the interface between Gage's Mountain and North Gage's Fan.	-	Valley floor widening observed along entire Belham since pre-eruption; implicit aggradation of between 0.3m (**B3**) and 9m (**B1**) along channel, average of 4.9m since pre-1995. **B1:** ~4m-wide single-threaded channel. **B1-3:** Braided channel form over much of valley floor. **B3-4:** ~2m-wide single-threaded channel. Lahar deposits terminate ~15m from Orange House. **B5:** single, 120m-wide braided channel complex. **Coast:** Progradation of up to ~50m from pre-eruption; coastal fan volume of 0.38x10^{5}m^3 (figure 4.)	Aerial photography, DSM analysis. Froude (2015)
03/2000 Large eastward-directed dome collapse (Carn et al., 2004)	-	-	-	**B4**: Large boulder-laden lahar on 20th March. Up to 1.5m of deposition. Wood debris and abundant boulder-size clasts (0.5m – 1m) observed resting on a sand base. **B5:** 0.2m March 2000 lahar deposits attributed to non-Newtonian flow dynamics. **Coast**: 20-30m of progradation following 20th March event.	(Carn et al., 2004; Barclay et al., 2007, Froude, 2015)
01/2001	-	-	-	**B4:** Sparce vegetation evident on bed surface within boulder clusters. Low amplitude erosion and channelisation to sand base between abundant boulders.	(Barclay et la 2007, Froude, 2015)
07/2001	-	-	Up to 10cm of tephra deposition associated with 29th July eastward dome collapse in area south of B3.	Large syn-eruptive lahar, observations limited.	Herd et al. (2005)

Table 1.1 (cont): Dates, locations and source of key observations within the Belham River Catchment. '-' indicates no observations available for a given location and date. TG = Tyer's Ghaut; FP = Farrell's Plain; HG = Hussey Ghaut; GF = Gage's Fan; SGH = St George's Hill; GH = Garibaldi Hill; CH = Centre Hills; MB = Middle Belham; LB = Lower Belham. Reference is made to transects from Figure 2.1, e.g., 'B1'.

09-10/2001				**B4:** 10m-wide subchannels had formed between boulders by September. Subsequent reworking by lahars established a braided channel system by October. First evidence of sand extraction activities.	(Froude, 2015)
01/2002	**FP:** significant revegetation in lower portions of fan; Continued growth of channel network. **TG:** Continued channel widening at rate of 0.1m month$^{-1,}$ erosion equivalent of 2.91x10^5+/-2.8x10^{4}m^3 over 35 months. **DR:** Upper section with braided valley floor. Lower section, immediately upstream from Lee's Channel confluence, clear multi-level terraces incised into 1999 valley floor.			**B1:** Multi-level terracing. Single channel with braided floor weaving around gravel-cobble cluster bed forms. **B2-3:** Single channel with braided floor weaving around gravel-cobble cluster bed forms. **B3-4:** Channel bed surfaces incised by 1.5m-deep sub-channels. **B4:** Analysis of 700m-long DSM upstream of B4 shows minimal change in gradient relative to pre-eruption surface. Reduced abundance of boulders, gravel-cobble bedforms between braided channels. Deposits reach base of Orange House walls. **B5:** Two incised sub-channels have shallower amplitude than between B3-4. **Coast:** ~20m of coastline retreat since 25/10/2001.	Ground survey, aerial photography (Barclay et al., 2007, Froude, 2015)
01/2003	**TG:** Continued channel widening at 1.17m month $^{-1}$. Phase 2 activity beginning to fill channel incised into relict Phase 1 deposits.				Ground survey (Barclay et al., 2007) Aerial photography Froude (2015)
06/2003	**TG:** Phase 2 activity ends; erosion to TG deposits has been reset. Estimated 2.11x10^{6}m^3 of Phase 1 - 2 sediment in storage. Sediment input into catchment restricted to rockfall and tephra fall until the end of 2006.			**B3-5:** Following 13 lahars**,** January 2002 sub-channels infilled; bed surface fining, high prevalence of sand-sized grains. Average channel bed elevation gain of 1m since January 2002; DSM extrapolation and analysis indicates approximately 1.77x10^{5}m^3 of sediment gain.	Ground photography Barclay et al. (2007) Froude (2015)
07/2003 (15/07: Major east-directed dome collapse 120x10^{6}m^3 DRE; Estimated 0.86x10^{6}m^3 tephra fallout over Belham catchment)	-	-	Up to 15cm of tephra fallout in Old Towne and other western portions of the catchment. Vegetation damage is widespread due to ash loading.	Observations limited: records suggest syn-eruptive lahars caused burial and damage to vegetation in Lower Belham Valley.	Herd et al. (2005) Edmonds et al. (2005) Barclay et al. (2006)

Table 1.1 (cont): Dates, locations and source of key observations within the Belham River Catchment. '-' indicates no observations available for a given location and date. TG = Tyer's Ghaut; FP = Farrell's Plain; HG = Hussey Ghaut; GF = Gage's Fan; SGH = St George's Hill; GH = Garibaldi Hill; CH = Centre Hills; MB = Middle Belham; LB = Lower Belham. Reference is made to transects from Figure 2.1, e.g., 'B1'.

03/2004				**B4:** ~1.5m of aggradation at the Orange House since May 2003. **B4-5:** Active sand extraction develops low lying areas which guide flows and subsequent channelisation. **Coast:** ~60m of coastline progradation evident since March 2003 – likely attributable to voluminous lahar(s) during/soon after July 2003 dome collapse.	Aerial photography Froude (2015)
06/2005	**TG:** Channel widening by 2.3m month^{-1} since 06/2003, equating to removal of $2.28x10^{6}$ +/- $2.8x10^{4}m^{3}$. Significant vertical erosion into bedrock evident.			**B3:** Flat valley floor, ~30m wide, medium-very coarse sand and gravel channels with width of 10-20m and depth of up to 0.7m. 15% areal coverage by cobbles, some nearby sites with up to 45% coverage by boulders (>0.5m diameter) and cobbles, vegetation present but in small quantities. **B4:** Single channel with braided base occupying ~10% of valley floor. 0.6m channel bed elevation loss since June 2003 attributed to incised channel observed switching from the south to north margin of valley. Implies channel depth of ~2m. Analysis of 2km-long DSM reveals decreased valley gradient upstream of the Sappit River confluence (0.025 to 0.02) and increased downstream (0.014 to 0.2) resulting from deposition in this section of channel since January 2002. Bed surface coarsening evident; dominated by cobbles and boulders (up to 1.5m diameter) with sand-rich ribbon channels (~20m width, ~0.2m depth). **B5:** Flat valley floor. Channels a few cm in amplitude and deposits dominated by planar sand beds. No boulders present, <10% areal coverage of cobbles.	Aerial and ground photography DSM analysis Susnik (2009) Froude(2015)
02-05/2006			Extensive vegetation damage attributed to caustic impact of hydrogen sulphide carried in the gas plume being blown by southerly winds through April/May	**Coast:** ~90m of coastal progradation since August 2002. Coastal fan volume of $0.8x10^{5}m^{3}$	Alexander et al. (2010); Satellite imagery

Table 1.1 (cont): Dates, locations and source of key observations within the Belham River Catchment. '-' indicates no observations available for a given location and date. TG = Tyer's Ghaut; FP = Farrell's Plain; HG = Hussey Ghaut; GF = Gage's Fan; SGH = St George's Hill; GH = Garibaldi Hill; CH = Centre Hills; MB = Middle Belham; LB = Lower Belham. Reference is made to transects from Figure 2.1, e.g., 'B1'.

05/2006 (Extreme lahar 20th May)	-	-		**B1-3:** Valley side erosion and bedrock exposure in 17m-wide, 2-3m-deep single-threaded channel. Bank vegetation severely damaged or destroyed. **B2-4:** Net erosion of ~7.7 x$10^4$$m^3$. Channel downstream of Sappit River 2m-deep 17m wide. **B3-4:** Deeply incised channel (up to 2m), more abundant and larger boulders (up to 3m diameter) between **B3** and **B4**. Orange House severely damaged. **B4:** 60% areal coverage by boulders (some greater than 2m diameter) **B4-5:** Net aggradation, deposits up to 1m in places. 15-20m-wide sand bedded channel with depth of 0.25m. Cobbles and boulders up to 2m in diameter scattered over valley floor. Depositional area increased from previously-observed 2-4m either side of channels, to full 250m valley width. **B5 – coast**: Channel bifurcation: ~70m-wide and 0.7m-deep channels incised into newly aggraded surface and into pre-existing deposits. Net deposition (~7.0x$10^4$$m^3$) despite channel incision; 15cm silt layers traceable for 100m. Depositional area increased to 500m width from previously observed 2-4m either side of channels. First observations of boulders being transported to the coast. Coastal progradation evident; middle portions of fans at channel mouths are incised causing 'indentations' in the coastline.	Susnik (2009), Alexander et al. (2010)
24/06/2006	**D2:** Bedrock exposed along much of channel upstream of Lee's Channel confluence.			**B1:** Bedrock exposure evident. **Coast:** ~75m of progradation since February 2006. Coastal fan volume of ~1.8x$10^5$$m^3$.	Satellite imagery
08/2006	-	-	Large proportion of distal vegetation damage from early 2006 has recovered.	**B4:** Valley floor now ~200m wide downstream of Belham Bridge.	Susnik (2009) Alexander et al. (2010)
11/2006	**TG:** Further 14m of lateral erosion into valley fill deposits since 2005. Presence of three discontinuous terraces.		Majority of distal vegetation damage observed in May 2006 has recovered.	**B1-4**: Channel incised by 20th May 2006 flow partially infilled; average ~1m aggradation from smaller subsequent flows. Estimated 1.1 – 2.5 x$10^5$$m^3$ deposited in this section since 06/06/2006. **B5:** Channels from 20th May 2006 totally filled Coastal progradation of an average of 67m.	Ground photography, Satellite imagery Susnik (2009), Alexander et al. (2010), Froude (2015)
01/2007 (Partial dome collapse, major northwest directed PDC)	4.5x$10^6$$m^3$ of deposition from single PDC. **TG:** Observational logs describe TG as being 'full'. Oblique photograph reveals TG filled to approximately the same degree as in 1999, new deposits fill previously incised channels. **DR**: Majority of deposition occurs here due to change in valley gradient and bend in channel.	-	Extensive vegetation damage on Gage's Mountain and east flank of St George's Hill.	**B1/2/3:** 2nd January PDC reaches Sappit River confluence.	De Angelis et al. (2007); MVO Obs (2014)

Table 1.1 (cont): Dates, locations and source of key observations within the Belham River Catchment. '-' indicates no observations available for a given location and date. TG = Tyer's Ghaut; FP = Farrell's Plain; HG = Hussey Ghaut; GF = Gage's Fan; SGH = St George's Hill; GH = Garibaldi Hill; CH = Centre Hills; MB = Middle Belham; LB = Lower Belham. Reference is made to transects from Figure 2.1, e.g., 'B1'.

