

## Chapter 26

### Consequences of long-term volcanic activity for essential services in Montserrat: challenges, adaptations and resilience

V. SWORD-DANIELS<sup>1\*</sup>, T. M. WILSON<sup>2</sup>, S. SARGEANT<sup>3</sup>, T. ROSSETTO<sup>1</sup>, J. TWIGG<sup>1</sup>,  
D. M. JOHNSTON<sup>4</sup>, S. C. LOUGHLIN<sup>3</sup> & P. D. COLE<sup>5,6</sup>

<sup>1</sup>*Civil Environmental and Geomatic Engineering Department, University College London, Gower Street, London WC1E 6BT, UK*

<sup>2</sup>*Department of Geological Sciences, University of Canterbury, Private Bag 4800, Christchurch, New Zealand*

<sup>3</sup>*British Geological Survey, West Mains Road, Edinburgh EH9 3LE, UK*

<sup>4</sup>*Joint Centre for Disaster Research, GNS/Massey University, PO Box 30 368, Lower Hutt 5010, Wellington, New Zealand*

<sup>5</sup>*Montserrat Volcano Observatory, Flemmings, Montserrat, West Indies*

<sup>6</sup>*Seismic Research Centre, University of the West Indies, St Augustine, Trinidad & Tobago, West Indies*

\*Corresponding author (e-mail: [victoria.sword-daniels.09@ucl.ac.uk](mailto:victoria.sword-daniels.09@ucl.ac.uk))

**Abstract:** Long-term volcanic activity at Soufrière Hills Volcano (SHV), Montserrat (1995–ongoing) has created challenges for society and the resilience of the essential services (infrastructure) that support it. This paper explores the consequences, adaptations and resilience of essential services through interviews with their staff. We find that quick fixes for essential service reinstatement in the north of Montserrat have prevailed. Yet, the legacy of this approach inhibits functionality through inadequate facilities and the perception of sites as temporary, stalling investment. Emigration resulted in staff shortages, retraining requirements and challenges for the viability of specialist services. Low-impact hazards exacerbate shortcomings in essential services, causing power cuts, corrosion, and temporary closures of schools, clinics and the airport. Adaptations developed over time include changes to roofing materials, the addition of back-up systems, collaborative working and the development of contingency plans. Resilience of essential services has improved through decentralization, adaptations, and via strong community networks and tolerance of disruptions. Barriers to increasing resilience include the expense of some adaptations and the current reluctance to invest in essential services, hindering development. We offer some lessons for policy and practice to guide post-crisis redevelopment, through engagement with the community and by complementing community-level adaptations with investment to address long-term needs.



**Gold Open Access:** This article is published under the terms of the CC-BY 3.0 license.

The Soufrière Hills Volcano (SHV), Montserrat began erupting on 18 July 1995, following centuries of quiescence (Sparks & Young 2002; Young *et al.* 2002). The ensuing disaster on Montserrat has become an example of the extensive impact of a long-term volcanic eruption in an exposed, proximal society. Dome collapses, Vulcanian explosions and flank failure significantly affected the southern two-thirds of the island (Kokelaar 2002). An Exclusion Zone was established in 1996, although its geographical coverage shifted throughout 1996–1997 (Aspinall *et al.* 2002). But it was not until 19 people lost their lives in the Exclusion Zone in 1997 (Loughlin *et al.* 2002a) that its enforcement became mandatory. The capital, Plymouth, was progressively destroyed by pyroclastic flows and lahars that first reached the town on 3 August 1997 (Pattullo 2000; Kokelaar 2002).

Almost two-thirds of the original population migrated overseas (Druitt & Kokelaar 2002), and the remaining population moved to the north of the island. However, there was limited housing available in the north to support the evacuated population in the long term (Clay *et al.* 1999). Approximately 60 people remain housed in shelters at the time of writing (Montserrat Community Services pers. comm.). Furthermore, the north of the island was not developed in terms of essential services (infrastructure). These sectors have faced many challenges in meeting the needs of the relocated population whilst operating out of temporary facilities, and with much equipment and investment lost in the evacuated south. The disaster has been protracted by the long-term volcanic eruption, and exacerbated by social, political and economic factors. These include complex institutional relationships within governance, the small size of the island and changing disaster management approaches (Wisner *et al.* 2004; Haynes 2005, 2006).

The last decade has been characterized by a shift in demographics (population emigration and immigration), economic hardship and the physical development of the north of the island (Clay *et al.* 1999). These shifts bring with them new needs, capacities and challenges for essential services. In addition, ongoing low-intensity acid rain and intermittent ashfall hazards have continued to disrupt essential services, exacerbating and highlighting their pre-existing shortcomings. The ongoing and evolving nature of the volcanic eruption has resulted in a state of uncertainty that has hindered recovery and development, but has also resulted in adaptations and increased coping capacities. While the population has adapted, there has been a failure to address changes needed to the initial essential services response, in order to ensure long-term viability.

This study investigates the consequences of long-term volcanic activity for essential services in Montserrat, addressing events throughout the course of the eruption, and the 2009–2010 ashfalls. The relevant essential service sectors on Montserrat include, but are not limited to: utilities, transport, communication systems, education, healthcare, hazard monitoring, emergency services and governance. We present a longitudinal and holistic summary of the challenges faced by essential services over time, analysed within four time periods: before the eruption; the immediate aftermath of the start of the eruption; successive development; and the context in 2010. This summarizes data derived from interviews with experienced staff. We then assess the resilience of essential services to volcanic hazards by exploring aspects of vulnerability, adaptations, coping strategies and capacities, as well as barriers to increasing resilience. Taking a holistic approach, we include the intertwined consequences of societal change for essential services,

and the effects of essential service disruption on society. Primary data for this analysis are presented using summaries and extracts (quotations) of interview data. Finally, we present a summary, and outline the implications of this study for policy and practice.

### Assessing the long-term consequences of volcanic hazards

Early displacements and impacts on Montserratian society (pre-2000) are well documented (Clay *et al.* 1999; Possekel 1999; Pattullo 2000; Skelton 2000), but there has been considerably less attention given to analysing social change or longitudinal effects of the eruption in the decade 2000–2010. Existing studies of the societal effects have focused on public health, risk perception, and the communication between scientists, authorities and the public (Baxter *et al.* 1999; Aspinall *et al.* 2002; Haynes 2005; Horwell & Baxter 2006; Haynes *et al.* 2008; Skinner 2008; Donovan 2010). Others have focused on national-level disaster management perspectives (Kokelaar 2002) and disaster risk reduction (DRR) implementation in policy (Mitchell 2006). None of these have included impacts on essential services, or the effects of essential service disruptions on society. This is seen to be a major gap in the literature, as here, as in other volcanic areas, disruption of essential services has been observed to lead to significant societal and economic impacts (Johnston 1997; Johnston *et al.* 2000; T. Wilson *et al.* 2012). For example, an investigation at four communities in the aftermath of the eruption of Mount St Helens in 1980 found that even small amounts of volcanic ashfall resulted in large impacts on society due to the significant disruption caused to businesses, the transportation network and community services (Warrick *et al.* 1981). This highlights that the interplay between essential services and the population is a critical element of how a society copes or deals with disaster.

Our understanding of the impacts of volcanic hazards on essential services is growing, with recent studies investigating water and wastewater systems (Stewart *et al.* 2006, 2009), electrical power (Wardman *et al.* 2012), transportation (Durand *et al.* 2001), telecommunications (Wilson *et al.* 2009), heating, ventilation and air-conditioning systems (Johnston *et al.* 2000), and computers (Gordon *et al.* 2005; G. Wilson *et al.* 2012). Some consideration has also been given to essential service network interdependence (cascading effects) in the assessment of volcanic impacts (T. Wilson *et al.* 2012). The effects of ashfalls (Spence *et al.* 1996; Pomonis *et al.* 1999; Blong 2003) and pyroclastic flows on buildings (Spence *et al.* 2004; Baxter *et al.* 2005), as well as effects on the aviation sector (Casadevall 1993; Casadevall *et al.* 1996; Guffanti *et al.* 2009; Drexler *et al.* 2011), have also been studied. Observations of the cumulative and interdependent impacts of volcanic ashfalls on essential services have highlighted the need to take a holistic approach to essential service risk management (T. Wilson *et al.* 2012). Yet, there have been few studies on the cascading effects of volcanic hazard disruption, and little research on the effects of ongoing volcanic hazards for essential services and society.

Societal effects due to volcanic eruptions have been investigated in the medium to long term by a variety of authors (Perry & Lindell 1990; Tobin & Whiteford 2002; Lane *et al.* 2003; Wisner *et al.* 2004; Wilson *et al.* 2011). These studies highlight how underlying vulnerabilities significantly influence how a population is affected by, and is able to recover from, a disaster. In particular, studies from Tungurahua Volcano, Ecuador (Tobin & Whiteford 2002), and Hudson Volcano, Chile (Wilson *et al.* 2011), highlight that long-term recovery during ongoing impacts from volcanic hazards is significantly influenced by social and economic conditions before the eruption, and key risk reduction decisions in the aftermath of the eruption.

Reducing pre-existing vulnerabilities, building capacities and increasing DRR measures are steps towards increasing resilience

(Twigg 2009). In long-term volcanic hazard environments there is a challenge to manage and reduce volcanic risk, whilst livelihoods and access to services are maintained. Kelman & Mather (2008) highlighted that risk reduction approaches need to be localized to establish and maintain community-based initiatives for living with risk. An integrated approach employing multiple strategies for reducing risks has been outlined in the Hyogo Framework for Action (UNISDR 2005). The UNISDR (2004) define DRR as ‘The conceptual framework of elements considered with the possibilities to minimize vulnerabilities and disaster risks throughout a society, to avoid (prevention) or to limit (mitigation and preparedness) the adverse impacts of hazards, within the broad context of sustainable development’ (p. 17).

In the early stages of an eruption, a crisis-style approach involving evacuation and temporary solutions for shelter and essential service provision prevails. However, in extended eruptions, evacuations can become permanent, transforming the situation into one of post-disaster resettlement. This is further complicated by ongoing hazards that may continue to affect essential service restoration and long-term recovery. Essential services need to be reinstated in order to create sustainable development opportunities in resettled communities (Usamah & Haynes 2012), and proactive and long-term risk reduction solutions need to be developed. Mercer *et al.* (2010) found that livelihoods and community needs and priorities should also be identified and accounted for in a participatory way, with communities engaged in the risk management and risk reduction process. During the post-disaster recovery process, services therefore need to be re-established whilst integrating the demands and expectations of the population of their essential services, and increasing the resilience of essential services and communities amid ongoing hazards.

Managing and reducing volcanic risk on small islands is especially complicated, as entire island populations may be evacuated and relocated, as in the cases of Niufo’ou in 1946, Tristan da Cunha, in 1961–1962 (Blong 1984) and Heimaey, Iceland in 1973 (Williams & Moore 1976). Small island states are also recognized to have unique vulnerabilities to disasters. Although social, cultural, political, economic and environmental contexts vary widely between different island states, some commonalities exist relating to challenges for sustainable development (Mercer *et al.* 2007). Briguglio (1995) found that small island economies are often vulnerable as they are exposed to foreign economic circumstances, as well as to natural hazards. They are also inhibited by their small geographical size, their remoteness and their insularity. Pelling & Uitto (2001) also identified vulnerabilities stemming from demographic factors, limited physical and social infrastructure, colonial history, weaknesses in governance, reliance on primary exports, and limited disaster mitigation capability, amongst other factors. This is not to say that there aren’t also significant benefits afforded to those living in small island developing states (SIDS), and global pressures also bring many positives. These include direct foreign investment, urbanization and institutional cooperation on the global scale (Pelling & Uitto 2001). However, the vulnerability of such SIDS generates a complex array of consequences when they are exposed to natural hazards.

Understanding and incorporating local context, as well as dynamic interactions between society and essential services, is vital for any long-term risk reduction solutions to be appropriate and effective. For successful risk management, Wisner *et al.* (2004) critiqued a sole focus on structural mitigation options, citing that they are often expensive, implemented in a top-down way (and so do not incorporate local methods of living with risk) and do not address the root causes of vulnerability. An example of an overly engineering-focused and politicized approach to risk management and resettlement amid ongoing lahars has resulted in the Philippines, following the eruption of Mount Pinatubo in 1991 (Leone & Gaillard 1999). Dykes were built to protect the population, but suffered deficiencies and have subsequently been

breached by lahars. Haste and a lack of planning also led to downstream-spreading basins occupying viable agricultural land, and therefore reducing income sources. The population were relocated into resettlement centres that had a shortage of basic public services (schools, hospitals, markets). A lack of involvement of the population in the reconstruction process resulted in undermining local capacities to self-organize, and created a culture of dependence on government and international aid (Leone & Gaillard 1999).

When summarizing available literature, it is clear that contemporary studies advocate for volcanic risk to be approached in a broader, more dynamic framework that integrates social science approaches with scientific hazard assessments to address risk reduction (e.g. Barclay *et al.* 2008). To this end, further holistic and empirical studies that identify vulnerabilities, risks and successful risk reduction measures for specific contexts are needed. In the context of Montserrat, exploring how long-term and ongoing volcanic hazards affect essential services and what implications this has for society is a critical gap in our understanding, particularly as this knowledge helps to identify risks and strategies for long-term risk reduction. This will also take steps towards informing the long-term management of such systems exposed to volcanic risk. In this paper, we discuss physical and social influences on essential services throughout the duration of the Soufrière Hills eruption, examining the changes that have occurred over time to essential service locations and design, the composition of society and the type of hazards faced. Such a holistic approach aims to better understand the challenges that essential services face, their vulnerabilities, the incorporation of adaptations to reduce risk and the development of resilience in essential services.

