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PERSPECTIVES

From anecdotes to quantification: advances in characterizing volcanic eruption impacts on the built environment

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Abstract
Over the past 20 years, our understanding of volcanic eruption impacts on the built environment has transformed from being primarily observational with small datasets to one grounded in field investigations, laboratory experiments, and quantitative modeling, with an emphasis on stakeholder collaboration and co-creation. Here, we summarize key advances and knowledge gaps of impacts across volcanic hazards and built environment types from the past 20 + years. Studies have concentrated on impacts from tephra fall (ash) and to buildings, with less examination of other hazards' impacts to critical infrastructure. As we look to the next decade, we speculate on likely research directions, including the increasing role of new technologies, higher resolution modeling, transdisciplinary collaborations, and evidence-based mitigative solutions.

Keywords Built environment · Decadal review · Volcanic consequences · Volcanic hazard · Volcanic impacts · Volcanic risk

Introduction

For millennia, societies have faced a variety of volcanic eruption impacts, from nuisance to major disruption to loss of life, home, and livelihoods. Today, over 1 billion people live within 100 km of an active volcano (Freire et al. 2019),

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Looking Backwards and Forwards in Volcanology: A Collection of Perspectives on the Trajectory of a Science

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and societies farther afield can experience physical and disruptive consequences from volcanic activity (Wilson et al. 2012). This contribution focuses on advances over the last 20+ years to characterize the impacts of volcanic eruptions on the built environment, where built environment is defined as "[person]-made or modified structures that provide people with living, working, and recreational spaces" (EPA 2020), including buildings and critical infrastructure (energy, water, transportation, telecommunication). We consider both direct (damage to specific asset or component) and indirect (system functionality loss) impacts (Merz et al. 2010). Not covered here are impacts to aviation (Mastin et al. in press), health (Stewart et al. this issue), agriculture (Craig et al. 2016; Wilson et al. 2011), or economies (e.g., Cardwell et al. 2021; Rodriguez et al. 2017; Zuccaro et al. 2013), or advances in hazard modeling.

While all volcanic hazards can adversely impact the built environment, most of the research effort to date has focused on tephra fall (ash) impacts (Figs. 1 and 2). This is due to a combination of factors, including high-profile explosive eruptions with large tephra deposits, comparatively frequent and larger ash footprints (relative to other hazards) that affect more communities, diverse impacts and impact mechanisms that can be gradational (contrary to perceived binary flow hazards: untouched/destroyed), and mitigative solutions beyond avoidance (Wilson et al. 2014a). Documentation of the 1980 Mount St. Helens eruption impacts was foundational (Blong 1984), and subsequent twentieth century research similarly focused on describing impacts from notable volcanic eruptions (Fig. 1), with some early attempts to identify systemic drivers of volcanic impacts (Johnston et al. 2000). In the last 20 years, such work has continued, accompanied by more approaches (see next section) to understand the causes and ramifications of specific impacts and wider systemic drivers. There has been a concerted effort to apply this knowledge to forecast eruption impacts from volcanoes around the world (Fig. 2). More recently, there is a growing focus on understanding dynamic, multi-hazard and cascading impacts, and their associated consequences for livelihoods and habitability, as well as quantifying damage ranges, interdependencies, and evidence-based mitigation.

Approaches

Previous approaches for identifying and characterizing the causes of volcanic impacts to the built environment (Fig. 1) include:

Post-eruption investigations—identifying and describing eruption consequences, including both qualitative and quantitative data, with comprehensive observations and data generally collected during dedicated impact investigation visits (e.g., Baxter et al. 2005; Blong 1984, 2003; Jenkins et al. 2013; Johnston et al. 2000; Magill et al. 2013; Spence et al. 1996; Wantim et al. 2018);