18/11/2007	**TG/DR:** Estimated 1.72x10^{6}m^3 removed by lahars since January 2007. **DR:** Deposition at D1 in 01/2007 increased channel width to 60m from 46m in 06/2006 and buried Dyer's Bridge. **D1:** Terraces formed in PDC deposit with channels occupying 30% of valley floor. **D2:** A network of narrow <10m channels had established as result of valley widening and fluvial flow energy loss.			**B1:** Channel bed aggradation of 7.2m. **B2**: Valley gradient upstream increase from 0.02 in November 2006 to 0.05. **Coast:** ~45m progradation since June 2006. Coastal fan volume of ~2.1x10^{5}m^3. **B3:** Valley base contained wide boulder bar forms, separated by sand-bedded channels **B4:** Predominantly sandy channel bed with boulder bar forms. **B5:** Channel bed aggradation of 0.7m. **Coast:** 76m of Coastal progradation since November 2006.	DSM analysis Satellite Imagery Darnell (2010) Froude (2015)
03/12/2008	**TG:** Deep incision into upper TG deposits, likely to correspond to channel forms similar to observed in 11/2006.	-	-	-	Oblique photograph (Froude, 2015)
02/01/2009 (PDC ~0.5 x10^{6}m^3)	**TG/FP:** Erosion to deposits reset. Valley filled to similar level as observed in Phase 1. Deposition from 02/01/2009 PDC considered similar to 08/01/2007.	-	-	-	Obgurn et al. (2014) Froude (2015)
09/2009	**TG:** Few superficial and narrow channels, shallow terrace evident in valley meander. **FP:** channel system re-established.			**B4:** Bed surface fining has occurred (predominantly sandy with cobble-boulder clusters) and Orange House buried by ~0.8m since December 2007.	Aerial and ground photography Froude (2015)
10/2009 - 02/2010 (08/01 large explosion PDC 3.4 x10^{6}m^3; 11/02 Partial dome collapse PDC 1.3 x10^{6}m^3)	**TG** totally filled and intrinsically linked to **FP** following 08/01 PDC. Overflow occurs into Hussey Ghaut	BAFs	Widespread vegetation damage on St George's Hill.	**B4:** Moderate lahar on 30th October observed transporting boulders of up to ~0.5m in diameter. 08/01 PDC reaches **Sappit River** (6km runout); 11/02 partial dome collapse pumiceous flow reaches **B3**; bed surface upstream of this point entirely covered by PDC deposit.	Stinton et al. (2014a,b) Cole et al. (2014) Ogburn et al. (2014)
05-06/2010	Summit drainage diversion from TG to Hussey Ghaut confirmed by DSM analysis. **TG:** DSM analysis shows maximum valley fill depth of ~35m, and 5.7+/-1.4x10^{6}m^3 added since 1999. **FP:** DSM analysis shows elevation loss, with a maximum of ~20m, 3.1+/-1.4 x10^{6}m^3 removed. Likely related to erosion caused by the partial dome collapse of February 2010 (Stinton et al., 2014) New channels in Tyer's/Hussey/Dyer's river indicate April 2010 lahar excavated estimated 1.10x10^{5}m^3 from PDC deposits	DSM-based watershed delineation indicates northward migration of Gage's Fan drainage divide since 1999; catchment size now 14.75km^2.	-	**B1-2:** Large lahar on 13/14 April excavates 18m-56m-wide channel. **B1:** Valley fill now exceeds 25 m depth compared to pre-eruption. **B2:** Valley gradient increased to 0.05, from 0.45 in November 2007. Valley fill exceeds 20 m depth. **B4:** Further 0.7m of burial of Orange House since September 2009; attributed to large lahar of 13/14 April. Valley fill exceeds 10 m depth. Bed surface predominately consisting of sand-sized sediment, with ~5% pumicious pebble-cobble fraction. **Coast:** ~35m of retrogradation since November 2007, but coastal fan has thickened by ~0.5m to ~2m, as also evidenced by the complete burial of the old jetty. Coastal fan volume of ~2.2x10^{5}m^3.	DSM analysis Ground photography Froude (2015)
08/2010	-	-	=	**B4:** Orange House totally buried by deposition from large lahar.	Ground photograpy

Table 1.1 (cont): Dates, locations and source of key observations within the Belham River Catchment. '-' indicates no observations available for a given location and date. TG = Tyer's Ghaut; FP = Farrell's Plain; HG = Hussey Ghaut; GF = Gage's Fan; SGH = St George's Hill; GH = Garibaldi Hill; CH = Centre Hills; MB = Middle Belham; LB = Lower Belham. Reference is made to transects from Figure 2.1, e.g., 'B1'.

(Hurricane Earl)					Froude (2015)
11/2010	-	-	-	**B4:** Bed surface consisting of 60% sand clasts, ~40% gravel; cobble-boulder bars present in centre of valley; sand-pebble bars present within ~15m wide sand-bedded channels.	Ground photography Froude (2015)
03/2011	**DR:** Channel widening at 4m month $^{-1}$ since June 2010. Equivalent of ~1.1 x10^5 +/- 1 x10^3 m^3 removed from 600 m section at either side of transect D2			**B1:** Bed surface covered by ~10m cobble-boulder bar forms, resting on a sandy bed. Narrow channels evident between these bars, some contained vegetation. **Coast:** Progradation of ~50m since June 2010. Coastal fan volume of 2.5x$10^5$$m^3$.	Satellite Imagery Ground photography Froude (2015)
03/2012	**DR:** Channel widening at 0.18m month $^{-1}$ since March 2011			**B1:** Bar forms evident in March 2011 partially buried by sand; channels had widened, bed surface covered in sand to medium sized pebbles. Fining resulted from 25 small-medium lahars. **B4:** Bed surface character remains similar to that observed in November 2010; lahars during intervening period predominantly confined to channels (~8m) between bars of coarser bed materials. **B5:** Sand extraction removed an estimated 9.0 x $10^4$$m^3$.	Ground photography Froude (2015)
09/2012	-	-	-	**B4:** Large lahar observed reworking bed surface but inducing limited net topographic change (~0.2m)	Field observations Froude (2015)
12/2012	-	-	-	**Coast:** Coastal fan reaches maximum extent; north outlet is now 256m from pre-eruption coastline with a volume of ~2.5 x$10^5$$m^3$.	Satellite Imagery
03/2013	**DR:** Channel widening at 0.08m month^{-1} since March 2012			**B1:** Flows since March 2012 incised (~0.2m deep) narrower channels within pre-existing channel bed; gravel bars delineate channel boundaries. **B2:** main channel has widened to 65m indicating further erosion of 1.3x$10^4$$m^3$ of sediment since June 2010. **B1-3:** Isolated blocks of PDC deposits exist on the inside banks of meander bends. **B4:** Sand-bedded channels have widened to ~27m since March 2012.	DSM analysis Ground photography Froude (2015)
04/2014	**DR:** Equivalent of ~1.2 x10^4 +/- 1 x10^2 m^3 removed since April 2014 from 600 m section at either side of transect D2.	-	-	**B1:** Two channels (~8m and ~15m wide). **B2:** Braided sub-channels evident in 12m-wide primary channel floor. **B3:** Dominated by mining pits. **B4:** Patches of vegetation between roadways/ tracks. **B5:** Channel bifurcation into two 15m-wide channels which each then adopt braided forms, terminating in vegetation before reaching the sea. **Coast:** Retrogradation of ~25m since December 2012. Coastal fan volume of 2.2x$10^5$$m^3$.	Satellite imagery
08-11/2016	-	-	-	**B4-5:** Both valley crossings eroded and gravel pits flooded by moderate lahars on 24/08 and 01/11.	MVO observations
09/2017 (Hurricane Maria)	**D2:** Up to ~4m lateral erosion to PDC terrace evident in two short (~30-40m) sections of the north channel margin. Reworking of bed surface evident.			**B1:** Up to 10m of lateral erosion to west channel margin. Reworking of bed surface and removal of vegetation evident. **B4-B5:** Both Valley crossing tracks are eroded and removed by flow.	MVO observations Comparison of helicopter surveys (September 2017 vs April 2018).

Table 1.1 (cont): Dates, locations and source of key observations within the Belham River Catchment. '-' indicates no observations available for a given location and date. TG = Tyer's Ghaut; FP = Farrell's Plain; HG = Hussey Ghaut; GF = Gage's Fan; SGH = St George's Hill; GH = Garibaldi Hill; CH = Centre Hills; MB = Middle Belham; LB = Lower Belham. Reference is made to transects from Figure 2.1, e.g., 'B1'.