### Eruption chronology and risk management

A chronology of significant events during the long-term eruption of the SHV that have had impacts on essential services and society is summarized in Table 26.1. The table includes events salient to this topic and is not a full chronology of the events to date. Since the onset of the eruption, lava-dome growth has continued through five cycles of pause and extrusion (Wadge *et al.* 2014), with pyroclastic flows generated mainly by dome collapse and fountain-column collapse from Vulcanian eruptions (Calder *et al.* 2002; Cole *et al.* 2002). However, since the relocation, the majority of the population has moved sufficiently far north, away from any potential high-impact hazards such as pyroclastic flows. Ashfalls and acid rain are the main volcanic hazards that affect the north of the island. Consequently, these low-impact, intermittent and geographically widespread hazards are what the majority of the population is now exposed to. Both high- and low-impact hazards have influenced the context of essential services on Montserrat today.

The management of volcanic risk has been primarily characterized by restricting access within proximal zones, the boundaries of which have changed over the years (Aspinall *et al.* 2002). A Hazard Level system has been in use since 1 August 2008 (replacing a previous Alert Level system) (MVO 2012) in order to manage and communicate risk for each zone, which varies depending on the level of volcanic activity (Fig. 26.1). Evacuations in proximal areas of some of these zones have occurred intermittently over the last decade (e.g. 2002–2003, 2007 and 2009–2010) as the hazard level and risk fluctuates. For example, Salem and surrounding villages became part of the Exclusion Zone from September 1997 to October 1998 when activity was at its peak and the risk management map was revised (Buffonge 1998; Kokelaar 2002). Essential services located in Salem today include the island's only secondary school, and a primary healthcare clinic. In addition, after the losses in Plymouth, Salem had developed into an ad hoc business district. The essential services and businesses in the area

were affected by uncertainty in their long-term viability and many were left contemplating relocation (Buffonge 1998). With the relocation to the north, and then further temporary evacuations prompted by changes in volcanic activity, the remaining population on Montserrat has learned to live with the uncertainty of the situation, which continues to hinder recovery and economic growth.

### Field work and data collection

An exploratory, qualitative semi-structured interview approach was undertaken to identify the consequences of volcanic activity for essential services on Montserrat. Long interviews (McCracken 1988) lasting approximately 1 h were conducted between 27 February and 12 March 2010 with a purposive sample of essential service managers and staff. Fourteen interviews were conducted (four interviews involved two participants) with 11 essential service sectors. These are listed in Table 26.2 and the locations are shown in Figure 26.2. Data gathered from interviews are subjective and dependent on the world view of the participant (Kay 2008), which is framed by their knowledge, interests and how they make meaning out of events or experiences. However, a universal truth is not sought in this approach, and the use of interviews allows rich, detailed information to be gathered about the participants' viewpoint, to gain an understanding of essential services within their context. The semi-structured technique also allows flexibility to explore relevant issues that emerge during the discussion (Sarantakos 2005). This approach was considered to be an appropriate way to collect often detailed technical information, and to gain in-depth insights relating to the participants' work and life, from a longitudinal perspective.

Engaging with a broad range of essential services enabled a wide range of impacts and perceptions to be explored. Essential service managers and operators are experts in their sectors, and those included in the study were long-serving; 13 of the 18 participants had been living in Montserrat prior to the onset of activity at SHV in 1995. Essential service sectors are small on Montserrat, and discussions with one or two expert participants in each sector can be considered to be representative.

Question topics included:

- a comparison of essential services and life on Montserrat before and after the volcanic crisis began (only asked of participants who lived in Montserrat prior to the onset of the eruption);
- the main changes observed to essential services over time;
- the consequences of past volcanic activity for essential services;
- the effects of ashfalls on essential services;
- the consequences of these effects for the participant at work and home;
- any strategies that are used to reduce or prevent impacts;
- the challenges for essential services today;
- the wants and needs of essential services for the future.

Other issues surfaced as participants commented on some broader social issues and these are discussed throughout this paper. These wider societal issues are derived from this purposive sample of interviewees, and are, therefore, not considered to be representative of society as a whole. However, the participants form valuable members of society, and have lived and worked in Montserrat for many years. Their comments on wider society are, therefore, important insights, albeit with limitations in their representativeness.

The interviews were digitally recorded, transcribed and analysed using Atlas Ti v5.5 software. We use thematic analysis (Gibson & Brown 2009) where data are interpreted qualitatively through a process of systematic classification, in order to identify core ideas (themes). These are derived from research interests

**Table 26.1.** A brief chronology of the main events of the eruption that have impacted essential services and society. This includes events relevant to the topic and is not a full chronology of the eruption to date

Date	Event	Impact
17 September 1989	Hurricane Hugo	90% of island property was damaged (Kokelaar 2002; Young 2004)
18 July 1995	Onset of Soufrière Hills eruption	Phreatic eruptions, stems jets and cold pyroclastic surges (Sparks & Young 2002)
3 April 1996	Final evacuation of Plymouth	British government offered a voluntary relocation package, but on the island the move was hoped to be temporary (Clay <i>et al.</i> 1999). Shelters were set up for evacuees, but only very basic health, shelter and social assistance was provided (Clay <i>et al.</i> 1999)
25 June 1997	Sustained partial collapse of the lava dome	Flows and surges travelled down Mosquito Ghaut and Paradise River valleys, and surges detached and travelled north (Loughlin <i>et al.</i> 2002b). Nineteen Montserratians were killed. This is known locally as 'Black Wednesday' (Brown 2010)
4 July 1997	Mandatory Exclusion Zone area defined	Abandonment of a microzonation approach to risk management and simplification of the risk maps (Kokelaar 2002)
August 1997	Pyroclastic flows reach Plymouth	Pyroclastic flows destroyed much of the town. The permanence of the relocation became apparent and infrastructure investment accelerated (Clay <i>et al.</i> 1999). Shelters reached a peak population of 1598 (Kokelaar 2002). Evacuation of Salem, Friths and Old Towne ordered on 15 August 1997 (Clay <i>et al.</i> 1999)
September 1997– October 1998	Exclusion Zone revised	Salem and Old Towne become part of the Exclusion Zone (Kokelaar 2002).
1998	Population decline	By early 1998, the island's population had reduced to 3000 (about 70%) (Kokelaar 2002).
8 October 2002–August 2003	Evacuation	Lower Belham valley and Isles Bay (including Old Towne) (Sparks & Hawkesworth 2004)
12–13 July 2003	Largest dome collapse to date and island-wide ashfall	Volume of 210 Mm <sup>3</sup> of material with a maximum ashfall thickness of 154 mm in Old Towne (Herd <i>et al.</i> 2005; Edmonds <i>et al.</i> 2006). The British Government approved an extra \$20 000 000 EC (approximately £5 million) budget supplement to enable the clean up of ash deposits after the dome collapse (GoM 2004)
20 May 2006	Second largest dome collapse to date	Volume of 115 Mm <sup>3</sup> of material (Trofimovs <i>et al.</i> 2012), with a maximum ashfall thickness of 30 mm in Friths (Loughlin <i>et al.</i> 2011)
15 February–21 July 2007	Evacuation	Evacuation of lower Belham Valley (including Old Towne) (CDERA 2007)
July 2008	Evacuation	Brief evacuation of lower Belham Valley (Carib Daily, 2008). Associated with an explosion on 29 July
1 August 2008	New Hazard Level system	The Hazard Level system replaced the previous Alert Level System (MVO 2012)
January 2009	Full evacuation	70 people were evacuated from the lower Belham Valley (Antigua Sun 2009)
December 2009–23 February 2010	Night-time evacuation	Partial evacuation of the Lower Belham Valley, Isles Bay and part of Old Towne
11 February 2010	Partial dome collapse	Volume of approximately 40–50 Mm <sup>3</sup> (Scientific Advisory Committee 2010). This ended the fifth phase of dome growth (MVO 2012)

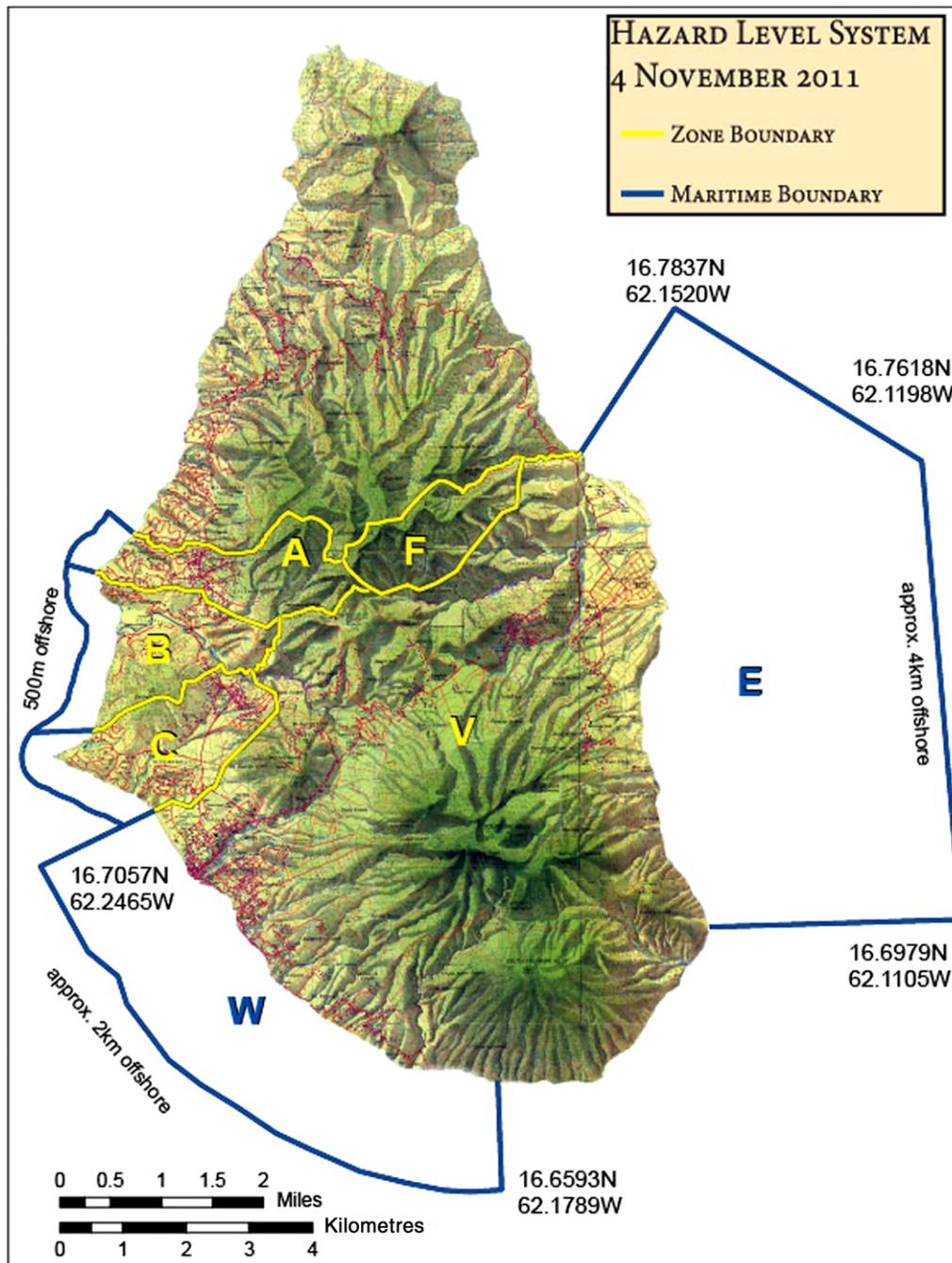
(*a priori*) and from examination of the data (*empirical*) (Gibson & Brown 2009). Patterns in the data and the relationships between the themes are sought, in order to interpret and make meaning of the data (Berg 2007). Similar or related themes were then grouped into overarching categories that form the core concepts in the study. The analytical process is subjective, and depends on how the researcher interprets and makes meaning of the data. However, the approach to analysis is systematic, and, through the analysis, the researcher also reflects on the context in which data were gathered and the ways in which meanings were formed, in order to interrogate and verify their interpretation. Data were triangulated by using several interviews to validate information across the dataset. Supporting insights were also sought from field observations and anecdotes provided from other meetings and conversations during the fieldwork. Finally, document analysis of secondary data was used to validate and support information gained through interviews (where literature and documents are available).

We have first analysed how essential services have been able to function throughout the course of the eruption during defined periods of time, using information summarized from interview data. Where secondary documents have been used for supporting insights, these are referenced. We then carry out a focused analysis of the resilience of essential services, where both summaries and extracts (quotations) of the data are used to present and discuss the main results of this work.

In the months immediately before fieldwork was undertaken for this study (February and 12 March 2010), the SHV was in a heightened state of activity in its fifth phase of lava extrusion. The Washington Volcanic Ash Advisory Center (VAAC) issued numerous ash advisories between 5 October 2009 and 9 March 2010 related to activity at the SHV (NOAA 2010). Explosions and pyroclastic flows associated with renewed dome growth generated volcanic ash, which coupled with variable wind directions, led to intermittent ashfalls in the inhabited NW part of the island. Between November 2009 and February 2010, thin but frequent ashfalls made ash an annoyance for many weeks (Scientific Advisory Committee 2010). Following the 11 February 2010 partial dome collapse, occasional ashfall, gases and acid rain continued to affect the wider population until March 2010. At this time, the island was also experiencing a drought, and ash was remobilized across the island causing increased disruption to the population.