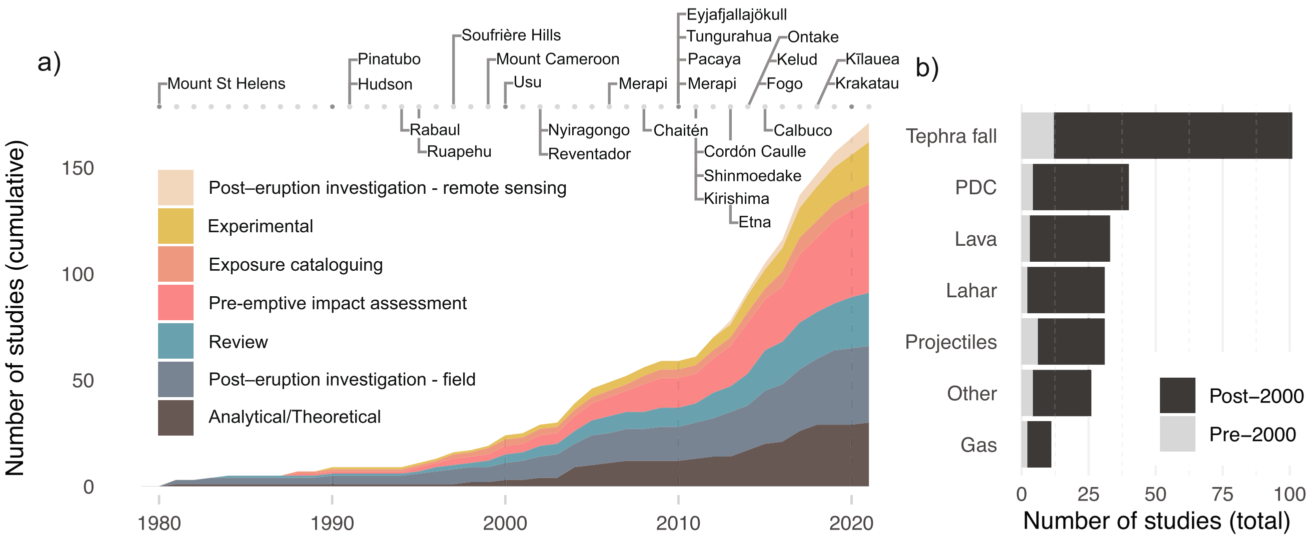


Fig. 1 Approaches used and hazards studied in articles on volcanic impacts to the built environment, published since 1980 (limited to English language publications; see Supplementary Information for selection methodology). **a** Stacked area chart timeline of approaches used, arranged by order of appearance in the literature. Volcanoes that have erupted since 1980 and been studied in these articles are highlighted. **b** Number of articles for a particular volcanic hazard. "Other" includes volcanic earthquakes, ground deformation, volcanogenic tsunami, edifice building, and sector collapse. A single study can adopt multiple approaches and study multiple hazards. Half of the articles since 1980 have been published in the last 7 years (2014 onwards). The 140 studies contributing to this analysis are indicated in Supplementary Information