05/2018		Base of fan revegetated; Narrow ~3m channel from main North Gage's Channel into Lee's Channel	Forested (Mesic – Rainforest)	**B1:** Three main channels interspersed by islands of vegetation. **B2:** Channels evident at B1 converged to form single threaded channel. **LB:** Dominated by gravel pits **B4- Coast:** Vegetation is well established, large >5m trees are common near B5. Extensive mining pits extend upstream to Middle Belham.	Field survey, aerial photography
29/03/2019	**TG/FP:** 0.32+/-0.16 x10^{6}m^3 eroded since June 2010. 10.6+/-2.66 x10^{6}m^3 remains in storage **DR:** 0.58+/-0.21 x10^{6}m^3 eroded since June 2010, equivalent of ~0.7 x10^4 +/- 0.8 x10^2 m^3 from 600 m section at either side of transect D2. 0.97+/-0.54 x10^{6}m^3 remains in storage.	0.12+/-0.06 x10^{6}m^3 eroded since June 2010. 9.46+/-3.12 x10^6 m^3 remains in storage.		**B1-2:** 0.20 +/- 0.13 x10^{6}m^3 material eroded since June 2010. 1.83+/-0.86m^3 remains in storage. **B1:** Valley floor has degraded by 2 m since 2013. **B2:** Valley Floor has degraded by between 2 – 8 m since 2013. **B3-5:** Mining pits now have volume of 0.64 +/- 0.28 x10^{6}m^3 compared to June 2010 surface. 0.28 +/- 0.21 x10^{6}m^3 remains in storage. **Coast:** Retrogradation of max ~25m since 2014. Coastal fan volume of 2.1x10^{5}m^3.	DSM analysis, satellite imagery (this study)
10/2020	-	-	-	**B1:** Single threaded channel now with reduced width of ~6m (2-pixel width). Other sub-channels have been revegetated,	Satellite Imagery (this study)
11/2020	Reactivation of channels is evident; vegetation at the margins of **HG** and draining **FP** has been removed.	New deposit with an area of ~6.2x10^{4}m^2 emanating from outlet summit-draining channel spreading north-westwards towards and partly into Lee's Channel; indicates lahar activity and implies notable erosion from upper North Gage's fan.	-	**B1:** Full ~130m-wide valley floor occupied by new deposit. **B2-3:** Mining pits infilled with up to 2m of lahar deposit. **B3-4:** Lahar deposit follows mining pits in single channel. **B4-Coast:** lahar reaches sea via single channel.	Satellite imagery Ground photography (MVO)
03/2022	**D1:** Steep-sided PDC deposits remain on margins. Vegetation widespread in relic channel to the south of a steep-sided island of PDC deposit. **D2:** Valley margins and surface of remnant PDC deposit desnsely revegetated. Active channel floor sparsely vegetated, dominated by 1-2 channels occupying between 10 and 50% of valley floor.	-	-	**B1-2:** 11/2020 deposit mostly revegetated. Narrow (occupying 5% of valley floor), single-threaded channel evident at B1, bifurcates into two and then reforms a narrow single channel towards B2. Quarrying activities have now reached B2.	Helicopter survey

Table 1.1 (cont): Dates, locations and source of key observations within the Belham River Catchment. '-' indicates no observations available for a given location and date. TG = Tyer's Ghaut; FP = Farrell's Plain; HG = Hussey Ghaut; GF = Gage's Fan; SGH = St George's Hill; GH = Garibaldi Hill; CH = Centre Hills; MB = Middle Belham; LB = Lower Belham. Reference is made to transects from Figure 2.1, e.g., 'B1'.

Appendix 1.3: Satellite imagery of changes post-2011

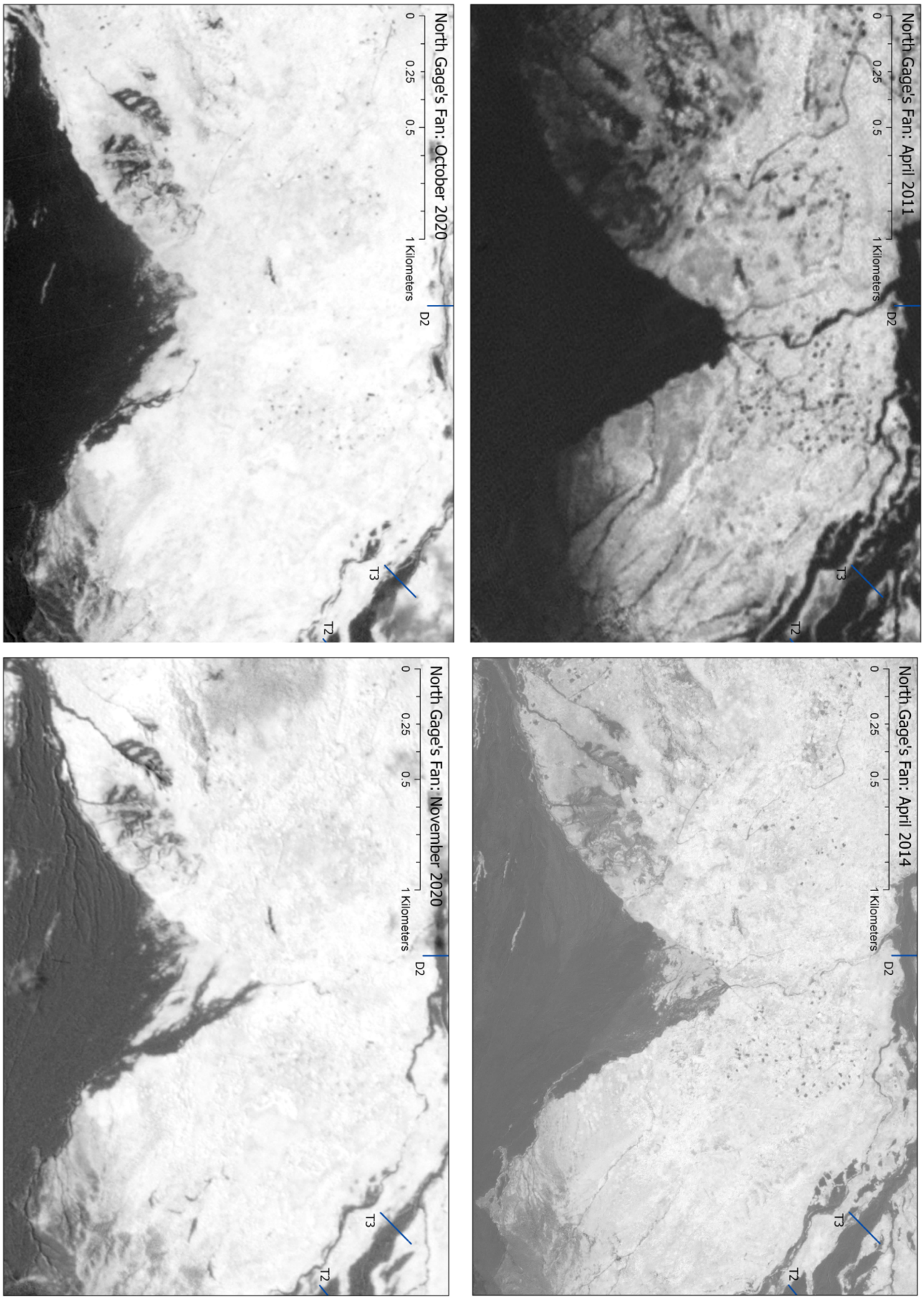


Figure 1.1: NDVI greyscale of the North Gage's Fan and Lee's Channel. Dark greys indicate bare surface/non-vegetation, lighter greys to white indicate vegetation. Note the seasonal vegetation brightness difference between a and b (post dry season), and c and d (late wet season). a) to c) show vegetation establishing on the lower fan and in Lee's Channel, d) shows the deposit formed on NGF after November 2020 lahar reaching to Lee's Channel. Image sources: a) RapidEye, b) Pleiades, c+d) PlanetScope.

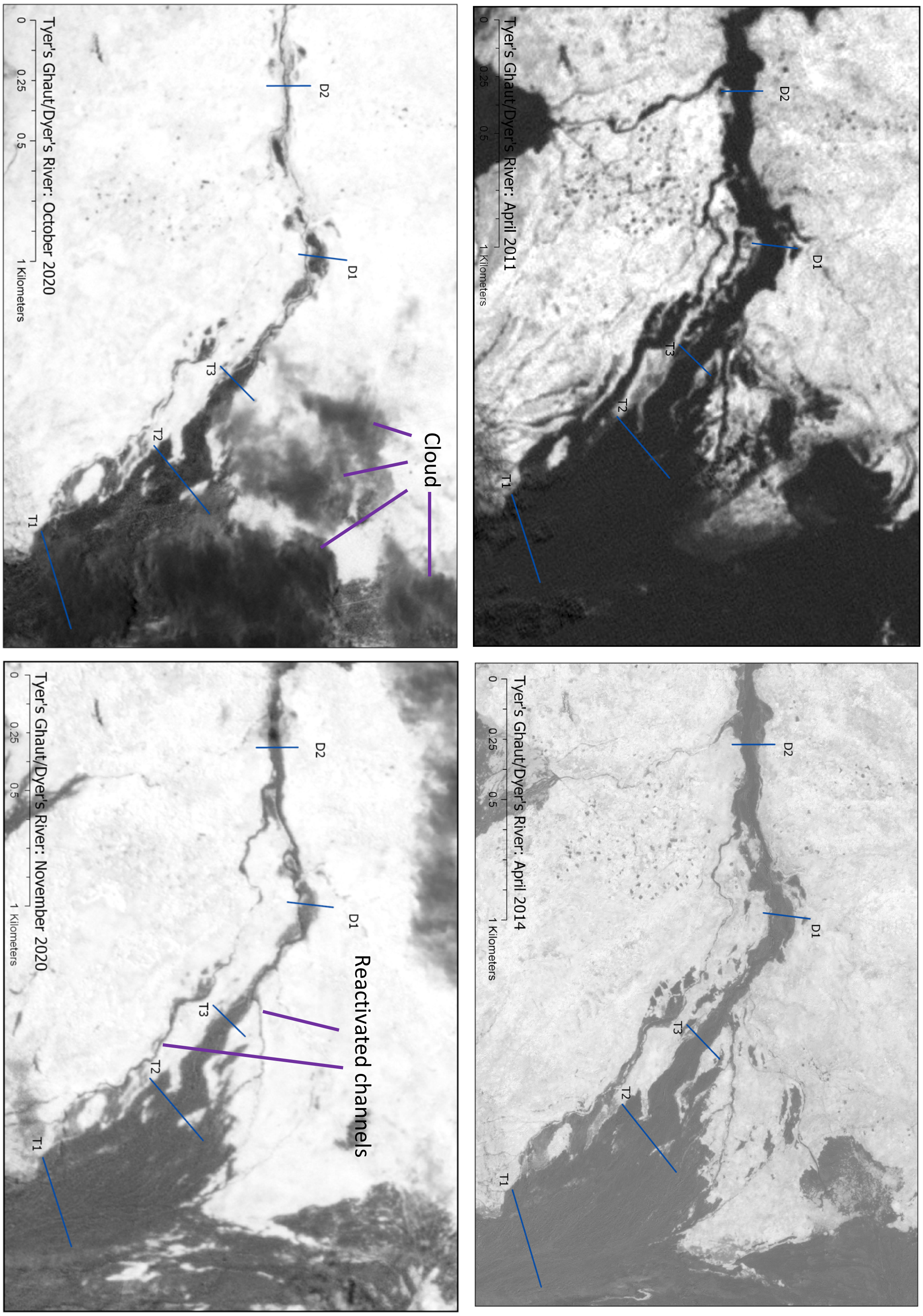


Figure 1.2: NDVI greyscale of Farrell's Plain, Tyer's Ghaut, Hussey Ghaut and Dyer's River. Dark greys indicate bare surface/non-vegetation, lighter greys to white indicate vegetation. Note the seasonal vegetation brightness difference between a and b (post dry season), and c and d (late wet season). a) to c) show vegetation establishing on the lower FP fan and along margins of Tyer's Ghaut, Hussey Ghaut and Dyer's River, d) channels reactivated by November 2020 lahar. Image sources: a) RapidEye, b) Pleiades, c+d) PlanetScope.