### Consequences of volcanic activity for essential services

The consequences of volcanic activity for essential services are discussed here throughout time, as the eruption progressed and essential services evolved within this context. Approximate time periods have been delineated for this discussion as follows: the context before the eruption began (pre-1995); the immediate



**Fig. 26.1.** Current Hazard Level system, updated 4 November 2011 (MVO 2012). As the Hazard Level changes, access restrictions change, reflected by a change in zone colour: green zones have unrestricted access; yellow are daytime access; orange has controlled access; and red is only accessible to essential workers.

aftermath of the start of the eruption (1995–1999); successive development (from 2000 onwards); and the context in 2010. Time periods are delineated based on distinct phases of recovery during the ongoing eruption. From 1995, the onset of the eruption prompted several staged evacuations, eventual relocation, and, afterwards, successive moves of essential services and the population. The first phase of establishing final locations for essential services, and quick refurbishment to make sites suitable for use, was being completed by 1999. This creates a natural time period for discussion. After this, little information regarding essential services or societal adjustment is available in the literature. The period from 2000 to 2010 is largely undocumented from this perspective, with the exception of some Government of Montserrat (GoM) budget statements that document progress in the development of infrastructure (GoM 2002, 2004, 2005) and Montserrat's Sustainable Development Plans (GoM 2003, 2010). Further detail was not available until the time of fieldwork in 2010. As such, this time period is long and the analysis necessarily descriptive, reflecting overall changes during this period. The purpose of

this discussion is to understand the ways in which the development of essential services was affected by ongoing volcanic activity, and the legacy of this development for their functionality today. Much of this information is derived from interview data and is presented as summaries in these sections, supported by document analysis and literature where available.

#### *Context before the eruption began*

In order to understand the significance of the effects of the volcanic activity on essential services and wider society, it is important to understand the island context before the eruption began. Montserrat is a UK Overseas Territory (formerly a British Overseas Dependent Territory) with a British Governor appointed by the Queen and the locally elected Government (GoM) headed by the Premier. The British Government currently supports Montserrat's economy through the Department for International Development (DFID), providing around 60% of the recurrent budget

**Table 26.2.** *Essential service sectors included in the interview sample and the number of participants for each*

Participating essential service sector	Number of participants
Hospital	2
Clinics (Salem, St Peters, Cudjoe Head, St Johns)	1
Power station, Montserrat Utilities Limited (MUL)	2
Water and wastewater, Montserrat Utilities Limited (MUL)	1
Montserrat Volcano Observatory (MVO)	2
ZJB Radio	1
Schools (St Augustine, Salem Secondary)	3
Disaster Management Coordination Agency (DMCA)	1
Public Works Department (PWD)	1
Fire, Search and Rescue Department (Fire Department)	1
Governor's Office	2
Ministry of Agriculture	1

(Ministry of Finance). Participants discussed Montserrat before the eruption in terms of aspects of the lifestyle, such as having comfortable living standards, recreational places to visit, and good standards of education and healthcare. These assets are also described in earlier literature (Clay *et al.* 1999; Possekel 1999; Skelton 2000). The island marketed itself as 'the emerald isle' and 'the way the Caribbean used to be', attracting a high-end tourism market and some residential expatriates. The population was mainly Montserratan, and interviewees made many references to Plymouth, indicating a strong attachment to place and pride in Montserrat.

Essential services were centred around Plymouth (approximately 4 km from the volcano). The airport was to the NE of the volcano, and the flanks of the volcano supported much agriculture. Facilities included an airport, the port and jetty at Plymouth, a bulk fuel terminal and a power station. Plymouth housed many schools, government buildings, the hospital, warehouses, banking sector, library, shops and commerce. There was no duplication of essential services owing to the small size of the island (Clay *et al.* 1999; Young 2004). The locations of essential services in 1995, as well as their current locations (in 2010) are shown in Table 26.3.

Previous disasters had been triggered by hurricanes, with particularly damaging events recorded in 1924, 1928 (Tomblin 1981) and 1989. Other hazards included volcano-seismic crises, which had occurred in the 1890s, 1930s, 1960s, 1989 and 1992–1995, but there had been no volcanic eruption since the island was colonized in 1632 (Kokelaar 2002). Past disasters were discussed in economic terms, causing the economy to stall temporarily, but from which Montserrat was able to recover. For example, the local economy had been impaired after Hurricane Hugo in 1989, where 90% of island property was damaged (Young 2004). The island received £16.8 million in aid from the UK to redevelop its essential services (Kokelaar 2002), following which Montserrat's economy recovered and the country was in budgetary surplus by 1995 (Skelton 2000). Some participants recalled this growing economy in the period before the eruption started, and an expectancy of a positive future for Montserrat's development:

Montserrat was growing, growing very well, in terms of education, in terms of economy. And at the same time we actually had just built a whole new hospital. (fireman)

#### *Immediate aftermath of the start of the eruption*

Phreatic explosions marked the onset of the eruption on 18 July 1995, which was then followed by lava-dome extrusion that began on 15 November 1995 (Cole *et al.* 2002). Several months later, the third and final evacuation of Plymouth on 3 April

1996 (Table 26.1) led to the relocation of 7000 people and the abandonment of most of the islands' essential services (Clay *et al.* 1999). This had significant consequences for essential services on Montserrat, which are discussed in the following sections.

*Effects of the relocation for essential services.* The necessary haste of the relocation resulted in ad hoc development in the north of the island as no new town centre was decided upon. Funds for essential service development were made available by the UK government in 1997 (Clay *et al.* 1999), but the majority of essential service networks had to be built from scratch, in a largely undeveloped landscape characterized by steep terrain with few viable sites for such installations.

Major rebuilding projects had to be started urgently. New housing developments had to be created to house the relocated population, requiring new road networks to be established around them. The Island's potable water supply is from springs, many of which were in the Exclusion Zone. There are springs in the north and a plentiful water supply on the island. However, water networks had to be built to supply water to new settlements, and to pipe water from productive springs in the south to the generally drier north of the island.

Other major installations included a power network, which had to be created to supply power to the north of the island. This urgent need was met by reconfiguring and splitting the original distribution feeder to the north. The power station in Plymouth was operated using diesel engines, the fuel for which was shipped to the island and stored at the bulk fuel terminal. The power station was still in operation, in combination with two generating sets in Salem until 1997. However, the bulk fuel terminal, power station and port were finally abandoned in Plymouth in June 1997 (Kokelaar 2002). When Salem was evacuated on 15 August 1997, the Montserrat Utilities Limited (MUL) power department relocated to a new site in Brades. The relocated power station became dependent on newly constructed emergency facilities at Carrs Bay, and on an emergency jetty at Little Bay to receive fuel shipments. The construction of these facilities in 1997 meant that there were no fuel shortages for power generation during the eruption. The port began to operate out of the new emergency jetty at Little Bay (although at a reduced capacity) from June 1997. A new government headquarters also had to be constructed in the north to house the offices of government, which was located in Brades.

Locations had to be found to house a variety of essential services and, at the time of the relocation, any suitable existing building was occupied by essential service head offices. Most head offices moved several times, and the locations found were in response to rapid, unplanned commercial developments, rather than the result of considered land-use planning. In addition to the shortages in suitable buildings, there was also a shortage of locations for storing relocated essential service goods and equipment. Storage solutions had to be found to house resources for a many essential services (Clay *et al.* 1999).

The Glendon Hospital in Plymouth, with a new extension constructed in the aftermath of Hurricane Hugo, was destroyed during the 1997 volcanic activity (Pattullo 2000). The hospital had a capacity of 67 beds, it was also air conditioned and was purpose-built (housed in one building). With the exception of the mental health unit, the clinics and the pharmacy that were in use at this time, the hospital had never been fully occupied. Some of the new equipment was salvaged and brought to the current site at St John's, which was originally a school building but was converted to house the hospital from September 1996 (Buffonge 1998). Owing to a lack of space on the new site, initially the operating theatre was set up in one of the clinics, 1 mile from the hospital. This involved the transfer of patients between the two sites in order to perform surgical procedures. The number of primary healthcare clinics also decreased from 12 to four with the

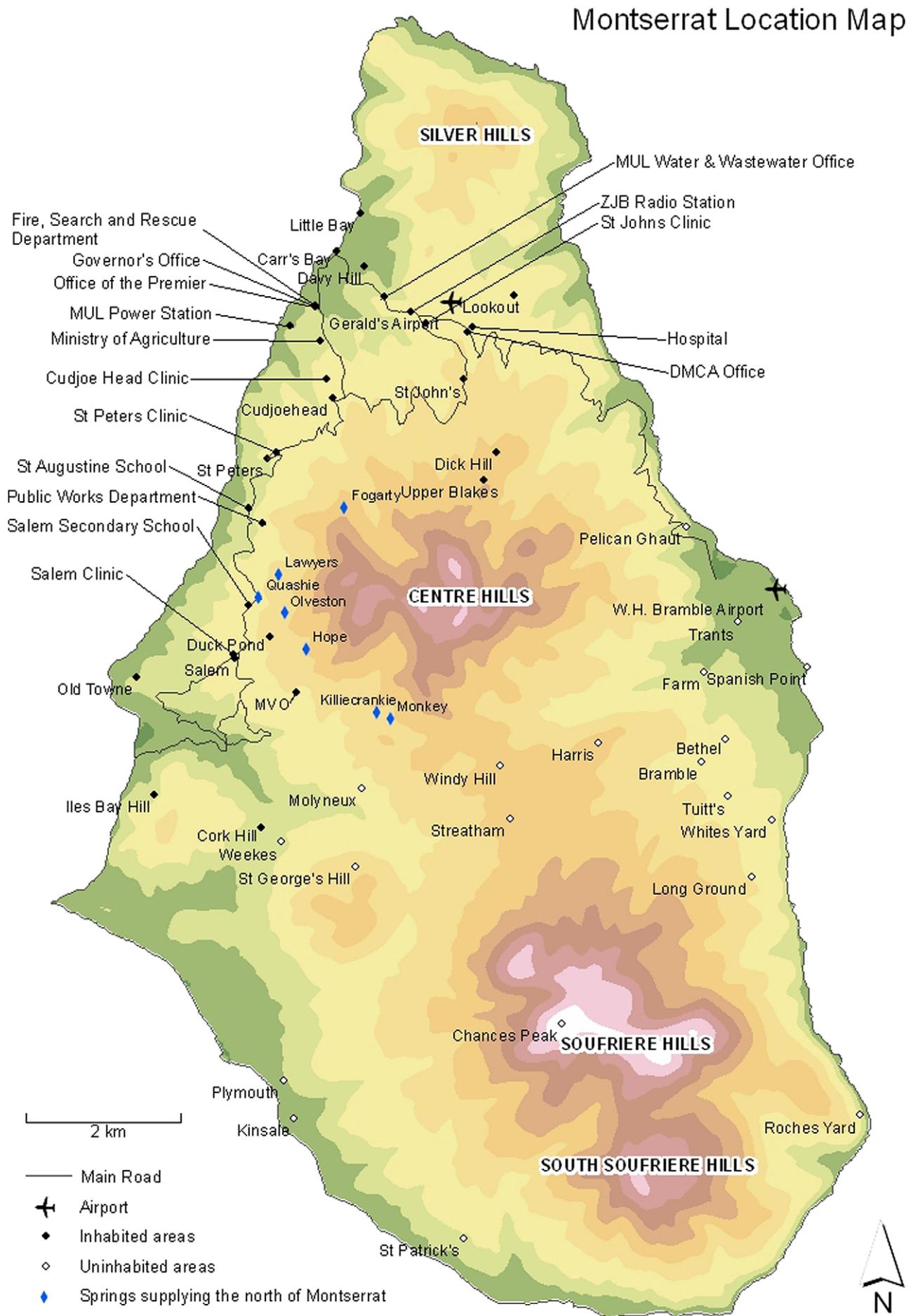


Fig. 26.2. Map of Montserrat with village locations marked. The locations of essential service sectors included in the interview sample are also shown.

**Table 26.3.** *Locations of essential service sectors in 1995 and their locations in 2010*

Essential service sector	Location in 1995	Location in 2010
Hospital (Old Glendon and New Glendon)	Plymouth	St Johns
Clinics	Harris, Molyneaux, Kinsale, Cork Hill, Long Ground, Bethel, St Patricks, Plymouth, Salem, St Peters, Cudjoe Head, St Johns (Wason 1994)	Salem, St Peters, Cudjoe Head, St Johns
Power Station, Montserrat Utilities Limited (MUL)	Plymouth	Brades
Water and wastewater, Montserrat Utilities Limited (MUL)	Plymouth	Sweeneys
Montserrat Volcano Observatory (MVO)	Plymouth (Aspinall <i>et al.</i> 2002)	Flemmings
ZJB Radio	Plymouth	Sweeneys
Schools (St Augustine, Salem Secondary)	Plymouth	Woodlands, Salem
Disaster Management Coordination Agency (DMCA)	Plymouth	St Johns
Public Works Department (PWD)	Plymouth	Woodlands
Fire, Search and Rescue Department (Fire Department)	Plymouth	Brades
Governor's Office	Plymouth	Brades
Ministry of Agriculture	Plymouth	Brades
Agricultural areas	The South and the Central Corridor (from Weekes to Farm)	Upper Blakes and Dick Hill, Duck Pond (GoM 2011)
Montserrat Technical College	Plymouth	n/a (Community College at Salem)
Police Headquarters	Plymouth	Brades
Prison and courts	Plymouth	Brades
Bulk fuel stores	Plymouth	Carrs Bay (GoM 2011)
Airport	Trants	Gerald's
Port	Plymouth	Little Bay
Market	Plymouth	Little Bay
Banks (Royal Bank of Canada, Barclays Bank)	Plymouth	Bank of Canada at Brades (Barclays Bank n/a)

Unless otherwise indicated, information on essential service locations in 1995 is derived from the Montserrat Tourist Board (1983) Tourist Map of Montserrat: emerald isle of the Caribbean. Unmapped locations were sought from participants during interviews.

implementation of the mandatory Exclusion Zone and abandonment of villages in the south.