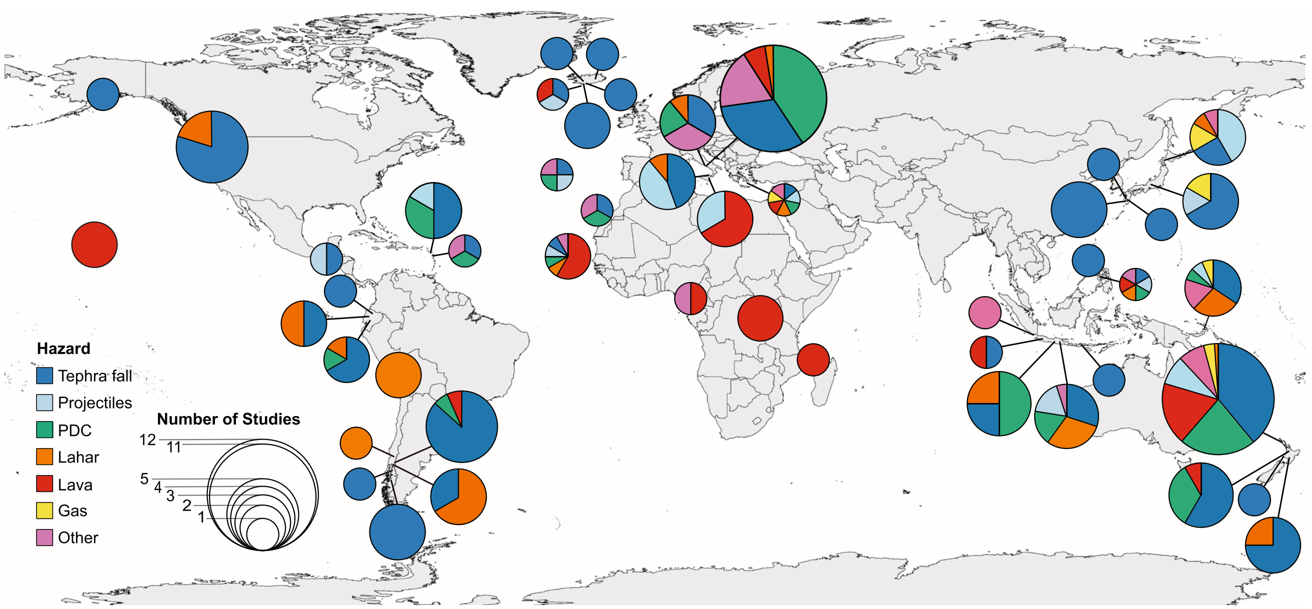


Fig. 2 Spatial representation of studies on volcanic impacts on the built environment, analyzed in Fig. 1, shown by volcano. Studies include post-eruption impact assessments and forward-looking risk assessments and scenario development. The size of the pie chart corresponds to the number of studies, and the hazards considered include tephra fall (dark blue), projectiles (light blue), pyroclastic density current (PDC: green), lahar (orange), lava (red), gas (yellow), and other (purple; includes volcanic earthquakes, volcanogenic tsunami, edifice building, and sector collapse). A single study may consider impacts from several hazards. The 99 studies contributing to this analysis are indicated in Supplementary Information

Controlled experiments—primarily laboratory studies, generally with "real" materials, removing the requirement for post-experiment scaling (e.g., Blake et al. 2016; Spence et al. 2004; Wardman et al. 2014);

Engineering calculations and theoretical modeling—often based on standards/approaches developed for other natural hazards (e.g., Petrazzuoli and Zuccaro 2004; Valentine 1998; Zuccaro and Ianniello 2004); and

Review—synthesis of observational, experimental, and modeling data (e.g., Stewart et al. 2006; Wilson et al. 2014a, 2012).

Across these approaches, there has been a push to identify and correlate key hazard intensity metrics (HIMs)—an often numeric characterization of the relationship between the severity of a hazard in a given location—to consequence, as described using a damage state or other ordinal scale or a numeric ratio, such as damage ratio. Numerous studies have developed vulnerability (% damage/loss relative to specified "worst-case" outcome) and fragility (probability of exceeding specified impact/damage state) functions (Rossetto et al. 2013) using data derived from one or more of the approaches catalogued above (e.g., Blake et al. 2017a; Blong et al. 2017; Wilson et al. 2017).

In parallel, several approaches have been used to prepare for and explore the potential ramifications of volcanic impacts to the built environment:

Cataloguing exposure—identifying assets that may be exposed to future volcanic activity (e.g., Jenkins et al. 2014; Marti et al. 2008; Pomonis et al. 1999);

Scenario development and analysis—exploring consequences of credible eruption scenarios (e.g., Blong and Aislabie 1988; Deligne et al. 2017; Spence et al. 2008; Zuccaro and De Gregorio 2019);

Risk modeling—probabilistic assessment of the likelihood of adverse impacts occurring (e.g., Biass et al. 2016; Magill and Blong 2005; McDonald et al. 2017); and

Systems analysis—identifying and characterizing interdependencies, particularly between various critical infrastructure networks (Sword-Daniels et al. 2015; Wild et al. 2019), but sometimes also between volcanic hazards in the context of impact severity (e.g., Williams et al. 2019; Zuccaro et al. 2008, 2018).

Additionally, considerable effort has gone towards making research findings useful and usable, through the development of sector-specific educational posters (Wilson et al. 2014b), now available in several languages (https://www.gns.cri.nz/Home/Learning/Science-Topics/Volcanoes/Global-Ash-Impact-Posters), web resources (https://volcanoes.usgs.gov/volcanic_ash/), and the coordinated availability of the research community to provide expert knowledge to responders during multiple crises within the last several years.