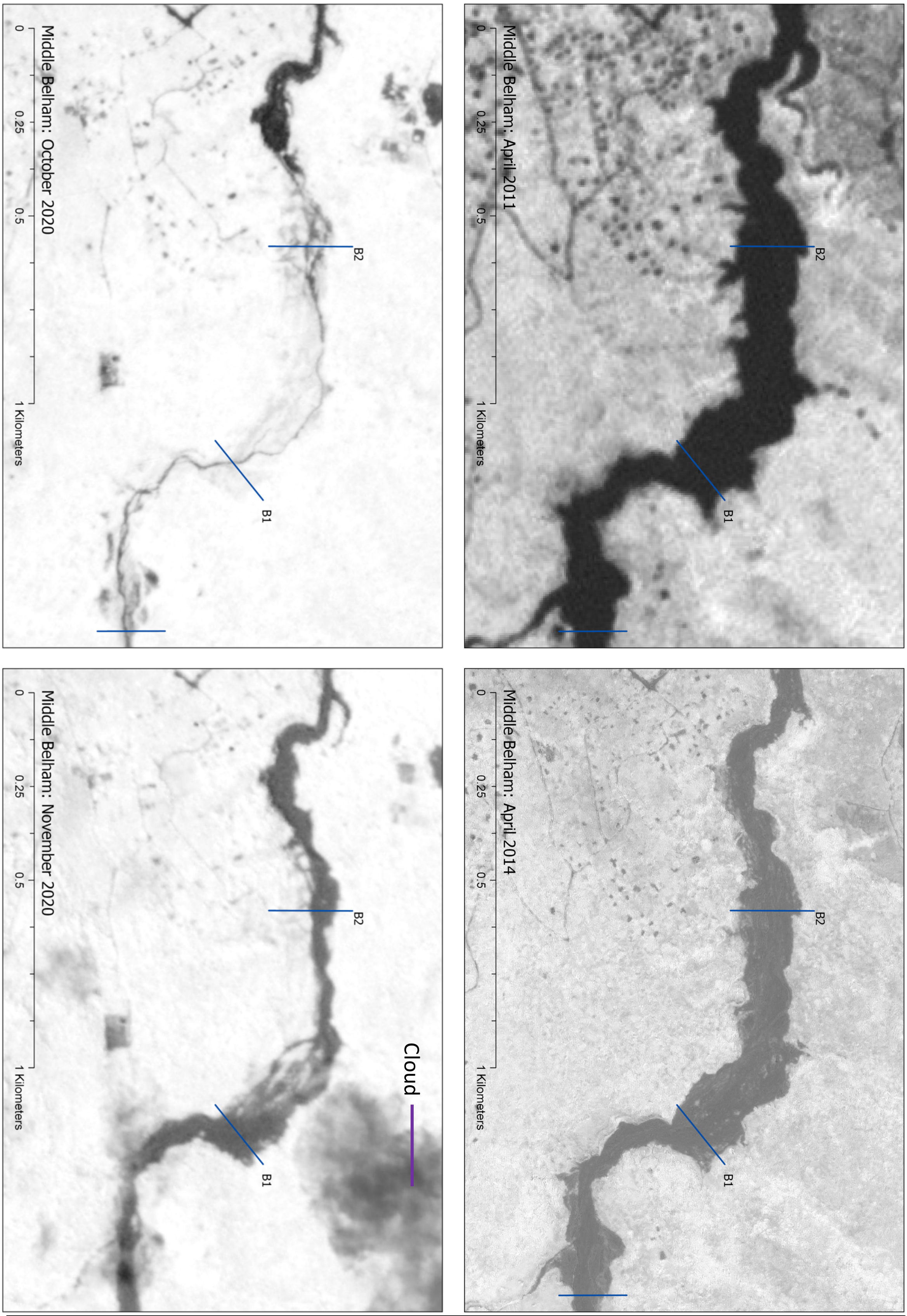


Figure 1.3: NDVI greyscale of the Middle Belham. Dark greys indicate bare surface/non-vegetation, lighter greys to white indicate vegetation. Note the seasonal vegetation brightness difference between a and b (post dry season), and c and d (late wet season). a) to c) show vegetation establishing on the valley floor, c) shows the narrow (6 m wide) single-threaded main channel, d) shows the inundation extent of the November 2020 lahar. Image sources: a) RapidEye, b) Pleiades, c+d) PlanetScope.

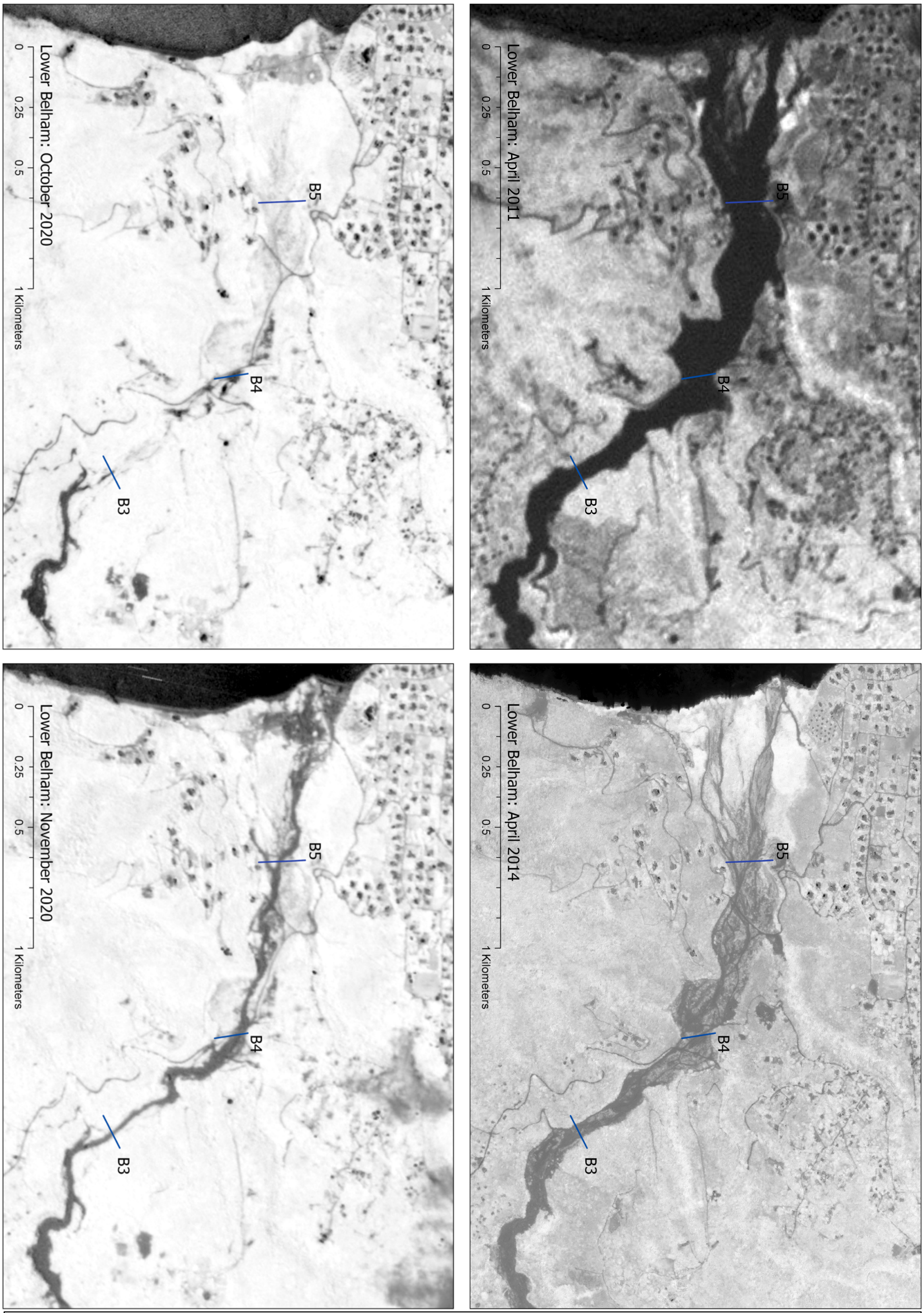


Figure 1.4: NDVI greyscale of the Lower Belham. Dark greys indicate bare surface/non-vegetation, lighter greys to white indicate vegetation. Note the seasonal vegetation brightness difference between a and b (post dry season), and c and d (late wet season). a) to c) show vegetation establishing on the valley floor, c) shows large mining pit upstream of B3, d) shows the inundation extent of the November 2020 lahar which reached the sea. Image sources: a) RapidEye, b) Pleiades, c+d) PlanetScope.