Disruptions continued to affect schools and the fire department, as locations had to be changed or could not be found. Schools were closed temporarily from the first evacuation of Plymouth in August 1995 until the end of September 1995, and subsequent evacuations required school buildings further north to be used as shelters. Classes had to be taught in tents and makeshift locations from April 1996. Some new facilities were built in 1997, but these then became used as shelters for evacuees from Old Towne and Salem in August 1997 (Buffonge 1998). The number of schools also decreased from three secondary school campuses (one senior secondary and one junior secondary school located in Plymouth, and a junior secondary in Salem), to one secondary school (located in Salem). The fire department was left without a building and relocated to a tent in Gerald's. They remained in Gerald's until a new fire station was built in 2002 at the site of the new government headquarters in Brades.

*Effects of emigration for essential services.* A significant feature of the social impacts of the ongoing eruption was the large-scale population emigration during the late 1990s. The 1991 census recorded a population of 10 639 (GoM 1991). Following the evacuation of Salem in August 1997, DFID announced an 'assisted passage scheme' to the UK, under which 2733 people left Montserrat (Pattullo 2000). A 'voluntary regional relocation package' for the Caribbean region was also announced at this time (Clay *et al.* 1999; Pattullo 2000). By early 1998, 70% of the population had left the island, leaving an on-island population of around 3000 (Kokelaar 2002). Since this time the population has risen, and the 2001 census recorded a population of 4491 (GoM 2001). Gender ratios in the period 1871–1991 suggested that in the past the migration of males exceeded that of females. However, the 2001 census also reported for the first time that males (2418) outnumbered females on the island (2073) (Possekkel 1999).

This suggests that more females than males emigrated during this period.

The interviewees suggested that there are many reasons why people left the island, although a lack of available shelter and education-interruption are given as predominant reasons. The population decrease had a knock-on effect to essential services as overall demand for services decreased, reducing the number of staff required at their facilities. Overall, the emigration of the population outweighed the reduced staffing needs, leaving a shortage of skilled staff in essential services. The reduced demand from a smaller population challenged the viability of some of the more specialist services on the island, particularly within the health sector. Resident specializations were lost because their costs could not be justified for the small population base.

People of all ages emigrated, but the emigration also caused a change in demographics. The percentage of the population between 0 and 29 years old disproportionately decreased between 1991 and 2001. This shows that the majority of emigrants were children and young adults (who were mainly female) (CCDP 2009). The percentage of the population aged over 60 remained stable between 1991 and 2001, at around 17% (CCDP 2009). However, emigration caused a change in social structure as extended families broke down. This led to an increased need for care homes for the elderly. A new elderly care home had to be built (funded by the Red Cross) to cope with this new challenge.

The number of working age people in Montserrat decreased, and the 'brain drain' left fewer skills on the island, reducing the capacity to boost the future economy. Those who stayed were often relatively junior and required training to be able to work in a more senior role. To compensate for the shortages in skilled occupations, there were incentives to attract other nationalities to Montserrat, and to fill the job vacancies created by the out-migration. These included a strong Eastern Caribbean (EC) dollar, and higher salaries than elsewhere in the region. The ageing demographic has been offset by immigration and the

working age population rose by around 7% between 2001 and 2006 (GoM 2011). The recent census of 2011 records a current population of 4922, with a slightly higher male (2546) than female (2376) population (GoM 2012a). The number of immigrants (mainly from the Caribbean region), grew from 18% in 2001 (GoM 2001) to 33% of the population (1634) by 2011 (GoM 2011).

### Successive development

As the population stabilized in the north, essential services were progressively developed to support the relocated communities throughout the last decade (2000–2010). Interviewees discussed few specific changes during this time and little literature is available for this period. A summary of projects implemented during this time period is not currently available on the DFID website. However, some infrastructure projects that were implemented on island are included in Budget Statements and other government documents for Montserrat, and are shown in Table 26.4. The decade has been characterized by adjustment and re-establishment of communities and essential services in the north, and some upgrading of facilities when funding could be obtained.

During this period, housing developments continued to be built, water and power networks were extended to these areas of new development, and the maintenance of roads continued. Some essential service facilities were refurbished, such as the Disaster Management Coordination Agency (DMCA) building, which was retrofitted in 2000. Some new facilities were also built. For example, the Montserrat Volcano Observatory (MVO) building was purpose-built in 2001–2002, and occupied in 2003, having undergone several relocations during the first years of the crisis (Aspinall *et al.* 2002).

On 12–13 July 2003, the largest dome collapse to date occurred, and generated an island-wide ashfall (Herd *et al.* 2005; Edmonds *et al.* 2006) (Table 26.1). The DMCA described how the inhabited areas from Salem and south to Isles Bay were heavily affected by ashfalls. This was declared a disaster area and DFID funded a 6 month clean-up operation to allow reoccupation. The clean-up process evolved over time during this period of successive development. Formerly relying on work crews to physically shovel ash,

the DMCA purchased a road sweeper to assist in the clean up of the roads. This increased the speed of cleaning and allowed the work crews to focus on clearing roadside drains of ash.

Following the 2003 dome-collapse event, water spring fluxes started to drop, despite rainfall on the island. During one of the interviews, an MUL employee described that the flux at Killiecrankie spring (that provides up to 60% of the total spring flux) dropped from around 300 000 to around 30 000 gallons/day over a 2 week period. Water rationing was implemented to manage the water supply. Later in the year, the island had very heavy rainfall and, after this, the spring yield recovered. MUL speculated during interview that the ash-coverage could have been a possible (although unproven) cause of the spring flux change, which may have prevented percolation into the spring recharge areas and promoted run-off. There have been no further decreases in spring yields since 2004.

The DFID funded a water pipeline rehabilitation project, which replaced many of the old water pipelines and installed reservoirs at Lawyers and Baker Hill in the north of the island. The works were completed in 2004 (GoM 2005). At the power station a fourth generating set had been installed in 2001 (GoM 2002), but failed in 2003 (GoM 2004). Two further generating sets were installed at the power station in 2004, but the 2005 Budget Statement refers to the continuing plans to build a modern power station (intended to be funded, in part, by the Caribbean Development Bank) (GoM 2005). The Montserrat Port Authority also refurbished equipment and had constructed a new warehouse in Little Bay in 2004 (GoM 2005). Finally, after having abandoned the old Bramble Airport and using temporary ferry and helicopter services to access the island since 1997, a new airport was built at Gerald's Bottom in the north of the island and completed in 2005.

The Montserrat Sustainable Development Plan was adopted in 1997 to guide redevelopment in the north of the island over the period 1998–2002. This has continued to be revised to fast-track development, with new plans developed for the periods 2003–2007 and 2008–2020 (GoM 2010). However, despite the sustainable plans, long-term viability has not always been considered in the development of facilities on the island. For example, a new hospital was not built, and, instead, the former school building that the hospital had occupied during the relocation was

**Table 26.4.** Implementation and completion dates of some of the infrastructure projects that were undertaken between 2000 and 2010

Projects implemented	Implementation period	Completion	Source
Emergency jetty at Little Bay	1997	1997	Clay <i>et al.</i> (1999)
Temporary Government Headquarters at Brades	1997	1999	Clay <i>et al.</i> (1999)
Improved nursery, primary and secondary education facilities	1998–2002	1998–2002	GoM (2003)
Re-establishment of hospital and clinics	1998–2002	1998–2002 (hospital completed by 1999)	GoM (2003), Clay <i>et al.</i> (1999)
Ferry and helicopter services implemented	1997	1997	GoM (2003), Clay <i>et al.</i> (1999)
Road construction programme in the north	1998–2002	1998–2002	GoM (2003)
Brades Police Headquarters	2001	2002	GoM (2002), GoM (2003)
Brades Fire Station	2001	2002	GoM (2002), GoM (2003)
Expansion of St Johns Health Centre	2001	2003	GoM (2002), GoM (2004)
MVO building	2001	2003*	GoM (2002), *interview
Hospital operating theatre (St Johns)	2002	2003	GoM (2002), GoM (2004)
Office of the Chief Minister, Development Unit and Ministry of Finance	–	2003	GoM (2004)
Renovation of St Peters Health Centre	2002	2004	GoM (2002), GoM (2005)
Montserrat Community College	2002	2004	GoM (2002), GoM (2005)
Hospital mortuary (St Johns)	2003	2004	GoM (2004), GoM (2005)
Montserrat Port Authority Landside Development	2002	2004	GoM (2002), GoM (2004)
Prison	2003	2004–2005*	GoM (2004), *interview
John A. Osborne Airport	2002	2005	GoM (2002), GoM (2010)
Cultural centre	–	2006	GoM (2010)

These include only the projects that are listed in available Government of Montserrat (GoM) documents, and literature. This is not, therefore, a complete summary of infrastructure projects undertaken on Montserrat during this period.

progressively redeveloped. This was achieved through refurbishment, and the addition of new buildings on the site. This decision was shaped by disagreements between the UK Government and the Government of Montserrat (GoM) about the level of facilities to be provided at either a new or an upgraded hospital, and DFID supported only the upgrading of the St John's Hospital site (Clay *et al.* 1999). Over the years, the health sector also faced increased costs of health services and of social services, which fall under the budget for health (GoM 2012c). Health services were also lost, such as the island-wide pharmaceutical service, where a pharmacist would accompany the doctor on clinic visits in order to fill prescriptions on site. This eventually could not be sustained owing to the reduced population and the reduced number of pharmaceutical staff at the hospital. Access to pharmaceutical supplies was further affected by a reduction in the number of pharmacies on the island, from four (three private and one public) to two (the government pharmacy at the hospital in St John's, and a private pharmacy in Brades).

### *Context in 2010*

After many years of volcanic activity (1995–2010), the context of essential services in Montserrat in 2010 is framed by the past effects of the eruption, and the continued low-impact hazards (e.g. volcanic ashfalls, acid rain and gases) that affect the inhabited northern areas. To date, there has been no replacement for Plymouth, although plans exist for developing Little Bay into the new town centre.

Cargo access to the island is restricted as the port continues to operate out of the old emergency jetty at Little Bay (see Fig. 26.2). Ongoing issues surround its susceptibility to large NW swells, which prevents ships from being able to dock, particularly between October and April. Weekly imported vegetables arrive from Dominica by ship, but become harder to obtain when seas are rough. The port also remains a critical access point to the island for passengers, particularly as the new airport at Gerald's Bottom has a limited carrier size owing to the length of the runway.

The power station operates using five temporary emergency generating sets that provide the island's power supply. Funding has finally been approved for a new power station (Caribbean News Now 2011), for which MUL have been negotiating a loan since 2003. The potential for using geothermal power is also being explored, and DFID has agreed to fund phase 1 of a geothermal exploration well-drilling programme, which started in 2013 (GoM 2012b). The power is distributed around the island using three radial feeders, which were built overground due to speed and cost at the time of the relocation. Some extensions of this system have been created to supply new housing developments, early phases of which were overground and later phases underground. As a result of overground construction, the existing overground lines are susceptible to wind storms and Montserrat's location in the Caribbean places them at high risk. As a result of this status, the insurance is too expensive for MUL to purchase and, consequently, the lines are uninsured. Underground piping for all utilities is now being installed. The water springs on the island are well protected from ashfalls and other contaminants by a system of concrete 'eyes' built into the source of the spring, which were developed prior to the onset of the eruption in order to prevent contamination and exploitation by trees. The water is connected by pipes to collection boxes and then to the mains, although the pipes are metal and are corroding due to age. Quashie, Fogarty, Killiecrankie, Monkey, Hope, Olveston and Lawyers springs supply the north of the island with water.

The St John's Hospital now has a capacity of 30 beds; however, the buildings form separate blocks on the compound, and staff and patients have to move inside and outside as they travel between buildings. Staff discussed the St John's site as being less than

ideal for a hospital facility in terms of layout, space and facilities. For example, there is no paediatric ward on the site, and paediatric cases are treated on the female ward, with the other inpatients. These issues arise mainly because the facility was not designed for long-term use; although there are now plans to build a new 38 bed hospital, which will occupy the same site and be built around some existing structures (The Montserrat Reporter 2011). The funding for this was approved in November 2012 (GoM 2012b).

Several new areas of settlement evolved in the north of the island over time, but issues surrounding the legacy of the relocation prevail. Montserratians' strong connection to place extends down to village level; for example, before the eruption began, schools and clinics were distributed at village level and people discussed communities at this scale. The relocations created new settlements that, even a decade later, were seen locally as not being 'true' communities. This is a significant social shift from pre-eruption Montserrat. In addition to changes in island settlement, there has also been a change in ethnicity. Immigration incentives in the region and emigration of the population, has meant that now only two-thirds of the current population are originally Montserratian (GoM 2011). The rest comprises other Caribbean nationalities (including, amongst others, those from Jamaica, Guyana, Dominica and St Vincent), as well as expatriates (from Europe and North America), and around 500 Hispanic residents (mainly from the Dominican Republic). Many of the interviewees said that those who remained were given more opportunities for training and progression at work as a result of the loss of colleagues overseas, and felt that in this way they had personally benefited from the emigration. Despite this, interviewees discussed some feelings that the new population demographic does not have the same skills levels as before the eruption.

### **Assessing the resilience of essential services to volcanic hazards**

In the following subsections, we carry out a focused analysis of the resilience of essential services to volcanic hazards. Resilience is a multi-faceted concept that has been defined by many authors, the characteristics of which have been explored in detail by Twigg (2009). We define resilience in a similar way to the broad definition used by Twigg (2009), considering the resilience of essential services to volcanic hazards to encompass the capacity to cope with shocks and to recover from them, and to adapt and improve system performance with time. Resilience is intrinsically linked to, and undermined by, pre-existing vulnerabilities. In this study, we therefore consider aspects of vulnerability, capacities, coping strategies and adaptation, as well as barriers to increasing resilience in our analysis. Primary data are presented as both extracts and summaries in these sections.