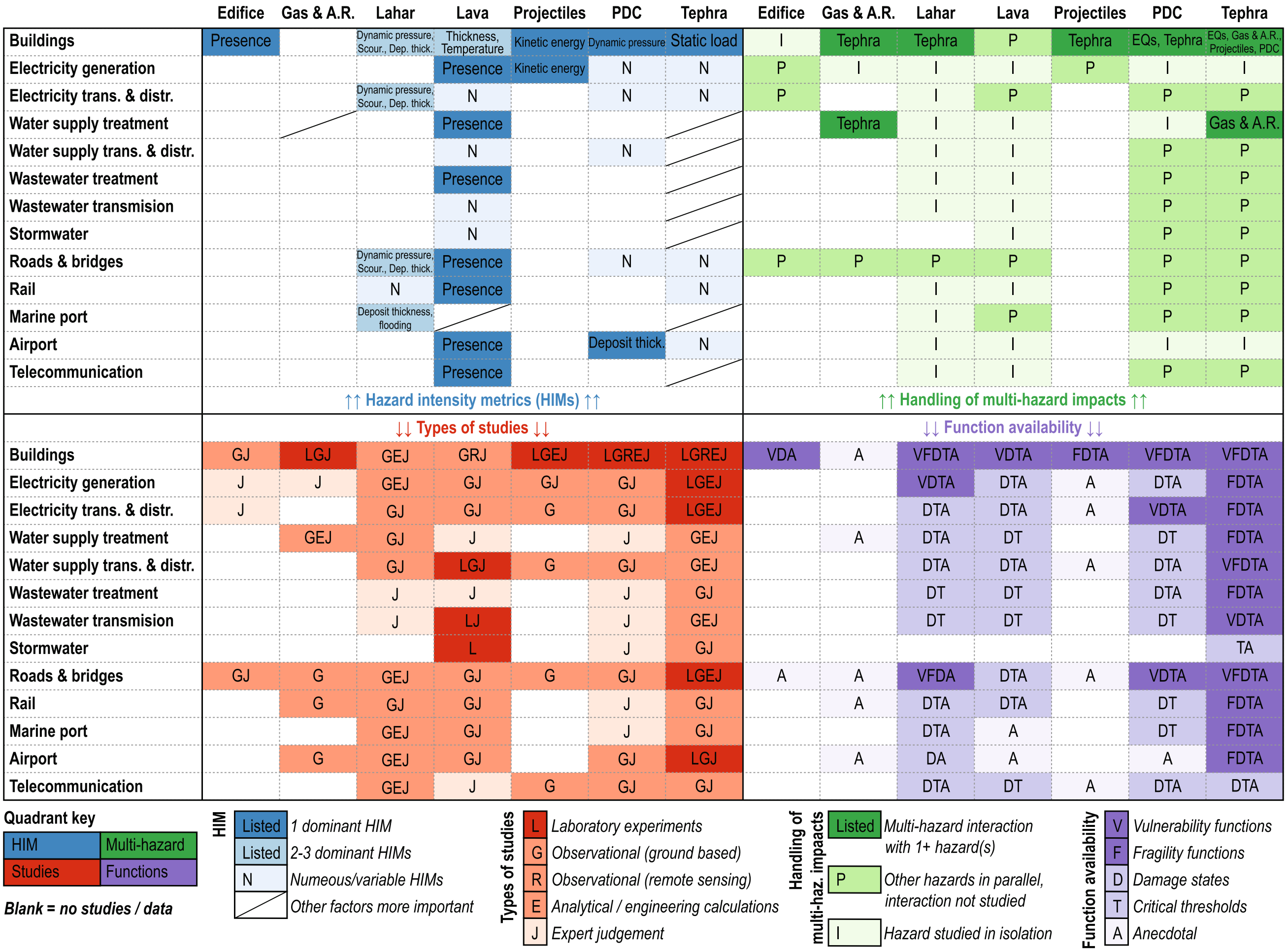
Advances

Below is a brief review of findings thus far, framed by consequence severity (Figs. 3 and 4). While much of the earlier work was focused on severe consequences, more recent studies consider a wider range of potential impacts. The following summaries are cumulative (e.g., *functionality loss* findings also encompass results from *nuisance*).

Nuisance impacts can occur with small quantities of tephra or distal lahars, either primary or remobilized, and accompanying gases. Considerable time and resources can be required for the increased, and at times constant and costly, maintenance of infrastructure systems, service provision, and clean-up (Hayes et al. 2015; Wilson et al. 2012), although pre-event planning is rarely undertaken.