Appendix 2: SedCas_Volcano files

This appendix is digital and contains the following files:

- SedCas_Volcano.py	- Main model code
- run.py	- Model initiation script
- modules.py	- Modules called upon by the SedCas.py and run.py scripts
- SHVinput.met	- Tab delimited file of input data
- SHVparameters.par	- Tab delimited file of parameter settings
- Sedcas.yml	- SedCas virtual environment
- SedCas_README.md	- Read me file for SedCas

Appendix 3.1: Interview protocol

Interview protocol for Mountain Aglow Evaluation

There were four general types of participant in this study:

1) Disaster Risk Reduction practitioners (with and without experience of the eruption);
2) Educational practitioners (with and without experience of the eruption);
3) Other stakeholders involved earlier in the process (all with experience of the eruption);
4) Members of the population previously uninvolved in the project (with and without experience of the eruption).

Interviews/focus groups were thus tailored according to the type of participant to account for their different perspectives.

DRR Practitioners

Staff of the MVO, DMCA and MRC are involved in Disaster Risk Management and disaster response, and part of their organisational mandates (for DMCA and MVO, at least) is to engage and educate the public; they therefore have unique perspectives pertaining to this. Further, as risk communicators (particularly those who are non-Montserratian with no eruption experience), they stand to benefit from the co-creative process by developing a greater appreciation of the lived experience of the eruption and socio-cultural context within which they work. Accordingly, these participants were asked questions specific to their role.

- What are your perspectives of the initiative?
    - (For those with eruption experience) did you feel the exhibit represented your personal experience and the experience of others you know?
    - Do you think there is a need/purpose for this type of initiative in Montserrat in terms of disaster readiness?
    - How important do you think it is that the exhibit includes the arts and stories about the lived experience of the eruption as told by Montserratians?
- Has the Mountain Aglow initiative contributed to and benefitted your disaster risk education and engagement activities? If so in what ways?
    - Do you think it is an effective means of engaging with the public?
    - Do you perceive that you have engaged with more people across a wider sector of the population through this initiative?
- What responses have you observed from visitors when hosting/visiting the exhibits? E.g.,
    - Have you witnessed people sharing their experiences?
    - Have you received feedback?
- What benefits do you think these exhibits offer the population of Montserrat?
- What benefits do you think this initiative has offered the other stakeholders and contributors?
- Can you offer any reflections about being involved in this co-creative process? E.g.,
    - Do you think co-creation has been beneficial? If so, in what ways?
    - Have you learned about the experience of the eruption?
    - Have you learned about the public you engage with and their perception of the volcano?

    - Have you learned about the societal/cultural importance of the eruption?
    - Has co-operation with other organisations through this process enhanced your work together? Why is this important?
    - Were there any challenges throughout this process?
- What improvements or additions do you think could be made to the exhibits and the undertaking of the initiative as a whole?
- Are you interested in participating in more projects like this in the future?

Educational practitioners

This group includes one representative of MoE (permanent secretary) and the 9 schoolteachers involved in focus groups. These individuals were approached because of their role in the Mountain Aglow Junior project, their involvement in implementing or teaching the volcano and hazards curriculum, and their unique perspectives on the effectiveness of the project when engaging Grade 5 and 6 pupils. Questions were posed specifically to garner perspectives about how the pupils engaged, whether they had learned from the experience, whether the project was complementary to the curriculum, as well as their personal perspectives as members of the population.

- What are your perspectives of the initiative? E.g.,
    - (For those with eruption experience) did you feel the exhibit represented your personal experience and the experience of others you know?
    - Do you think there is a need/purpose for this type of initiative in Montserrat, specifically with respect to young people?
    - How important do you think it is that the exhibit includes the arts and stories about the lived experience of the eruption as told by Montserratians?
- Has the Mountain Aglow initiative contributed to and benefitted your teaching of the hazards curriculum? If so in what ways? E.g.
    - Is the exhibit complementary to the hazards curriculum?
    - Have your pupils been more engaged with this part of the curriculum?
- What responses have you observed from children when they have interacted with and participated in activities related to this initiative?
    - What do you think they have learned from most?
- What benefits do you think these exhibits and being involved in this initiative offer the pupils?
- What benefits do you think this initiative/these exhibits offer the wider population of Montserrat?
- Can you offer any reflections about being involved in this co-creative process? E.g.,
    - Do you think co-creation has been beneficial?
    - (For those without experience) Have you learned anything about the volcano or experience of the eruption?
    - Have you learned anything about DRR at large?
    - Has co-operation with other organisations (i.e., DRR organisations) through this process enhanced your work together? Why is this important?
    - Were there any challenges of this process?
- What improvements or additions do you think could be made to the exhibits and the undertaking of the initiative as a whole?
- Do you think more initiatives like this in the future would be beneficial?

Other stakeholders/contributors

Other stakeholders interviewed in this study include representatives of the MNT, MAC, MPL, MTGA, and other members of the population who had been involved in the project previously. Perspectives were sought from these people in a more general manner, pertaining to their perceptions of being involved in the process and what benefits they had felt themselves, or observed from others. MNT, in their role as a public educational body, have also been involved in hosting the exhibits and assisting with the logistics the storage, transportation and construction/dismantling of the exhibits, thereby having additional important perspective. Both MNT and MTGA interact with tourists and thus were asked questions related to this too.

- What are your perspectives of the initiative? E.g.,
    - (For those with eruption experience) did you feel the MA exhibit represented your personal experience and the experience of others you know?
    - Do you think there is a need/purpose for this type of initiative in Montserrat?
    - How important do you think it is that the exhibit includes the arts and stories about the lived experience of the eruption as told by Montserratians?
- What benefits do you think these exhibits offer the population of Montserrat?
- What benefits do you think this initiative offers the other stakeholders and contributors?
- Can you offer any reflections about being involved in this co-creative process? E.g.,
    - About the volcano or experience of the eruption?
    - About DRR at large?
    - Has co-operation with other organisations through this process been beneficial to you?
    - Were there any challenges of this process for you?
- What improvements or additions do you think could be made to the exhibits and the undertaking of the initiative as a whole?
- Do you think more initiatives like this in the future would be beneficial?

Other members of the population

Other members of the population (n = 2) were approached for interview to gather their perspectives as individuals who had not been involved but had visited the exhibits. These

- What are your perspectives of the initiative? E.g.,
    - (For those with eruption experience) did you feel the MA exhibit represented your personal experience and the experience of others you know?
    - Do you think there is a need/purpose for this type of initiative in Montserrat?
    - How important do you think it is that the exhibit includes the arts and stories about the lived experience of the eruption as told by Montserratians?
    - Did you learn from the exhibits? If so, what did you learn?
- What benefits do you think these exhibits offer the population of Montserrat?
- What improvements or additions do you think could be made to the exhibits and the undertaking of the initiative as a whole?
- Do you think more initiatives like this in the future would be beneficial?

Participant	Community role	MA Involvement	I/FG	Contact reason
Director of MVO	Scientific lead of the MVO. Responsible for issuing official statements of the MVO.	Latterly peripherally involved with MA.J	Interview	Perspective of directing key organisation involved in volcanic risk assessment/ communication and as someone who had experienced parts of the eruption.
MVO Scientist	Part of scientific team responsible for monitoring the activity of Soufrière Hills Volcano. Co-leader of the Mountain Aglow Junior initiative.	Primary MVO partner in MA project	Interview	Perspective of working for key organisation involved in volcanic hazard and risk assessment/ communication and taking a lead role in MA/MAJ and as someone who hat not experienced the eruption.
MVO Outreach and Education Officer	Responsible for running the outreach and education activities of the MVO. Co-led Mountain Aglow Junior initiative.	Key MVO partner in MA.J initiative.	Interview	Perspective of directing public outreach of key organisation involved in volcanic hazard and risk assessment/ communication and taking a lead role in MAJ and as someone who had not experienced the eruption.
DMCA Operations Manager	Responsible for coordinating disaster preparedness and relief activities on Montserrat.	Interviewed during consultation phase, primary contact in DMCA.	Interview	Perspective of directing key organisation involved in natural hazard and risk assessment/ communication and as someone who had experienced the eruption.
DMCA Media Officer	Responsible for outreach activities and media interaction of the DMCA. Co-led Mountain Aglow Junior initiative.	Key DMCA partner in MA.J initiative.	Interview	Perspective of directing public outreach of key organisation involved in natural hazard and risk assessment/ communication and taking a lead role in MAJ and as someone who had experienced the eruption.
Permanent Secretary of Education	Responsible for the development and maintenance of national curriculum. Also member of the board of MNT.	Not previously involved.	Interview	Perspective of overseeing and managing education practice on Montserrat.
Operations Manager of the Montserrat Red Cross	Leads and coordinates response of MRC in the event of disaster.	Interviewed during consultation phase.	Interview	Perspective of overseeing and managing humanitarian disaster response on Montserrat and as someone who had b experienced the eruption.
Volunteer for Montserrat Red Cross	Coordinates volunteers for MRC.	Interviewed during collation phase.	Interview	Perspective as previous contributor and as someone who had experienced the eruption.
Director of the Montserrat National Trust	Oversees and directs activities of the MNT.	Primary contact in MNT. Interviewed during initial consultation phase.	Interview	Perspective as director of key community institution involved in education and as someone who had experienced the eruption.
Head Librarian	Oversees and directs activities of the public library.	Interviewed during initial consultation phase.	Interview	Perspective as director of key community institution involved in education and as someone who had experienced the eruption.
Primary school teachers (x9)	Responsible for the teaching the hazards-related curriculum	Key partners and facilitators during MAJ initiative.	3x Focus groups, 1 per school.	Perspectives on the engagement of school children with the MA initiative. Perspectives from people both with and without experience of the eruption.
Member of the Tour Guides Association	Tour guide	Part of focus group during initial consultation phase.	Interview	Perspective as someone who operates within the tourism industry and as someone who had experienced the eruption.
Member of the Tour Guides Association	Tour guide	Not previously involved.	Interview (not recorded)	Perspective as someone who operates within the tourism industry and as someone who had experienced the eruption.
Member of the Parliamentary Opposition	Involved in local politics	Not previously involved.	Focus group	Perspective of someone previously not involved in the project and had experienced the eruption.
Events Manager of the Montserrat Arts Council	Responsible for organisation of all public events held by MAC	Involved in organisation of launch event for MA.J	Interview	Perspective as someone involved in the celebration of arts in Montserrat and as someone who had experienced the later stages of the eruption.
Non-resident Montserratian	N/A	Not previously involved.	Focus group	Perspective as someone previously not involved in the project and had not experienced the eruption.
Montserratian calypsonian	Songwriter, music teacher	Contributed calypsos to MA, and delivered workshop in MA.J initiative.	Interview	Perspective of one of the musicians who produced music in response to the eruption and who has been involved with schools workshops.
Exhibit visitors (numerous)	N/A	Not previously involved.	Informal anonymous conversations	Perspective of people previously not involved in the project and as people with or without experience of the eruption.