#### *Vulnerability of essential services to volcanic hazards*

Vulnerability is considered to be socially constructed, developing progressively across society to create the pre-existing conditions that influence people's capacity to cope, resist and recover from natural hazards (Wisner *et al.* 2004). We consider the vulnerability of essential services to volcanic hazards to comprise pre-existing characteristics that influence their sensitivity to volcanic hazards, and their capacity to cope and recover from them. Vulnerabilities are physical, social and organizational and affect the consequences for essential services when exposed to volcanic hazards.

*Vulnerability to volcanic ashfalls.* With relocation to the north of the island, the volcanic hazards to which the island's essential services are subjected have changed since the onset of the eruption.

The inhabited north of the island is intermittently affected by ash-falls and acid rain (and, occasionally, gases in the Belham Valley area), and these hazards exacerbate the pre-existing essential service shortcomings. Each essential service is vulnerable to different consequences of ashfall, both direct and indirect, which inhibit functionality. This creates a complex picture of challenges for risk reduction that are often specific to each essential service.

Aircraft flights are affected by ashfalls, locally and throughout the Caribbean. The dome collapse on 11 February 2010 affected airports and airlines, causing closures and cancellations. LIAT (Leeward Islands Air Transport) did not fly due to ash in the atmosphere (Dominica News Online 2010), and flights to Dominica, Guadeloupe, Antigua, Barbuda, St Kitts and Nevis, and St Maarten were disrupted on 11–13 February (AFP News Agency 2010). Ash falling on the island is blown from trees and areas surrounding the road networks, causing continued redistribution onto roads and drains until rainfall washes the ash away. During interviews, the Public Works Department (PWD) described that ash blocks the drains by the roads, which can change the drainage pattern and allow new gullies to form at the sides of the roads when it rains. The gullies allow soil and debris to be washed onto the roads, causing obstructions. In the long term, bridges and the road network can become eroded, and in the Exclusion Zone this has led to bridges and sections of road being washed away.

At the power station, generator intake filters become blocked as a result of ash, causing the generators to shut down. It takes about 2 or 3 days during periods of ashfall for intake filters to become blocked. As a result of using high-speed emergency generating sets to produce the base load, there are inherent problems in power-supply reliability. MUL observed that there have been times when they have had load-sharing because of a lack of available plant to meet the demand (lasting 1–2 weeks, around once a year). Power cuts are experienced periodically on the island. Some of these are a result of the inadequate power infrastructure, and some are scheduled power outages for general maintenance on the distribution network (works are not done live owing to lack of equipment and training). Others are caused by a combination of volcanic ash and rain on the insulators, resulting in electrical flashover (unintended electrical discharge). Cascading effects are observed to emanate from the power cuts. For example, at the power station, generator alternators have broken in the past as a result of the trips to the power supply. Overall, the use of high-speed emergency generating sets and overhead power lines makes the power system vulnerable to ashfall impacts from filter blockages and flashover. The reliability of the island's power supply suffers from this poor infrastructure design, created in necessary haste during the volcanic crisis, but which has remained the solution to date. Such vulnerabilities of the system design demonstrate that the current power infrastructure is not fit for purpose. The planned new power station will alleviate such system vulnerabilities. Power cuts also affect other sectors. For example, power outages compromise the refrigeration of medical supplies at the clinics. These include vaccines, which can lose their potency if not kept within specified temperature ranges.

At the MVO, computing servers can overheat within 30 min without air conditioning. In 2007 (4 years after installation at the new MVO building), air conditioning units shut down from blockages due to ash, and, as a result, expensive computer equipment overheated and failed. Ash also covers the solar panels at the MVO field monitoring stations (mainly continuous GPS and seismometer stations) and can prevent them from generating power. This can result in the temporary loss of some monitoring stations. For example, in late December 2009, the MVO had only three seismometers working out of 10, as a result of ash-covered solar panels. In addition, Electronic Distance Measurement (EDM) mirrors can become covered by ash, preventing EDM measurements from being made. The MVO discussed that

these disruptions can affect their ability to monitor the volcano effectively.

There is an increase in water usage following an ashfall event, as people use water to clean homes, facilities and businesses. Demand increases from around 350 000 to about 500 000 gallons/day (c. 40% increase). However, the total spring yield is around 850 000 gallons/day and so the island has ample water supply during these times. Septic tanks and soakaways form the main wastewater system, but there is an extended aeration system in some areas (e.g. Davy Hill) for treating wastewater, and the settling ponds are open to the atmosphere. Turbidity in the ponds increases from ash contamination, which can prevent bacterial break-down of waste material. However, from around December 2009 to March 2010 (during the period of intermittent ashfalls), MUL reported that, through normal processes, they reduced the turbidity to <2 NTU (Nephelometric Turbidity Units).

Physical vulnerabilities in many essential service networks exacerbate ashfall impacts and inhibit their functionality. A common example is that most essential service buildings (and homes) on Montserrat have tropical slatted windows. This design allows ash to enter buildings because they cannot be properly sealed, and corrosion compounds this issue on aluminium slats. A few interviewees identified that hung windows provide improved sealing and better prevent ash ingress. Despite this knowledge, this change is not yet apparent on a large scale in Montserrat.

Some other common issues for many sectors included: cleaning and maintenance, corrosion, costs of replacement and repair, power failures, and water shortages. Typical residential construction is reinforced concrete moment-resisting frame structures with (unreinforced) concrete block masonry. These have either concrete roofs, or wooden truss roofs, covered with galvanized sheeting or shingles. The mixed construction type is a Montserrat design standard, locally deemed appropriate for hurricane design. However, galvanized sheeting is susceptible to corrosion from both the sea air, and volcanic ash and gases. Corrosion of roofs affects essential service offices as well as homes, as many offices occupy buildings that were previously residential. Additional aspects of corrosion in the home also included showers, fridges, fans, microwaves, cutlery and TVs. The cost of replacing household items was also raised in interviews.

Other occasional references were made to temporary airport and business closures, and the economy suffering as a result of ongoing volcanic activity. This is mainly because the residential tourists returned home early during the ashfalls from October 2009 to March 2010. Service sectors such as hotels also become affected by the ash, when clients move out or cancel reservations due to the amount of ash in the area. This is unappealing for visitors and can also cause some discomfort, and service sectors have lost business as a result. These impacts express some of the widespread effects and economic aspects of living with ashfalls.

Families and friends became globally dispersed following the large-scale population emigration. This loss of family support and the lack of extended family networks, continues to affect both work and home life for those who stayed on the island. Traditionally, childcare support was provided by such extended social groups, so the breakdown of social networks on the island has reduced the capacity of working parents (including essential service staff) to juggle both families and work. The loss of support networks reduced the capacity of essential service staff to respond during volcanic events. Such personal circumstances were seen to shape decision-making for some essential service sectors during heightened activity, often in response to risk or threat (and not necessarily realized impacts). For example, schools closed temporarily in January 2010 (the Salem secondary school closed for 3 days, St Augustine for 1 day). This was due to the risk of children's health in an ashy school environment, a heightened awareness of which has been raised by previous public health studies on Montserrat (Baxter *et al.* 1999). Clinics

are also affected by personal priorities, such as the safety of family members, and the need to collect children and have them close-by during volcanic events. This prompted temporary closure of a clinic in January 2010. Other personal circumstances also shape decision-making during volcanic events. One clinic closed temporarily because the nurse did not own a car. This meant that the nurse would not be able to leave the area quickly in the event of a volcanic emergency, and it was considered too high risk for them to remain in the area. In these examples, individual social factors outside of the workplace influence the operation of essential services during heightened volcanic activity.

*Cumulative impacts of essential service disruption.* Interviewees listed a range of issues that affected them personally. Many discussed the effect that ash has on their outlook on life, and there were many comments in interviews and through anecdote about ash causing people to 'feel down', tired or depressed. This is attributed to the constant need for cleaning, the knowledge that ash is falling and the sense of confinement inside the house or when wearing an ash mask. Temporary power outages caused by ash-induced flashover affects air conditioning and lights in the home, exacerbating issues of discomfort. One interviewee describes the situation:

It's not the power cut, it's when it comes back on. The major problem are the surges when they switch it back on, and people lose their television sets, electronics, and their refrigerators, and somebody was telling me... 24 new fridges bought this year because their old fridges were damaged when the surge comes back on, so that is a real problem. And you get fed up of having no power, especially if you rely on fans for cooling and it's a hot afternoon and it's a dusty afternoon, you got all your windows closed for the ash. (Governor's Office)

Despite this complex array of consequences, it was found that no single impact was prioritized by the interviewees. Following an open discussion of the effects of ashfalls, participants were prompted to select which of the discussed effects had the greatest impact on them. They indicated that, in some way, the series of smaller effects contributed to the overall challenge of living and working in Montserrat. One interviewee encapsulated this viewpoint when asked which essential service disruption affected them the most:

I would say all. Because they are a small area, small community and we depend on each of them... it occurs in a continuum, so it has a ripple effect, so if something goes wrong here, it affects other agencies, other departments, so it really just affects everybody... it would no longer be business as usual, because it would slow down any kind of activity on the island... it cuts across the whole sphere of development. (DMCA)

*Overarching vulnerabilities of essential services.* Overarching vulnerabilities include power and water networks. Overhead power lines are vulnerable to both electrical flashover on insulators due to ash contamination, and wind damage during hurricanes, for which they are not insured. In addition, MUL discussed the continued volcanic threat to wells and fresh water springs on the border of the Exclusion Zone. Water wells in the Belham Valley were drilled to augment water supply during low spring fluxes in 2003. The wells are now under threat from pyroclastic flows and lahars, which continue to fill up the Belham Valley. As a direct response to their vulnerability, MUL are looking at relocating the well controls to higher ground to enable their continued operation should they become covered by deposits. A geophysical survey was also carried out in order to identify locations to drill for groundwater if it becomes necessary.

Other vulnerabilities related to reliance on funding sources for implementing plans or making changes, a general shortage of skilled professionals on island and having ageing essential service staff (MUL). The PWD also discussed a lack of funding for necessary maintenance operations. These local and institutional vulnerabilities allow continual disruption from known impacts to essential services, and reduce essential service resilience.

### *Capacity assessment of essential services*

*Adaptations to essential services.* The consequences of the long-term eruption of the SHV, and the vulnerability of essential services to volcanic hazards, have led to the development of adaptations across essential services and society. These comprise permanent physical, social or organizational changes, which improve essential service functionality within the environment or reduce risk. In addition, coping strategies have been identified, which comprise temporary changes or reactive responses that act to reduce volcanic impacts.

Overall, there have been significant losses and lessons learned as a result of the abandonment of Plymouth and the ongoing eruption. One important outcome from the loss of Plymouth was the move towards the decentralization of essential services:

So I think that we've learned not to put all our eggs in one basket... we've got supermarkets up there now, and supermarkets over here, rather than all being within 100 yards of each other (Governor's Office)

This process began unintentionally, mainly because there was no new town centre, but it is an important outcome for essential service sectors into the future. Decentralization reduces the exposure of essential services as a whole, and therefore reduces risk.

There are some common physical adaptations across essential service sectors that have been developed in response to the low-impact hazards that intermittently affect the north of the island. Essential services have made physical changes to their buildings, such as the installation of Plexiglas and air conditioning to reduce ash ingress (e.g. at clinics, hospital, ZJB Radio). Because most essential service buildings are not purpose-built, these solutions are installed when possible alongside other retrofitting or refurbishments. For example, at the hospital, these were installed during gradual renovations of the St John's site over the last decade. Installation of Plexiglas without accompanying air conditioning cannot be undertaken in Montserrat's climate. This is because Plexiglas prevents windows from being opened, which allows fresh air to cool the building naturally. Other adaptations observed include the change in roofing style away from galvanized sheeting, which has been found to corrode more rapidly since the onset of persistent ashfall and gas. Shingled or concrete roofing styles are now more commonly used. These changes are made when galvanized roofs need to be replaced, and are also seen in new-builds. However, there was also some degree of uncertainty in choosing a roofing style that is appropriate for the regional hazards, discussed in the context of Haiti Earthquake on 12 January 2010, the Maule Earthquake and Tsunami, Chile on the 27 February 2010:

[L]ooking at Haiti... I know the structures are weak, yes. And then looking at Chile... and you're wondering what next? Where is next?... concrete roof might be better for somebody with the ash... but not for earthquake. (teacher)

More specific adaptations were found to be particular to essential service sectors. These include back-up measures and system design changes. Some of the back-up measures have been adopted in response to negative experiences in the past. For example, the MVO now has back-up air-conditioning systems, and also stand their air-conditioning units on breeze blocks to allow ashfall to pass through them and so prevent blockages. These adaptations were made after the critical system failure in 2007. Design changes include the installation of protection switches at the power station to prevent damage to alternators, and to clear any faults from ash-induced flashover. MUL observed that the alternators now break less often as a result of this measure.

Some adaptations are incidental and were developed in response to other pressures or needs (Stern *et al.* 2006). These adaptations were not created specifically to alleviate volcanic impacts, but do act to increase resilience in the volcanic context. For example, electricity feeders have been set up for separate districts, but can

also be used to isolate faults on the power distribution network, and confine power outages to the affected sector. Another example is the development of a government back-up intranet system, which is housed at the DMCA as a result of its superior construction for hurricanes.