Table 3.1: List of interviewees, their previous involvement in the project, the type of interview, and the reason for contact with them.

Appendix 3.2: Feedback form

Thank you for visiting Mountain Aglow!
We would like to invite you to give some feedback about your experience with the exhibits.

Please rate how informative/interesting you found each panel:

	Not interesting 1	2	3	4	Very interesting 5
Falling Ash and Stones:	☐	☐	☐	☐	☐
Volcano Island:	☐	☐	☐	☐	☐
Before and After:	☐	☐	☐	☐	☐
The Volcano's Guts/Watching the Volcano:	☐	☐	☐	☐	☐
Moving, Crossing and Leaving:	☐	☐	☐	☐	☐
Moments of light and laughter:	☐	☐	☐	☐	☐

Please rate how important the following aspects of the exhibits were to you:

	Not important 1	2	3	4	Very important 5
Stories about experiencing the eruption:	☐	☐	☐	☐	☐
It includes Montserratian music/calypso/poetry:	☐	☐	☐	☐	☐
The pictures that tell the history of Montserrat:	☐	☐	☐	☐	☐
The information about how volcanoes work:	☐	☐	☐	☐	☐
It is a mobile exhibit and is very accessible:	☐	☐	☐	☐	☐
The exhibit has music, sounds and lights:	☐	☐	☐	☐	☐
It was created by and for the people of Montserrat:	☐	☐	☐	☐	☐

What kind of reflections did the exhibits prompt and how did it make you feel?

____

____

In what ways do you think the exhibits could benefit Montserrat, now and in the future?

____

____

If you have any other comments, please write them overleaf.

Appendix 3.3: Ethics

Ethics ETH2122-1359 : Mr James Christie

Date Created	23 Feb 2022
Date Submitted	16 Mar 2022
Date of last resubmission	17 Mar 2022
Date forwarded to committee	17 Mar 2022
Researcher	Mr James Christie
Category	PGR
Supervisor	Dr Teresa Armijos Burneo
Faculty	Faculty of Science
Current status	Approved

Ethics application

Applicant and research team

Principal Applicant

Name of Principal Applicant
Mr James Christie

UEA account
ntv17zyu@uea.ac.uk

School/Department
School of Environmental Sciences

Category
PGR

Primary Supervisor

Name of Primary Supervisor
Dr Teresa Armijos Burneo

Primary Supervisor's school/department
School of International Development

Other research team members

Name of any other member of the research team where applicable.
Karen Pascal

Name of research team member's organisation/institution where applicable.
Montserrat Volcano Observatory

Name of any other member of the research team where applicable.
Kathleen Retourne

Name of research team member's organisation/institution where applicable.
Montserrat Volcano Observatory

Project details

Project title
Evaluation of the Mountain Aglow exhibit as a means of complementing volcanic risk communication on the island of Montserrat.

Project start date
17 Mar 2022

Project end date
29 Mar 2022

Describe the scope and aims of the project in language understandable by a non-technical audience. Include any other relevant background which will allow the reviewers to contextualise the research.
Formal risk communication methods typically involve the dissemination of risk messages to the wider public by authorities/decision makers, informed by expert opinions. This applies to a wide variety of contexts, including the communication of volcanic risk. Montserrat has endured a volcanic crisis for more than 25 years. Since its inception in July 1995, the eruption of Soufriere Hills Volcano has wrought widespread destruction over the island. It has rendered the southern two-thirds of the island uninhabitable, necessitating the evacuation and relocation of ~10,000 people. The assessment of the developing situation, resultant evacuation, and the ongoing management of the crisis, has involved risk communication and policies implemented by decision making authorities (the UK/Montserrat governments), informed by scientific experts (based primarily at the Montserrat Volcano Observatory).

Studies (e.g. Armijos et al 2017) have found that both formal and informal modes of risk communication improve community resilience in the face of volcanic risk. Montserrat has a strong oral and musical heritage; there has been a rich artistic response to the impact of the eruption, taking the form of music, poetry and stories. In 2019, the Mountain Aglow exhibit was deployed to Montserrat. This exhibit collated stories, songs and poetry, and combined them with scientific knowledge, to create an immersive multi-media exhibit to share the lived experience of the eruption. Critically, the intent was for this exhibit to be co-created with the Montserratian population, so as to encourage more 'informal' exchange of knowledge and experience within the community, to thereby increase resilience within this context of ongoing volcanic crisis.

The aim of this research is to evaluate the success of this project, both with respect to potential measurable impacts, as well as to reflect upon the successes and potential points of improvement within the consultation, co-creation, design, and production process.

Provide a brief explanation of the research design (e.g. interview, experimental, observational, survey), questions, methodology, and data gathered/analysis. If relevant, include what the participants will be expected to do/experience.

This work will involve speaking to a variety of people from across Montserratian society - from government officials to the general public. The aim is to assess the impact the exhibit has had so far, examine the perceived benefits of the exhibit for the community, and gather any other feedback about the exhibit itself and the means by which it was produced.

The methodology of the research will involve: focus groups with relevant members of organisations/community groups (e.g. teachers); interviews with stakeholders/contributors to the exhibit; informal conversations with visitors to the exhibit; general observation at events; exhibit visitors will be invited to complete feedback forms.

Questions posed to each individual/group will depend on their role within society. For example, disaster management officials and scientists of the Montserrat Volcano Observatory have a unique role in risk communication. A key evaluative insight with respect to their roles is whether they perceive or have observed, the exhibit to be complementary to their preexisting communication efforts. By contrast, teachers, who headed facilitate a recent campaign by the MVO to tour the exhibit around primary schools, have unique insights with respect to how school-aged members of the population interacted/engaged with the exhibit. One of the most important aspects of the exhibit was the co-creation with Montserratians who had experience of the eruption. A key part of this evaluation is assessing how well the finished product has conveyed the lived experience of the eruption and examine whether the co-creation has enabled a sense of ownership of the exhibit, thereby encouraging its use as a catalyst for sharing. With regards to individual members of the general public, questions will be tailored towards assessing whether the exhibit has added to their understanding of volcanic processes, the geophysical history of the island, and the experience of the eruption.

Detail how any adverse events arising in the course of the project will be reported in a timely manner.

Adverse events will be reported immediately to colleagues at the Montserrat Volcano Observatory, as well as to Prof. Jenni Barclay at UEA who is supervising this work and has extensive experience working in Montserrat and with its community.

Will you also be applying for Health Research Authority approval (HRA)?

No

Indicate if you are applying for approval for an experiment to be conducted in the School of Economics' Laboratory for Economic and Decision Research (LEDR).

No

Is the project?:

none of the options listed

Does the project have external funding administered through the University's Research and Innovation Services (RIN)?

No

Will the research take place outside of the UK?
Yes

Will any part of the project be carried out under the auspices of an external organisation, or involve collaboration between institutions?
Yes

Do you require or have you already gained approval from an ethics review body external to UEA?
No

Does this new project relate to a project which already has ethics approval from UEA?
No

Research categories

Will the project involve human participants?
Yes

Will the project involve the use of live animals?
No

Will the project have the potential to affect the environment?
No

Will the project have the potential to affect culturally valuable, significant or sensitive objects or practices?
No

Will the project involve security sensitive research?
No

Human participants - selection and recruitment

How many Participant Groups are there who will receive tailored participant information?:
More than four

Name of Participant Group 1.
Government officials (e.g. Disaster Management)

Name of Participant Group 2, if applicable.
Scientific authorities (Montserrat Volcano Observatory Staff)

Name of Participant Group 3, if applicable.
Staff of other interested institutions (e.g. Red Cross, Tourism Board)

Name of Participant Group 4, if applicable.

Teachers/educational staff

Names of other Participant Groups, if applicable.
General public (visitors to the exhibit from a variety of potential backgrounds/sectors of society)

How will the participants be selected/recruited?
Participants will be both targeted and selected randomly. There are particular people, e.g. stakeholders of the project, with whom I would like to speak; these people will be targeted directly. I expect to speak to approach at least 20 people in this way (for either interview or focus group). Otherwise, members of the general public will be randomly selected via informal interaction in proximity to the exhibit. AT this time it is uncertain how many participants will be approachable in this way (there is uncertainty regarding which events we will be attending).

In terms of UEA participants only, will you be advertising the opportunity to take part in this project to?:
None of the above (i.e. UEA's Student Insight Review Group (SIRG) does not need to be informed)

What are the characteristics of the participants?
Participants are likely to vary widely as I hope to speak with as great a variety of people as possible to assess how the exhibit is perceived across different groups within the community. This may therefore include people from a range of backgrounds (e.g. Montserratians/immigrants from other islands/tourists/European or American ex-pats; some visitors to the exhibit may have protected characteristics (e.g. all genders, disabilities, etc.). Some activities will involve school groups as they have created the new exhibit and part of the purpose of the events is to celebrate and showcase to the pupils and their families. I will be at these events as an explainer and facilitator, all school groups will be accompanied by their teachers or their families.

Will the project require the cooperation of a gatekeeper for initial access to the individuals/groups to be recruited?
Yes

Who will be your gatekeeper for accessing participants?
I will attend public events in association with Karen Pascal/Kathleen Retourne of the Montserrat Volcano Observatory, who have invited me to attend/participate in a number of local events.

How and when will a gatekeeper permission be obtained?
I have received verbal permission to attend said public events from Karen Pascal of the Montserrat Volcano Observatory (the general invitation to the main event is included below, other events may be attended and permission acquired accordingly).

Provide any relevant documentation (letters of invite, emails etc).
How will you record a gatekeeper's permission?
If more gatekeeper permission is needed, for example, to additional events, I will request this is given in writing.