Other adaptations include permanent behaviour changes, which were observed at the clinics in response to ashfalls. They have developed a response to power cuts in the absence of a working generator, in order to protect vaccines and other refrigerated drugs. Ice packs are placed inside medical stores to keep supplies cool, and fridges are kept closed to reduce the temperature change during power outages. This response protects supplies during any power cut, whether volcanically induced or otherwise. Routines have also been developed at the clinics for the protection of equipment from ash:

[B]ecause it costs so much to replace or repair . . . the first thing we do in an ashfall is to secure our equipments. We have little sheets, we have plastic bags . . . that can be pulled over filing cabinets, pulled over computers . . . we actually advise everyone at the end of every day, because we're not sure what we're going to find when we come back in the morning, we cover up, everyday. (nurse)

Covering healthcare equipment to protect it became a lesson learned from Hurricane Hugo in 1989, where water damage was the main cause of equipment loss. Consequently, protection strategies were adopted quickly at the clinics after the onset of volcanic activity, in order to reduce volcanic effects. Other routine responses to ashfalls have included the fire department assisting vulnerable sectors with ash clean-up, including the hospital, clinics, schools and elderly care homes. They focus on areas of most need, and have been acting in this capacity since volcanic ash first started falling in Plymouth. Clean up of ash is also carried out by the PWD, who are responsible for maintaining the island's roads and drains. They have found that using open drains rather than pipes helps to prevent ash blockages and reduce the knock-on effects of flow-regime changes. The PWD highlighted that costs of maintenance of road networks are high, and that clean-up costs associated with ashfalls increase exponentially with ash depth.

In addition to such routines, some contingency plans have been developed for emergency response and temporary relocations. For example, plans are in place for relocating the nurse at one clinic:

[W]e have to put plans in place that if that nurse has to move, where would I relocate [the nurse] to so that the service continues? And so we've actually delegated one of the room upstairs Cudjoe Head Clinic, for that nurse, in the event that [the nurse] has to move further round (nurse)

Other examples included developing advisory messages for the community. These include notices on ZJB Radio to ask people to reduce their use of water during ashfall clean-up activities, in order to prevent water shortages. Advisories through the radio are also given for those driving during ashfalls, which prevents congestion or accidents on the roads:

I find that over the years we've developed a sort of a way of dealing with it, so you find once there's ash, somebody calls the radio station and say '... there's some ash in Salem'. The person on the radio start advising drivers to . . . take your time. . . if you're heading into this area there's ash' . . . and you'll find people themselves . . . informing other drivers. (the MVO)

Despite these adaptations to the environment, some problems with the developed contingency plans have been discovered through trial and error. In early 2010, one of the schools had to temporarily relocate further away from the volcano owing to the amount of ashfall at their site and the on-island fear of health effects for children. During this relocation, problems with the contingency plans emerged and were discussed by a parent during an interview:

They tried to have class in . . . an open hall. They weren't able to create a division, so class activities in one, affected the other classes. (MUL)

Contingencies are still evolving and lessons continue to be learned from experience, as and when they are found wanting.

General coping strategies that are adopted include cleaning following ashfalls, which was carried out across all essential services. Swift cleaning is said to reduce the corrosive effects of the ash on metals (such as aluminium windows and galvanized roofs), and ease ash removal. It also minimizes the contamination of the workplace by ash, which is particularly important for the hospital, clinics and schools. The on-island fear of long-term health effects for children is often discussed, and has made ash clearance from schools a local priority. People also close windows and doors during ashy periods, and some sectors stockpile ash masks (e.g. DMCA and clinics). These responses reduce the immediate effects of the ash and minimize its persistence in the environment.

In addition, acceptance of the ongoing hazards and impacts was also found to be a common coping mechanism. This acceptance acts to reduce stress in the population when volcanic activity increases. One interviewee describes the situation, referring to the volcano:

[I]t is the bigger player in the game. We cope with it, but we can't control it. We . . . just accept that it causes the problem, and then soon as its willing to . . . allow us to work, then we can work and deal with it as best we can (the PWD)

*Capacities to reduce the effects of volcanic disruption.* As well as the many adaptations and coping strategies that have been discussed, there are also resources within society, both physical and social, that form capacities. These act to reduce the impacts of essential service disruptions on life. Some facilities have physical capacities including back-up systems such as generators for essential services (including DMCA, MVO, Hospital, ZJB Radio), which prevent cascading impacts from power outages. Other capacities include community-wide services such as a good bus system (for travelling around the now dispersed settlement areas, and for school evacuations), and the development of shared responsibilities between agencies for the maintenance of certain sites and stations. Collaboration and community assistance are observed in the prioritization of vulnerable essential services in times of need (schools, elderly care homes, clinics); for example, during ashfall clean-up operations. Societal capacities also include strong community networks, which relieve to some extent the pressure on working parents, who balance work and life commitments. This was evident when discussing school closures and how children were looked after during these times,

[I]n most cases, we'll have a big brother or sister that can stay home with them. We still have a good community . . . and it's really safe . . . the smaller ones will go to the regular babysitters, and friends look out for friends. (ZJB Radio)

Strong community networks reduce the need for staff to leave work in response to school closures, and in this way directly contribute to the continuity of other essential services. In discussing essential service functionality, tolerance for disruptions to life was seen to be high in general amongst participants. A manager discussed the population's tolerance to disruptions of the electricity sector:

[T]here's also a lot of understanding generally from the public in terms of the challenges we are facing. They pretty much know we are operating a temporary facility here, and secondly . . . those who have lived here long enough are quite aware that the ash affects the supply . . . They don't really blame us too much with that, they're understanding . . . Just part of the challenge of living on this island. (MUL)

Tolerance of disruptions is a social capacity that serves to ease pressure on essential service sectors that are under-resourced and coping with inadequate infrastructure. A tolerant population will reduce the demands and expectations of the population of their essential services, and therefore reduce stress for both essential service sectors and the population.

#### *Barriers to increasing resilience*

Adaptations and capacities have increased the resilience of essential services in Montserrat, but there remain overarching barriers to improving the resilience of essential services. During

conversations about the context of essential services in 2010, it emerged that in many cases their sites are still being viewed as temporary. This perception has stalled the redevelopment of some facilities, as there is a reluctance to invest in a site when the location may not be permanent:

[W]e're in temporary buildings; the main office up there is temporary. But we're looking at putting down a permanent structure, but most likely it will be in this general vicinity. (Ministry of Agriculture)

[T]he long-term plan was to move the school anyway, because ... if we keep viewing this site as temporary, they're reluctant to spend any money on it. (teacher)

The perception of essential service sites as temporary appears to be a legacy of the relocation, generating an unwillingness to consider anything to be permanent until its permanence is explicitly made clear. This has stalled investment in the permanent development of the sites and, despite inadequacies, Montserratians have had to 'make do' with the facilities they have.

In addition to the uncertainty in the permanence of essential service sites, there is also uncertainty in the long-term viability of some populated locations on Montserrat. These concern the future development in Little Bay and, in particular, the future of Salem, which was evacuated from 15 August 1997 to 1 October 1998 (Clay *et al.* 1999) (Table 26.1). The evacuation appears to have had a long-term effect on the perception of Salem as a viable and stable area for occupation. Salem remains in Zone A (Fig. 26.1) and, as such, may still be vulnerable to any future heightened volcanic activity. The uncertainty surrounding its future viability has created a reluctance to consider the clinic in Salem to be a fully operational site, and has resulted in the development of contingency arrangements for its possible relocation:

So we actually dedicated one room for storage for Salem Clinic. And so some of the stuff is still there now, until we're exactly sure exactly what's happening in that area. (nurse)

For some essential services, without investment to improve systems and create adequate facilities there is a limit to their resilience, despite the efforts of the staff to implement adaptations. The expense of some known adaptations is also an important consideration that is shaping decision-making, and the development of further resilience. Costs and benefits must be weighed in order to decide to what extent adaptation is necessary. This represents a barrier to resilience, exemplified during a discussion of costs and the feasibility of adaptive options that are being considered:

[M]uch of the old concrete structures on island have been basically rotted away by ashfall ... You then start saying ... we should be building in very high grade concrete, which would be sulphur resistant ... and suddenly you're talking about building in very very expensive materials, which is not really on the agenda, because you're into spending money that is disproportionate to the cost of recovery on the island. (the PWD)

*Future prospects for Montserrat.* Overarching barriers to further development on Montserrat were discussed in interviews, including: the low population number, low skills levels in the population (for starting new businesses), the economy in grant aid and financial dependence on the UK, the difficulty in attracting investment while the volcano is active, and the perception of Montserrat within the region as somewhere undesirable to live. The uncertainty of the changing pattern of hazards as valleys fill up with deposits was also touched upon in conversation:

I think it's changed a little bit, and I want to build, and you feel a little bit different because it's [the hazard] not gone as predicted (teacher)

Uncertainty in the hazard evolution will remain to some extent whilst the volcano is active, and may continue to affect investment on Montserrat, which in turn is interlinked with the low population number and the struggling economy. However, plans and ideas for the future development of the island were also discussed by participants. These related to expanding facilities on the island such as building a new hospital and new schools. Other suggestions were

to look to the region for good development ideas, such as Anguilla, where design standards are high but the aesthetic of buildings is also good. The importance of place and the social priority of good standards of living were discussed earlier, but also emerge here in looking to develop resilient structures and maintain the aesthetic value of buildings. Rebuilding, and rebuilding well, has emerged as a local priority.

In terms of outlook for the future, the Governor's Office during interviews placed much emphasis on the development of Little Bay town centre as a catalyst for investment. Discussion also related to many areas of opportunity for the future including: developing production lines for various businesses to enable them to develop in the region, attracting cruise ships and moving to 'open skies', which would allow an opportunity for more flight paths (and a move away from the sole dependence on Antigua for getting to Montserrat). These aspects all point towards diversification of the economy, which is a positive step towards resilience in Montserrat's future.

## Summary and implications for policy and practice

### *Legacies of an ongoing eruption on a small island*

The consequences of the long-duration volcanic eruption for Montserrat have highlighted many issues that relate to extended disasters on small islands. A fragile economy, space restrictions and a small population characterized some of the vulnerabilities on Montserrat, which were exacerbated by complex relationships within governance (Haynes 2006). In Montserrat, the ongoing volcanic activity resulted in the establishment of an Exclusion Zone, which included the main town, Plymouth. This necessitated the permanent relocation of the exposed population to a limited geographical area in the north of the island. This area was rural and not developed in terms of infrastructure or sufficient housing to relocate the population. The north was generally drier, with steep terrain and most of the land was, and still is, privately owned. Only 1176 acres of 9980 acres is Crown land (GoM 2011). The limited land area owned by the Government, coupled with the lack of focal point for development – in particular a new capital – resulted in an ad hoc relocation of essential services. This heterogeneous relocation ultimately became permanent.

Relocation schemes were made available to the population by the UK Government, and a multitude of issues including lack of shelter and education-interruption ultimately resulted in significant emigration, mainly to the UK and within the Caribbean region (Clay *et al.* 1999). Women, children and skilled workers were the main emigrant groups. This left behind a small population and fewer skilled workers (Possekel 1999). The break down of extended family groups on the island left a large elderly population that needed new institutional care, and also reduced social capacities for balancing work and childcare. Some essential service employees who remained on the island were promoted, initially with little support for their training. They took up the challenge to manage and restore essential services in order to meet the basic needs of the population. Subsequent training and promotion of essential service staff is seen as a positive outcome from the otherwise largely negative impacts of emigration.

The reinstatement of basic infrastructure in the north of the island, including water, power and road networks, a port, airport, housing, schools and a hospital, amongst many other essential services was a significant challenge. This urgent need was met through quick fixes for infrastructure reinstatement in the north, which was supported by the provision of emergency funding and regular budgetary aid from the DFID because of Montserrat's UK Overseas Territory status. However, such necessary quick fixes during a crisis have resulted in long-term issues. Chronic

volcanic hazards (including ash and acid rain) create long-term challenges for essential services, such as ongoing cleaning, replacement and repair. Maintenance costs increase in order to ward off corrosion and preserve the longevity of resources. These maintenance costs need to be balanced against the costs of long-term mitigation solutions. The vulnerabilities created by temporary fixes can result in disruptions to services, particularly through exposure to ash. These in-built vulnerabilities require readdressing in order to ensure that essential services remain viable for long-term occupation of the north.

*Positive outcomes for the future.* There are positive outcomes from the legacy of the eruption for Montserrat. Now that essential services are decentralized in the north, exposure to volcanic hazards and, therefore risk, has been reduced. If a strategic choice were made to move to a decentralized model for essential services, this would implicitly involve proactive planning for site selection and would reinforce risk reduction.

The future plans for upgrading essential service facilities on the island, and for looking to the region for good ideas for development, if acted upon, would also be positive steps towards developing a good standard of essential services on the island. These investments in 'purpose-built' facilities would reduce vulnerabilities stemming from physical design (e.g. the power station and hospital) and, therefore, reduce risk.

In Montserrat, the new capital is long-awaited by the population and could act as a catalyst for development on the island. A future development of a new centre has the potential to ease the 'temporary' mindset of much of the island's development to date, and stimulate the economy. However, any future development of a new town centre should involve careful planning and a fully participatory process that accounts for the wants and needs of the community.

### Summary

The main findings of this study are focused on three key themes: quick fixes, resilience-building and essential service–society continuum.

*Quick fixes.* There has been a huge loss of essential service assets on Montserrat, and the urgency of relocation meant that siting of essential service facilities was often opportunistic, rather than carefully planned. Urgency also led to 'quick fixes' for essential service reinstatement. Such reactive policies in post-disaster reconstruction have been seen in other areas to increase the long-term vulnerability of populations by failing to address the root causes of vulnerability (Ingram *et al.* 2006). This tension between necessary short-term response and long-term development after disasters has been recognized elsewhere (Ingram *et al.* 2006; Sterner *et al.* 2006). In Montserrat, essential service facilities have been improved over time, although the perception of many sites as 'temporary' has led to difficulty in attracting funding to invest in their full development. For example, Salem secondary school and MUL Power have both suffered from lack of investment due to the temporary nature of their sites. MUL Power had been applying for funding since 2003, only gaining approval for a new power station in 2011. Lacking the necessary investment, many facilities remain unfit for purpose, despite many adaptive strategies employed by staff. This impedes recovery on the island, as essential service staff have to 'make do' with inadequate facilities. For successful post-disaster resettlement, sustainable development opportunities are needed, which includes provision of appropriate essential services (Usamah & Haynes 2012). In Montserrat, the 'quick fixes' for essential services should, therefore, be readdressed to enable further development of the island towards its sustainable goals (GoM 2010).

The evolution of the eruption and its consequences has left behind a legacy of considerable uncertainty in terms of: future hazards, the viability of specific locations on Montserrat (close to the volcano) and investment. Lack of investment in upgrading essential services has also cultivated uncertainty at a local level, which is a critical factor shaping Montserrat's future development.

*Resilience-building.* Many adaptive strategies have been adopted across essential service sectors. This is manifested through permanent changes to essential services over time, including installation of air conditioning and Plexiglas to reduce ash ingress, roofing material changes, protection switches at the power station to prevent damage, permanent covering of sensitive equipment, collaborative working and development of contingency plans. There are also coping strategies; some of which are necessarily reactive including cleaning, and shutting windows and doors during ash-falls. Overall, adaptations and coping strategies have contributed to increasing the resilience of essential services over the course of the eruption. The decentralization of essential services in the north of the island will reduce exposure of essential services and, therefore, reduce risk, further contributing to its resilience. However, there is an imperative for investment in essential services to increase their resilience, ensure their long-term viability, relieve stress and to reduce the impacts of disruptions on society. This is also fundamental as it is likely to ease the critical uncertainty that is stalling development. Plans to build a new hospital, new capital and a new power station take steps towards critical investment, and their realization will be a marked improvement in essential service resilience and in the quality of life for society.

*Essential service–society continuum.* The holistic approach to this study has demonstrated the complexity of volcanic living, both as a legacy of relocation that continues to affect essential services and the population today, and the overlain issues of ongoing activity. The population emigration left a lack of skilled professionals within essential service sectors, and extensive re-training has been required to manage this deficit. The low population has also challenged the viability of specialist services, and makes further specialization of services unavailable on the island. However, social capacities contribute significantly to the resilience of the community, and to the functioning of essential services. Social tolerance and acceptance of essential service disruptions minimizes the population demands of their essential services, and reduces stress for struggling essential service sectors. These include community networks that assist parents to juggle work and life in the aftermath of large-scale emigration. Decision-making related to personal circumstances has an impact on essential service functionality in response to hazards or perceived risk, causing temporary closures. This highlights that work–life interrelationships are imperative considerations that shape capacities and, ultimately, the functionality of essential services in volcanic environments. Such complex interrelationships can only be understood and accounted for by taking a holistic approach to studies of essential services risk and resilience.

### Implications for policy and practice

It is recommended that the following lessons from this study are applied to policy and practice:

- Leadership, clear policy guidelines and community engagement need to guide post-crisis redevelopment with risk reduction and resilience as critical foci. The amount and timeliness of funding during a disaster critically affects the long-term vulnerability of essential services. Quick fixes, if and when made in crisis phases, must be readdressed with time to reduce vulnerabilities, and to ensure long-term viability and functionality of essential services.

- Community-level adaptations that have been identified in Montserrat could provide useful guidelines for risk reduction and the enhancement of resilience in other volcanic areas. However, these must be adjusted to the local context to ensure the applicability, acceptance and appropriateness of such measures.
- Appropriate and timely investment at an essential service level can complement bottom-up adaptations and approaches to reducing impacts made at the community level. The approach to investment should be participatory, to account for the wants, needs and expertise of those managing and operating essential services. This is likely to ensure the feasibility and success of essential services in the long term. In a considered approach, this will not reduce the choices available for future development and adaptation of services (Sterner *et al.* 2006) in response to dynamic changes in demand. Investment in essential services could also provide the community with greater certainty about the future viability of the place, and is likely to stimulate confidence as this would provide visible evidence of government willingness to enhance the current conditions.

We would like to thank J. Barclay and two anonymous reviewers for their excellent reviews and suggestions, which have improved this manuscript significantly.

We are indebted to all of the people who participated in this research in Montserrat; both interviewees and others who interacted with the researcher in the field (V. Sword-Daniels), and engaged with the project. Without the thoughts, information and the time taken by others to participate in this research, this work could not have been carried out.

We also wish to thank the staff at the Montserrat Volcano Observatory for their support and resources, which greatly helped in undertaking the fieldwork in Montserrat.

We gratefully acknowledge the following funding sources: BGS through the BUFI fund for the invaluable financial support that covered the travel costs; EPSRC for funding this research through the Urban Sustainability and Resilience EngD programme at University College London (V. Sword-Daniels, T. Rossetto and J. Twigg); the New Zealand Ministry of Science and Innovation Natural Hazard Platform Grant C05X0804 (T. M. Wilson and D. M. Johnston). This paper is published with the permission of the Executive Director of the British Geological Survey (NERC).

## References

- AFP NEWS AGENCY. 2010. Ash from Montserrat volcano disrupts Caribbean flights. *AFP News Agency*, 12 February.
- ANTIGUA SUN. 2009. 70 evacuated in Montserrat, Antigua experiences heavy ash fall. *Antigua Sun*, 4 January.
- ASPINALL, W. P., LOUGHLIN, S. C. *ET AL.* 2002. The Montserrat Volcano Observatory: its evolution, organization, role and activities. In: DRUITT, T. H. & KOKELAAR, B. P. (eds) *The Eruption of Soufrière Hills, Montserrat, from 1995 to 1999*. Geological Society, London, *Memoirs*, **21**, 71–91.
- BARCLAY, J., HAYNES, K. *ET AL.* 2008. Framing volcanic risk communication within disaster risk reduction: finding ways for the social and physical sciences to work together. In: LIVERMAN, D. G. E., PEREIRA, C. P. G. & MARKER, B. (eds) *Communicating Environmental Geoscience*. Geological Society, London, *Special Publications*, **305**, 163–177.
- BAXTER, P. J., BONADONNA, C. *ET AL.* 1999. Cristobalite in volcanic ash of the Soufrière Hills Volcano, Montserrat, British West Indies. *Science*, **283**, 1142–1145.
- BAXTER, P. J., BOYLE, R., COLE, P., NERI, A., SPENCE, R. & ZUCCARO, G. 2005. The impacts of pyroclastic surges on buildings at the eruption of the Soufrière Hills volcano, Montserrat. *Bulletin of Volcanology*, **67**, 292–313.
- BERG, B. L. 2007. *Qualitative Research Methods for the Social Sciences*. 6th edn. Pearson/Allyn & Bacon, Boston, MA.
- BLONG, R. 1984. *Volcanic Hazards: A Sourcebook on the Effects of Eruptions*. Academic Press, Sydney.
- BLONG, R. 2003. Building damage in Rabaul, Papua New Guinea, 1994. *Bulletin of Volcanology*, **65**, 43–54.
- BRIGUGLIO, L. 1995. Small Island developing states and their economic vulnerabilities. *World Development*, **23**, 1615–1632.
- BROWN, L. 2010. *Birth of a Mountain: Montserrat's Volcano – An Eyewitness Account*. Sargeant Press, Blackwater, Isle of Wight, UK.
- BUFFONGE, C. 1998. *Volcano Book 3: Events in Montserrat During 1997*. Ideal Printers, Montserrat.
- CALDER, E. S., LUCKETT, R., SPARKS, R. S. J. & VOIGHT, B. 2002. Mechanisms of lava dome instability and generation of rockfalls and pyroclastic flows at Soufrière Hills Volcano, Montserrat. In: DRUITT, T. H. & KOKELAAR, B. P. (eds) *The Eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999*. Geological Society, London, *Memoirs*, **21**, 173–190.
- CARIBBEAN NEWS NOW! 2011. *Report 8 June 2011*. *Caribbean News Now*. <http://www.caribbeannewsnow.com>
- CARIB DAILY. 2008. *Reports: 30 July 2008, 31 July 2008, 5 January 2009, and 6 January 2009*. [www.caribdaily.com/news-highlights/montserrat](http://www.caribdaily.com/news-highlights/montserrat).
- CASADEVALL, T. J. 1993. Volcanic hazards and aviation safety: lessons of the past decade. *Flight Safety Foundations, Flight Safety Digest*, **2**, 9–17.
- CASADEVALL, T. J., DELOS REYES, P. J. & SCHNEIDER, D. J. 1996. The 1991 Pinatubo eruptions and their effects on aircraft operations. In: NEWHALL, C. G. & PUNONGBAYAN, R. S. (eds) *Fire and Mud: Eruptions and Lahars of Mount Pinatubo, Philippines*. Philippine Institute of Volcanology and Seismology and University of Washington Press, Seattle, WA, 1071–1088.
- CCDP 2009. *2000 Round of Population and Housing Census Data Analysis Sub-Project*, National Census Report. Caricom Capacity Development Programme, Montserrat.
- CDERA 2007. *Report 24 July 2007*. Caribbean Disaster Emergency Response Agency. [www.cdera.org](http://www.cdera.org)
- CLAY, E., BARROW, C., BENSON, C., DEMPSTER, J., KOKELAAR, P., PILLAI, N. & SEAMAN, J. 1999. *An Evaluation of HMG's Response to the Montserrat Volcanic Emergency*. Evaluation Summary (EVSUM) EV635. Department for International Development (DFID), London.
- COLE, P. D., CALDER, E. S. *ET AL.* 2002. Deposits from dome-collapse and fountain-collapse pyroclastic flows at Soufrière Hills Volcano, Montserrat. In: DRUITT, T. H. & KOKELAAR, B. P. (eds) *The Eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999*. Geological Society, London, *Memoirs*, **21**, 231–262.
- DOMINICA NEWS ONLINE 2010. *LIAT suspends flights due to airborne volcano ash clouds*. 11 February. [www.dominicanewsonline.com](http://www.dominicanewsonline.com)
- DONOVAN, A. R. 2010. *Emerald and Andesite: volcanology at the policy interface on Montserrat*. PhD thesis, Department of Geography, University of Cambridge.
- DREXLER, J. M., GLEDHILL, A. D., SHINODA, K., VASILIEV, A. L., REDDY, K. M., SAMPATH, S. & PADTURE, N. P. 2011. Jet engine coatings for resisting volcanic ash damage. *Advanced Materials*, **23**, 2419–2424. <http://dx.doi.org/10.1002/adma.201004783>
- DRUITT, T. H. & KOKELAAR, B. P. 2002. Preface. In: DRUITT, T. H. & KOKELAAR, B. P. (eds) *The Eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999*. Geological Society, London, *Memoirs*, **21**, ix–x.
- DURAND, M., GORDON, K., JOHNSTON, D., LORDEN, R., POIROT, T., SCOTT, J. & SHEPHARD, B. 2001. *Impacts of, and Responses to Ashfall in Kagoshima from Sakurajima Volcano – Lessons for New Zealand*. Institute of Geological & Nuclear Sciences Science Report **2001/30**.
- EDMONDS, M., HERD, R. A. & STRUTT, M. H. 2006. Tephra deposits associated with a large lava dome collapse, Soufrière Hills Volcano, Montserrat, 12–15 July 2003. *Journal of Volcanology and Geothermal Research*, **153**, 313–330.
- GIBSON, W. J. & BROWN, A. 2009. *Working with Qualitative Data*. Sage, London.
- GORDON, K. D., COLE, J. W., ROSENBERG, M. D. & JOHNSTON, D. M. 2005. Effects of Volcanic Ash on Computers and Electronic Equipment. *Natural Hazards*, **34**, 231–262.
- GOM 1991. *1991 Population & Housing Census*. Government of Montserrat, Statistics Department, Ministry of Finance and Economic Development, Montserrat.
- GOM 2001. *2001 Population & Housing Census*. Government of Montserrat, Statistics Department, Ministry of Finance and Economic Development, Montserrat.