Is there any sense in which participants might be 'obliged' to participate?

No

Will the project involve vulnerable groups?

No

Will payment or any other incentive be made to any participant?

No

Include any other ethical considerations regarding participation.

At public events, I will be approaching visitors, introducing myself, explain my research and purpose, ask permission to speak with them/ask them questions and explain how this may assist my research. Any person I approach may choose to participate in conversation with me, in which case they provide verbal consent, or decline. No data will be collected from persons who decline to participate.

As part of general observations of interactions with the exhibit, I will make notes of general behaviours of all visitors, none of which will include any information that renders any individual identifiable.

Human participants - consent options

By which method(s) will consent to participate in the research be obtained?:

Participant Information Sheet and Consent Form

Verbal

Other, please specify

To clarify, all participants in interviews will sign a consent form an be given information sheet will be provided to people I am interviewing for them to keep after the interview. Those I speak to on an informal basis will receive an introduction, give verbal consent, and then be given an information sheet to keep.

Human participants - information and consent

Participant Information and Consent

Will opt out consent for participation in the research be used?

No

You can generate a Participant Information Text and Consent Form for this application by completing information in the Participant Information Text and Consent Form Generator tab. Alternatively you can upload your Participant Information Text and Participant Consent Form which you have already prepared. Confirm below:

Upload prepared Participant Information Text and Consent Form.

Upload the Participant Information Text and Consent Form.

Enter participant group number and name.

This is a general consent form for all participants; wording may be adapted for particular people

When will participants receive the participant information and consent request?

Prior to any formal interviews or focus groups, participants will be provided with full information regarding the purpose of the research and asked to sign a consent form. Prior to informal in situ conversations I will explain my purpose for conducting the research and request verbal consent.

How will you record a participant's decision to take part in the research?

For formal interviews and focus groups I will acquire consent using the consent form provided. In the case of informal conversation, I will request consent verbally following a full verbal briefing/explanation of the research. For feedback forms, consent is implied (no personal information will be obtained anyway).

Human participants - method

Which data collection methods will be used in the research?:

Interview

Observation

Focus group

Anonymous questionnaire

If your research involves any of the methods (including Other) listed above, upload supporting materials.

How have your characteristics, or those of the participants influenced the design of the study or how the research is experienced by participants?

My characteristics (British white male) may have an influence on the responses from participants, many of whom are of Afro-Caribbean ethnicity living in a British Overseas Territory. The characteristics that I possess have been referred to by participants during previous work who have advised that I may not receive full disclosure/responses as a foreigner. I have conducted human participant-based research in Montserrat since 2014 and understand the implications of my positionally and status as a researcher; I will thus take the necessary precautions to minimise potential perceived power imbalances and to strictly ensure participants voluntarily participate in the activities. I am also working closely with local partners who understand the different cultural background of the island and will follow their guidance.

Characteristics of individual potential participants have influenced the research design in terms of which questions I believe they are most likely to be able to help answer (e.g. disaster management officials will be able to answer questions about disaster management).

Will the project involve transcripts?

Yes

Select ONE option below:

Other

If yes provide details.

Transcription of relevant portions interviews may be performed to assist analysis. Any transcription required will be done by me.

Provide an explanation if you are not offering the participant the opportunity to review their transcripts.
N/A

Will you be capturing photographs or video footage (digital assets) of individuals taken for University business?
No

Is this research using visual/vocal methods where respondents may be identified?
No

Will it be necessary for participants to take part in the study without their knowledge and consent at the time?
No

Will deception or incomplete disclosure be used?
No

Will the participants be debriefed?
No

Will substances be administered to the participants?
No

Will involvement in the project result in, or the risk of, discomfort, physical harm, psychological harm or intrusive procedures?
Yes

If yes, provide details.
Potentially. While the topics of discussions with participants will be the exhibits, the exhibit itself provides details of a difficult and traumatic time in the lives of some of the contributors. Conversations may involve discussion of these aspects (for example, the fear associated with hearing rocks falling onto the roof during an eruption, or the loss of livelihood/loss of homes/displacement/separation of families) with respect to how the exhibit has captured/portrayed these experiences. To limit potential discomfort these subjects will not be approached directly by me (documenting the experiences of people was the purpose of previous work in 2019), instead there is a possibility participants may wish to share their experiences. I will also remind participants that they may stop the proceedings at any time if they feel uncomfortable. In the event that a participant does get upset, I will pause or cease proceedings; I am also trained in mental health first aid so can respond effectively to such an occurrence.

Will the project involve prolonged or repetitive testing?
No

Will the project involve potentially sensitive topics?

Yes

If yes, provide details.

Interviews may involve discussion of experience of the volcanic eruption; this may lead to the discussion of traumatic experiences and losses incurred by the eruption and the associated evacuation.

Will the project involve elite interviews?

Yes

If yes, provide details.

I intend to speak with Disaster Management officials, as well as any government officials who may have valuable insights into the potential benefits of the exhibit from an official perspective.

Will the project involve any incitement to, encouragement of, or participation, in an illegal act (by participant or researcher)?

No

Will the research involve an investigation of people engaged in or supporting activities that compromise computer security or other activities that may normally be considered harmful or unlawful?

No

Does the research involve members of the public in participatory research where they are actively involved in undertaking research tasks?

No

Does the research offer advice or guidance to people?

No

Is the research intended to benefit the participants, third parties or the local community?

Yes

Provide an explanation.

This research is an evaluation of the Mountain Aglow exhibit and the processes involved in its conceiving, co-creation and deployment. The exhibit itself was intended to be co-created with the people of Montserrat in order to then be used by the island to complement/encourage conversations within the community about livingin a multi-hazard environment, with particular ffocus on prolonged volcanic activity. Our evaluation thus sets out to examine any benefits already being felt, perceived benefits for the future, but also any points of improvement both in terms of process and materially. The exhibit is designed to in such a way that enables it to be updated or modified or improved in time; its evaluation will allow the potential for such changes.

What procedures are in place for monitoring the research with respect to ethical compliance?

I will be working closely with partners at the Montserrat Volcano Observatory, I will be in close contact with my supervisor Prof. Jenni Barclay (who has extensive experience working on Montserrat and with its community), and I also have a contact on the island who has been involved with ethical evaluations of our previous activities with Mountain Aglow.

Does the study involve the use of a clinical or non-clinical scale, questionnaire or inventory which has specific copyright permissions, reproduction or distribution restrictions or training requirements?

No

Include any other ethical considerations regarding data collection methods.

N/A - this work will not involve photography of participants or any additional material which would render participants identifiable.

Health and safety - participants

Is there a possibility that the health and safety of any of the participants in this project including a support person (e.g. a care giver, school teaching assistant) may be in question?

Yes

If yes, describe the nature of any health and safety concerns to the participants and the steps you will take to minimise these.

The main risk to participant health and safety is the present COVID-19 pandemic. To minimise the risk posed by the research party to participants, the UK-based members have 1) been triple vaccinated, 2) passed a pre-flight PCR SARS-COV-2 test, 3) quarantined for 5 days, 4) passed a quarantine exit lateral flow test administered by the Montserrat Ministry of Health. Further to this, I am aware of the Montserrat COVID-related restrictions (mask wearing in public indoor spaces, use of hand sanitiser, attendance limit of 75 people at group events); I am also aware of the potential higher risk COVID poses on a small island such as Montserrat, owing to the relatively limited medical facilities, so I shall maintain additional vigilance with regards to COVID-19 mitigation measures.

As stated previously, there remains the potential for sensitive subjects to be discussed during interviews. There is thus the possibility of participants becoming upset by their discussion (psychological harm/discomfort). To minimise this risk, such topics will not be approached directly. Indeed the purpose of the work is not to gather information about what participants have experienced (e.g. evacuations), but rather their perspectives on the exhibits, which make reference to said sensitive topics.

What procedures have been established for the care and protection of participants?

I have carried out a comprehensive COVID-19 risk assessment, have taken the listed steps above to reduce my potential exposure and transmission of te virus.

I am trained in mental health first aid, and have experience holding these types of interviews, so I am well equipped to provide a confident and immediate response to any potential upset caused by discussions.

Describe your safeguarding protocol. What procedures are in place for the appropriate referral of a participant who discloses an emotional, psychological, health, education or other issue during the course of the research or is identified by the researcher to have such a need?

Any safeguarding concern that arises will be reported immediately to my supervisor, Jenni Barclay and to project partners at the Montserrat Volcano Observatory who have greater knowledge of the island/systems in place for such occurrences.

What is the possible harm to the wider community from their participation or from the project as a whole?

I do not envisage this project leading to harm for the wider community.

What precautions will you take to minimise any possible harm to the wider community?

N/A

Health and safety - researcher(s)

Is there a possibility that the health and safety of any of the researcher(s) and that of any other people (as distinct from any participants) impacted by this project including research assistants/translators may be in question?

Yes

If yes, how have you addressed the health and safety concerns? Describe any safeguards included and relevant protocols.

Again the main risk is COVID-19, however, as stated previously, numerous measures have been taken/are in place to mitigate COVID-19 risk.

There is a small risk of confrontation associated with face to face interviews/focus groups in which sensitive topics arise in the discussion. Again, said sensitive topics will not be approached directly in questioning; any disclosure of sensitive issues will be entirely voluntary on the part of the participant. If confrontation arises, the protocol is to defuse and leave the situation.

Risk assessment

Are there hazards associated with undertaking this project where a formal risk assessment will be required?

Yes

If yes, has a risk assessment been undertaken?

Yes

If yes, upload your Risk Assessment Form.

Research outside the UK

State the countries where research will be undertaken.

Montserrat

Has formal permission/a research permit been sought to conduct this research in the host overseas country?
No

If no, explain why this is not necessary/appropriate.
Such a permit is not required. I am a researcher officially affiliated with the Montserrat Volcano Observatory and have been involved in previous projects here

Upload the approval correspondence where relevant.