- GoM 2002. *Budget Statement*. Government of Montserrat, Development Unit, Ministry of Economic Development and Trade, Montserrat.
- GoM 2003. *Montserrat Sustainable Development Plan 2003–2007: Vision Statement*. Government of Montserrat, Ministry of Economic Development and Trade, Montserrat.
- GoM 2004. *Budget Statement*. Government of Montserrat, Development Unit, Ministry of Economic Development and Trade, Montserrat.
- GoM 2005. *Budget Statement*. Government of Montserrat, Development Unit, Ministry of Economic Development and Trade, Montserrat.
- GoM 2010. *Montserrat Sustainable Development Plan 2008–2020*. Government of Montserrat, Ministry of Economic Development and Trade, Montserrat.
- GoM 2011. *Physical Development Plan for North Montserrat (2012–2022)*. Consultation Draft. Government of Montserrat, Physical Planning Unit, Ministry of Agriculture, Land, Housing and the Environment, Montserrat.
- GoM 2012a. *Census 2011: Montserrat at a Glance*. Government of Montserrat, Statistics Department, Ministry of Finance and Economic Management, Montserrat.
- GoM 2012b. *Ministerial Statement on DFID Aid for Hospital Improvements*. Government of Montserrat, Montserrat.
- GoM 2012c. *UK Agrees to Fund Geothermal Development on Montserrat*. Government of Montserrat, Montserrat. [www.gov.ms](http://www.gov.ms)
- GUFFANTI, M., MAYBERRY, G. C., CASADEVALL, T. J. & WUNDERMAN, R. 2009. Volcanic hazards to airports. *Natural Hazards*, **51**, 287–302.
- HAYNES, K. 2005. *Exploring the Communication of Risk During a Volcanic Crisis: A Case Study of Montserrat, WI*. PhD thesis, School of Environmental Sciences, University of East Anglia.
- HAYNES, K. 2006. Volcanic island in crisis: investigating environmental uncertainty and the complexities it brings. *Australian Journal of Emergency Management*, **21**, 21–28.
- HAYNES, K., BARCLAY, J. & PIDGEON, N. 2008. The issue of trust and its influence on risk communication during a volcanic crisis. *Bulletin of Volcanology*, **70**, 605–621.
- HERD, R., EDMONDS, M. & BASS, V. A. 2005. Catastrophic lava dome failure at Soufrière Hills Volcano, Montserrat, 12–13 July 2003. *Journal of Volcanology and Geothermal Research*, **148**, 234–252.
- HORWELL, C. J. & BAXTER, P. J. 2006. The respiratory health hazards of volcanic ash: a review for volcanic risk mitigation. *Bulletin of Volcanology*, **69**, 1–24.
- INGRAM, J. C., FRANCO, G., RUMBAITIS-DEL RIO, C. & KHAZAI, B. 2006. Post-disaster recovery dilemmas: challenges in balancing short-term and long-term needs for vulnerability reduction. *Environmental Science & Policy*, **9**, 607–613.
- JOHNSTON, D. M. 1997. *Physical and Social Impacts of Past and Future Volcanic Eruptions in New Zealand*. PhD thesis, Massey University, Palmerston North.
- JOHNSTON, D. M., HOUGHTON, B. F., NEALL, V. E., RONAN, K. R. & PATON, D. 2000. Impacts of the 1945 and 1995–1996 Ruapehu eruptions, New Zealand: an example of increasing societal vulnerability. *GSA Bulletin*, **112**, 720–726.
- KAY, J. J. 2008. Chapter 1: An introduction to systems thinking; and Chapter 2: Framing the situation: developing a system description. In: WALTNER-TOEWS, D., KAY, J. J. & LISTER, N. E. (eds) *The Ecosystem Approach: Complexity, Uncertainty, and Managing for Sustainability*. Columbia University Press, New York, 3–14 and 15–34.
- KELMAN, I. & MATHER, T. A. 2008. Living with volcanoes: the sustainable livelihoods approach for volcano-related opportunities. *Journal of Volcanology and Geothermal Research*, **172**, 189–198.
- KOKELAAR, B. P. 2002. Setting, chronology and consequences of the eruption of Soufrière Hills Volcano, Montserrat (1995–1999). In: DRUITT, T. H. & KOKELAAR, B. P. (eds) *The Eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999*. Geological Society, London, Memoirs, **21**, 1–43.
- LANE, L. R., TOBIN, G. A. & WHITEFORD, L. M. 2003. Volcanic hazard or economic destitution: hard choices for Baños, Ecuador. *Environmental Hazards*, **5**, 23–34.
- LEONE, F. & GAILLARD, J.-C. 1999. Analysis of the institutional and social responses to the eruption and the lahars of Mount Pinatubo volcano from 1991 to 1998 (Central Luzon, Philippines). *GeoJournal*, **49**, 223–238.
- LOUGHLIN, S. C., BAXTER, P. J., ASPINALL, W. P., DARROUX, B., HARFORD, C. L. & MILLER, A. D. 2002a. Eyewitness accounts of the 25 June 1997 pyroclastic flows and surges at Soufrière Hills Volcano, Montserrat, and Implications for disaster mitigation. In: DRUITT, T. H. & KOKELAAR, B. P. (eds) *The eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999*. Geological Society, London, Memoirs, **21**, 211–230.
- LOUGHLIN, S. C., CALDER, E. S. ET AL. 2002b. Pyroclastic flows and surges generated by the 25 June 1997 dome collapse, Soufrière Hills Volcano, Montserrat. In: DRUITT, T. H. & KOKELAAR, B. P. (eds) *The Eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999*. Geological Society, London, Memoirs, **21**, 191–209.
- LOUGHLIN, S. C., BAXTER, P. J. & CHRISTOPHER, T. 2011. Ash fall and gas impacts before, during and after a total lava dome collapse on 20 May 2006 at Soufrière Hills Volcano, Montserrat. Abstract 70, presented at 2011 Soufrière Hills Volcano 15 Years On Conference, MVO, Montserrat, W.I., 4–8 April 2011.
- MCCRACKEN, G. 1988. *The Long Interview: Qualitative Research Methods*. Sage, Newbury Park, CA.
- MERCER, J., DOMINEY-HOWES, D., KELMAN, I. & LLOYD, K. 2007. The potential for combining indigenous and western knowledge in reducing vulnerability to environmental hazards in small island developing states. *Environmental Hazards*, **7**, 245–256.
- MERCER, J., KELMAN, I., TARANIS, L. & SUCHET-PEARSON, S. 2010. Framework for integrating indigenous and scientific knowledge for disaster risk reduction. *Disasters*, **34**, 214–239.
- MITCHELL, T. C. 2006. *Building a Disaster Resilient Future: Lessons from Participatory Research in St Kitts and Montserrat*. PhD thesis, Department of Geography, University College London.
- MONTERRAT TOURIST BOARD 1983. *Tourist Map of Montserrat: Emerald Isle of the Caribbean, Scale 1:25 000*. Ministry of Overseas Development, London.
- MVO 2012. Montserrat Volcano Observatory, Flemmings, Montserrat. [www.mvo.ms](http://www.mvo.ms)
- NOAA 2010. *Washington VAAC 2009 and 2010 Volcanic Ash Advisory Archives*. National Oceanic and Atmospheric Administration, Washington, DC. <http://www.ssd.noaa.gov/VAAC/ARCH10/archive.html>.
- PATTULLO, P. 2000. *Fire from the Mountain: The Tragedy of Montserrat and the Betrayal of its People*. Constable and Robinson, London.
- PELLING, M. & UITTO, J. I. 2001. Small island developing states: natural disaster vulnerability and global change. *Environmental Hazards*, **3**, 49–62.
- PERRY, R. W. & LINDELL, M. K. 1990. *Living with Mount St. Helens – Human Adjustment to Volcano Hazards*. Washington State University Press, Pullman, WA.
- POMONIS, A., SPENCE, R. & BAXTER, P. 1999. Risk assessment of residential buildings for an eruption of Furnas Volcano, Sao Miguel, the Azores. *Journal of Volcanology and Geothermal Research*, **92**, 107–131.
- POSSEKEL, A. K. 1999. *Living with the Unexpected: Linking Disaster Recovery to Sustainable Development in Montserrat*. Springer, Berlin.
- SAC 2010. *Fourteenth Report of the Scientific Advisory Committee on Montserrat Volcanic Activity*. Part 1: Main Report, 14 April. Scientific Advisory Committee, London.
- SARANTAKOS, S. 2005. *Social Research*, 3rd edn. Pelgrave Macmillan, Basingstoke, Hampshire.
- SKELTON, T. 2000. Political uncertainties and natural disasters: montserratian identity and colonial status. *Interventions*, **2**, 103–117.
- SKINNER, J. 2008. The text and the tale: differences between scientific reports and scientists' reportings on the eruption of Mount Chance, Montserrat. *Journal of Risk Research*, **11**, 255–267.
- SPARKS, R. S. J. & HAWKESWORTH, C. J. (eds) 2004. *The State of the Planet: Frontiers and Challenges in Geophysics*. American Geophysical Union, Geophysical Monographs, **150**.
- SPARKS, R. S. J. & YOUNG, S. R. 2002. The eruption of Soufrière Hills, Montserrat (1995–1999): overview of scientific results. In: DRUITT, T. H. & KOKELAAR, B. P. (eds) *The Eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999*. Geological Society, London, Memoirs, **21**, 45–69.
- SPENCE, R. J. S., POMONIS, A., BAXTER, P. J., COBURN, A. W., WHITE, M., DAYRIT, M. Field Epidemiology Training Team. 1996. Building

- damage caused by the Mount Pinatubo Eruption of June 15, 1991. In: NEWHALL, C. G., PUNONGBAYAN, R. S. (eds) *Fire and Mud: Eruptions and Lahars of Mount Pinatubo, Philippines*. Philippine Institute of Volcanology and Seismology and University of Washington Press, Seattle, WA, 1055–1061.
- SPENCE, R. J. S., BAXTER, P. J. & ZUCCARO, G. 2004. Building vulnerability and human casualty estimation for a pyroclastic flow: a model and its application to Vesuvius. *Journal of Volcanology and Geothermal Research*, **133**, 321–343.
- STERNER, T., TROELL, M. *ET AL.* 2006. Quick fixes for the environment: part of the solution or part of the problem? *Environment*, **48**, 20–27.
- STEWART, C., JOHNSTON, D. M., LEONARD, G. S., HORWELL, C. J., THORDARSON, T. & CRONIN, S. J. 2006. Contamination of water supplies by volcanic ashfall: a literature review and simple impact modelling. *Journal of Volcanology and Geothermal Research*, **158**, 296–306.
- STEWART, C., PIZZOLON, L., WILSON, T., LEONARD, G., JOHNSTON, D. & CRONIN, S. 2009. Can volcanic ash poison water supplies? *Integrated Environmental Assessment and Management*, **5**, 713–716.
- THE MONTSERRAT REPORTER 2011. The new \$20 million hospital – the study of healthcare and expenditures. *The Montserrat Reporter*, 11 December.
- TOBIN, G. A. & WHITEFORD, L. M. 2002. Community resilience and volcano hazard: the eruption of Tungurahua and evacuation of the Faldas in Ecuador. *Disasters*, **26**, 28–48.
- TOMBLIN, J. 1981. Earthquakes, volcanoes and hurricanes: a review of natural hazards and vulnerability in the West Indies. *Ambio*, **10**, 340–345.
- TROFIMOV, J., FOSTER, C. *ET AL.* 2012. Submarine pyroclastic deposits formed during the 20th May 2006 dome collapse of the Soufrière Hills Volcano, Montserrat. *Bulletin of Volcanology*, **74**, 391–405.
- TWIGG, J. 2009. *Characteristics of a Disaster Resilient Community: A Guidance Note. Version 2*. Department for International Development (DFID), London.
- UNISDR 2004. *Living with Risk: A Global Review of Disaster Reduction Initiatives*. United Nations International Strategy for Disaster Reduction, Geneva.
- UNISDR 2005. *Hyogo Framework for Action 2005–2015: Building the Resilience of Nations and Communities to Disasters*. World Conference on Disaster Reduction, 18–22 January 2005, Kobe, Hyogo, Japan. United Nations International Strategy for Disaster Reduction, Geneva.
- USAMAH, M. & HAYNES, K. 2012. An examination of the resettlement program at Mayon Volcano: what can we learn for sustainable volcanic risk reduction? *Bulletin of Volcanology*, **74**, 839–859, <http://dx.doi.org/10.1007/s00445-011-0567-8>
- WADGE, G., VOIGHT, B., SPARKS, R. S. J., COLE, P. D., LOUGHLIN, S. C. & ROBERTSON, R. 2014. An overview of the eruption of Soufrière Hills Volcano, Montserrat from 2000 to 2010. In: WADGE, G., ROBERTSON, R. E. A. & VOIGHT, B. (eds) *The Eruption of Soufrière Hills Volcano, Montserrat from 2000 to 2010*. Geological Society, London, *Memoirs*, **39**, 1–39, <http://dx.doi.org/10.1144/M39.1>
- WARDMAN, J. B., WILSON, T. M., BODGER, P. S., COLE, J. W. & JOHNSTON, D. M. 2012. Investigating the electrical conductivity of volcanic ash and its effect on HV power systems. *Physics and Chemistry of the Earth, Parts A/B/C*, **45–46**, 128–145, <http://dx.doi.org/10.1016/j.pce.2011.09.003>
- WARRICK, R. A., ANDERSON, J., DOWNING, T., LYONS, J., RESSLER, J., WARRICK, M. & WARRICK, W. 1981. *Four Communities Under Ash After Mount St Helens*. Institute of Behavioural Science, University of Colorado, Boulder, CO.
- WASON, A. T. 1994. *Vulnerability Survey of Health Facilities in Montserrat, West Indies*. Pan American Health Organization, Bridgetown, Barbados. (Contract number ASC-94/00167-0.)
- WILLIAMS, R. S. & MOORE, J. G. 1976. *Man Against the Volcano: The Eruption of Heimaey, Vestmannaeyjar, Iceland*. United States Geological Survey, Reston, VA.
- WILSON, T., DALY, M. & JOHNSTON, D. 2009. *Review of Impacts of Volcanic Ash on Electricity Distribution Systems, Broadcasting and Communication Networks*. Report for the Auckland Engineering Lifelines Group. Auckland Regional Council, Technical Publication **051**.
- WILSON, T., COLE, J., CRONIN, S., STEWART, C. & JOHNSTON, D. 2011. Impacts on agriculture following the 1991 eruption of Vulcan Hudson, Patagonia: lessons for recovery. *Natural Hazards*, **57**, 185–212.
- WILSON, T., STEWART, C. *ET AL.* 2012. Volcanic ash impacts on critical infrastructure. *Physics and Chemistry of the Earth, Parts A/B/C*, **45–46**, 5–23, <http://dx.doi.org/10.1016/j.pce.2011.06.006>
- WILSON, G., WILSON, T., COLE, J. & OZE, C. 2012. Vulnerability of laptop computers to volcanic ash and gas. *Natural Hazards*, **63**, 711–736, <http://dx.doi.org/10.1007/s11069-012-0176-7>
- WISNER, B., BLAIKIE, P., CANNON, T. & DAVIS, I. 2004. *At Risk: Natural Hazards, Peoples' Vulnerability and Disasters*, 2nd edn. Routledge, London.
- YOUNG, I. J. 2004. *Montserrat: Post Volcano Reconstruction and Rehabilitation – A Case Study*. Department for International Development, Montserrat.
- YOUNG, S. R., VOIGHT, B. *ET AL.* 2002. Hazard implications of small-scale edifice instability and sector collapse: a case history from Soufrière Hills Volcano, Montserrat. In: DRUITT, T. H. & KOKELAAR, B. P. (eds) *The Eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999*. Geological Society, London, *Memoirs*, **21**, 349–361.