Does the research comply with the relevant legal requirements of the host overseas country?
Yes

Provide details.
This research will operate entirely in line with and within the laws of Montserrat

If relevant, have you taken out travel and health insurance for the full period of the research?
Yes

If relevant, have you reviewed the Foreign, Commonwealth and Development Office (FCDO) guidance and applied for a visa?
Yes, no visa required (British Overseas Territory)

Work with external partners and collaborators

Provide details of the external organisation(s)/institution(s) involved with this project.
Montserrat Volcano Observatory are the main project partner. The Mountain Aglow exhibit was left in the care of the MVO in Novemeber 2019 and they have continued to work with it. The project has a number of other partner organisations, such as the Montserrat Disaster Management Coordination Agency (DMCA), the Montserrat Red Cross, the Montserrat National Trust. However, MVO are the only project partners who will be contributing to this work by helping to facilitate events and meetings.

Has agreement to conduct research in, at or through another organisation/institution been obtained?
Yes

Provide details.
I am an affiliated researcher with the Montserrat Volcano Observatory.

Upload the correspondence where relevant.

Does any external Co-applicant need to seek ethics approval in connection with this project?
No

Data management

Will the project involve personal data (including pseudonymised data) not in the public domain?
No

Will you be using secondary personal data not in the public domain?
No

Will any personal data collected be processed by another organisation(s)?
No

Will the project rely on data supplied by others (internal or external sources)?
Yes

If yes, provide details of the data supplied by others (internal or external sources.)
Data for this research will be derived from input from participants during interviews, conversations, focus groups and feedback forms. The volume of this data is uncertain at this point in time, as recruitment is yet to occur.

Will the project involve access to records of sensitive/confidential information?
No

Will the project involve access to confidential business data?
No

Will the project involve secure data that requires permission from the appropriate authorities before use?
No

Will you be using publicly available data from the internet for your study?
Yes

If yes, provide details about the publicly available data from the internet you will be using for your study.
This study may make reference to information available on www.mountainaglow.com, which was another outcome of the first part of the Mountain Aglow project.

Will the research data collected in this study be deposited in a repository to allow it to be made available for scholarly and educational purposes?
Yes

Provide details.
The data will be stored in a NERC repository in line with my conditions of funding by NERC. The results of the findings of this evaluation will be published in a thesis and potentially scientific journal article.

Who will have access to the data during and after the project?

Other members of the research group.

Where/how do you intend to store the data during and after the project?

On UEA's secure cloud, OneDrive.

How will you ensure the secure storage of the data during and after the project?

Sharing of the data will only occur via the secure cloud, and permissions only given to relevant project partners.

How long will research data be stored after the study has ended?

In line with GDPR, as this data is for scientific purposes, retention of data will be kept under review

How long will research data be accessible after the study has ended?

See above answer

How are you intending to destroy the project data when it is no longer required?

All data will be stored electronically, within secure data storage facilities; destruction of data will involve complete erasure of relevant files/folders.

Appendix 3.4: Consent Form

Consent form

Dear participant,

Thank you for offering your time to speak with us today about the Mountain Aglow project.

In case you are unfamiliar with the project and its background, or would like a brief reminder:

Mountain Aglow is a multi-media exhibit relating to the eruption of the Soufriere Hills Volcano, and the experiences of people who lived through it. The aim of the exhibit was for it to be a means of collating and celebrating the artistic expression that came out of the experience of the eruption. Arts are a highly effective means of describing experiences to others who may not have been through them. Traditionally, knowledge and guidance about the volcano has come from the Montserrat Volcano Observatory and government organisations, such as the Disaster Management Coordination Agency. However, in communities near other volcanoes (such as La Soufriere, St Vincent), artistic expressions, in the form of song/calypso, poetry and story, have been found to assist and complement the official/formal advice, and help improve the resilience of communities near the volcano. In Montserrat, the experience of the eruption inspired a wide range of art; Mountain Aglow seeks to bring these artistic expressions together with scientific knowledge. In doing so, it aims to encourage conversation and the sharing of experience within the community, and thereby contribute to strengthening community disaster resilience in Montserrat.

Why we would like to talk to you today:

We would like to speak with you today to explore your perspective of the Mountain Aglow exhibits. You have been selected for interview either because of previous involvement in earlier stages of the project, or you have shown particular interest in the exhibits. The Mountain Aglow exhibit has now been in Montserrat for more than two years, and with the recent arrival of the new Mountain Aglow Junior, we would like to take the opportunity to evaluate the project as a whole. To do this, we are speaking with multiple people/groups of people from across the community to hear their opinions about the exhibits; what they like or find most interesting, what they learn from them, and more widely ask them what sort of benefits they think the exhibits might have for the community. We also wish to evaluate our own work as co-creators and managers of the project at large. Feedback from people like yourself is paramount for initiatives like this; we hope that this evaluation will offer important and constructive insights to partners of this project and other organisations who may carry out similar projects in future.

Your information, how we will use it, and your consent:

The information you provide during this interview will be used solely for our evaluation of the Mountain Aglow project and the publication of our findings. Your details will be processed confidentially and details of this interview will be stored securely in line with the General Data Protection Regulation (GDPR - EU 2016). Access to this information will strictly be granted only to members of the Mountain Aglow team based at the University of East Anglia and the Montserrat Volcano Observatory. Unless you have a specific role in the community. You will not be personally identified in any materials related to this work;

however, we may refer to your job title where it is relevant for our purposes of evaluation (e.g. teacher, government official).

Your right to end proceedings at any time:

Your participation in this interview/focus groups is entirely voluntary. Our intention is for you to be completely comfortable in sharing your perspectives. If at **any time** during our session you feel uncomfortable, you retain an absolute right to cease the proceedings. In the event you do decide you wish to terminate the session, please say so immediately. Once again, this session is solely for understanding your perspectives about the exhibits, we do not seek any information outside of this (e.g. specific experiences you have had). However, we acknowledge and understand that the topics we discuss may relate to upsetting or distressing experiences; we will not directly question you about such things, but if you are comfortable and wish to share an experience or story, it will be treated with utmost respect and confidentiality.

If you have any issues regarding this interview/focus group session, or you would like to retrospectively withdraw your consent from this study, please contact the lead researcher on island, James Christie at j.christie@uea.ac.uk. Alternatively you may contact the lead project partner at the Montserrat Volcano Observatory, Karen Pascal, at pascalk@mvo.ms. Withdrawal of consent will be possible until 30th April 2022.

Your indication of consent:

☐ I consent to taking part in this interview session and thereby grant permission for the information I provide to be used in the evaluation as described above (for evaluative and publication purposes).

☐ I consent to the audio recording of this interview session for the purposes of assisting evaluation.

☐ I understand that my consent may be withdrawn until 30th April 2022, after which point information I provide may be used in publications relating to this evaluation.

Signed: ________________________

Print name: ________________________

Date: ________________________

We greatly appreciate your valuable input to this evaluation.

James Christie (on behalf of the Mountain Aglow team)

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Appendix 3.5: Code Table

Code	Description	File count	Total reference
Experience Conveyance	*Specific reference to the importance of experience sharing. Any mention of experiences being shared as a result of interaction with the exhibits.*	18	57
Positive Perception	*Any reference to a positive perception about the exhibit (e.g., 'I think it's beautiful', 'I think it's a great initiative', etc.)*	18	74
Identified need	*Any reference to a need that this initiative addresses (e.g., younger generation do not have experience of the eruption).*	16	37
Improvement of general awareness	*Any discussion of members of the community having improved awareness of the volcano, hazards, or the disaster history of Montserrat.*	16	56
Youth Education	*Any discussion of how the exhibit specifically benefits the young people of Montserrat, predominantly with regards to education about the volcano, disasters generally, or Montserrat's history.*	16	82
Community benefits	*Any mention of benefits to the community (e.g., the project having brought people together, both individually and with institutions). Quite a broad code with many overlaps.*	14	43
Feelings	*Any reference to emotions or feelings induced by interacting with the exhibit, both for the participant, or observed by the participant in other people.*	14	34

Table 3.2: Codes used for thematic analysis of interview transcripts/other written evidence and the frequency of reference to each theme/count of the number of files (individual interviews) in which each code is referenced.

DRR Reach	*Any discussion of how the exhibit has impacted specifically on the reach of DRR activities (e.g., increasing relevance and accessibility of materials related to DRR to certain population groups).*	11	33
Preparednes_yes	*Any mention of the exhibit enhancing/complementing or directly improving preparedness in Montserrat.*	11	25
Arts Benefit	*Any mention of the benefits of specifically including arts in the exhibits/project.*	9	11
Improved cross-institutional cooperation	*Specific discussion of this initiative improving the working relationship between relevant institutions. Also includes improved trust between inidividuals and said institutions.*	8	28
Limitations	*Discussion of any limitations of the initiative.*	8	15
Personal benefit	*Participant specifically describes how the initiative has benefitted them personally.*	7	11
Co-creation_con	*Any mention of difficulty during the co-creation process (not necessarily cons, but points of conflict or challenges).*	6	27
Further use	*Any reference to ideas of how the exhibit might be used in the future. Any reference to how the exhibit might be enhanced/built upon in the future (e.g., use for hurricanes).*	6	16
Points of improvement	*Reference to ways in which the initiative could be improved (e.g., youtube walk-through videos).*	6	13
Story shared	*Whenever a participant shares their own experience during their interaction with me.*	6	21

Table 3.2 (cont): Codes used for thematic analysis of interview transcripts/other written evidence and the frequency of reference to each theme/count of the number of files (individual interviews) in which each code is referenced.

Cultural continuance	*Covers specific reference of both the exhibit's ability to work as a means of continuing cultural understanding, as well as its part in enhancing general historical knowledge within the community.*	5	12
Co-creation_pros	*Any mention of the benefits of the co-creation process (e.g., individuals feeling heard, improving trust in institutions).*	4	15
Tourism Benefits	*Any reference to benefits the initiative offers the tourism sector.*	4	7
DRR activity	*Any mention of any DRR activity making use of the exhibits or following on from the initiative.*	3	9
Poreparedness-no	*Any instance where a participant does not agree that the initiative improves preparedness.*	3	4
No enhanced collaboration	*Any instance of a participant not feeling that the initiative enhanced cooperation between institutions.*	1	1

Table 3.2 (cont): Codes used for thematic analysis of interview transcripts/other written evidence and the frequency of reference to each theme/count of the number of files (individual interviews) in which each code is referenced.

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