Functionality loss across critical infrastructure sectors can occur with minimal to no permanent asset damage and with low hazard intensity (Wilson et al. 2014a). For example, electrical transmission lines can flashover (short circuit) with as little as 3 mm of tephra accumulation, resulting in electricity disruption "downstream" (Wardman et al. 2012c, 2014). While physical damage is unlikely, clean-up is often required for service restoration. Likewise, tephra deposits as thin as 0.5 mm can obscure road markings,

Fig. 3 Photos of impacts to the built environment at different consequence severity and for different volcanic hazards: (**a**) Nuisance: minor corrosion to farming equipment that occurred *overnight* (observed by the photographer and confirmed by the farmer) as a result of gas and/or tephra during the explosive phase of the 2010 eruption of Eyjafjallajökull, Iceland (credit: SF Jenkins); (**b**) Functionality loss: tephra induced flashover (short-circuiting) across a porcelain insulator during laboratory experiments (left) and the thin layer of damp tephra responsible (right) (credit: JB Wardman and G Wilson); (**c**) Asset damage: cracked window glass and melting of plastic components such as light fixtures (center), plastic piping and water tank (upper right), and PVC sheet roofs (rear of property) by low-energy, dilute pyroclastic density currents during the 2010 eruption of Merapi, Indonesia (credit: SF Jenkins); (**d**) Asset destruction: roof collapse and structural damage to walls from ~ 50 cm of tephra fall on a timber frame building during the 1994 eruption of Rabaul, Papua New Guinea (credit: RJ Blong)



	Edifice	Gas & A.R.	Lahar	Lava	Projectiles	PDC	Tephra	Edifice	Gas & A.R.	Lahar	Lava	Projectiles	PDC	Tephra
Buildings	Presence		Dynamic pressure, Scour., Dep. thick.	Thickness, Temperature	Kinetic energy	Dynamic pressure	Static load	I	Tephra	Tephra	P	Tephra	EQs, Tephra	EQs, Gas & A.R., Projectiles, PDC
Electricity generation				Presence	Kinetic energy	N	N	P	I	I	I	P	I	I
Electricity trans. & distr.			Dynamic pressure, Scour., Dep. thick.	N		N	N	P		I	P		P	P
Water supply treatment		╱		Presence			╱		Tephra	I	I		I	Gas & A.R.
Water supply trans. & distr.				N		N	╱			I	I		P	P
Wastewater treatment				Presence			╱			I	I		P	P
Wastewater transmision				N			╱			I	I		P	P
Stormwater				N			╱				I		P	P
Roads & bridges			Dynamic pressure, Scour., Dep. thick.	Presence		N	N	P	P	P	P		P	P
Rail			N	Presence			N			I	I		P	P
Marine port			Deposit thickness, flooding	╱			╱			I	P		P	P
Airport				Presence		Deposit thick.	N			I	I		I	I
Telecommunication				Presence			╱			I	I		P	P
	↑↑ Hazard intensity metrics (HIMs) ↑↑							↑↑ Handling of multi-hazard impacts ↑↑						
	↓↓ Types of studies ↓↓							↓↓ Function availability ↓↓						
Buildings	GJ	LGJ	GEJ	GRJ	LGEJ	LGREJ	LGREJ	VDA	A	VFDTA	VDTA	FDTA	VFDTA	VFDTA
Electricity generation	J	J	GEJ	GJ	GJ	GJ	LGEJ			VDTA	DTA	A	DTA	FDTA
Electricity trans. & distr.	J		GJ	GJ	G	GJ	LGEJ			DTA	DTA	A	VDTA	FDTA
Water supply treatment		GEJ	GJ	J		J	GEJ		A	DTA	DT		DT	FDTA
Water supply trans. & distr.			GJ	LGJ	G	GJ	GEJ			DTA	DTA	A	DTA	VFDTA
Wastewater treatment			J	J		J	GJ			DT	DT		DTA	FDTA
Wastewater transmision			J	LJ		J	GEJ			DT	DT		DT	VDTA
Stormwater				L		J	GJ							TA
Roads & bridges	GJ	G	GEJ	GJ	G	GJ	LGEJ	A	A	VFDA	DTA	A	VDTA	VFDTA
Rail		G	GJ	GJ		J	GJ		A	DTA	DTA		DT	FDTA
Marine port			GEJ	GJ		J	GJ			DTA	A		DT	FDTA
Airport		G	GEJ	GJ		GJ	LGJ		A	DA	A		A	FDTA
Telecommunication			GEJ	J	G	GJ	GJ			DTA	DT	A	DTA	DTA

Quadrant key

HIM	Multi-hazard
Studies	Functions

Blank = no studies / data

HIM
- Listed *1 dominant HIM*
- Listed *2-3 dominant HIMs*
- N *Numeous/variable HIMs*
- ╱ *Other factors more important*

Types of studies
- L *Laboratory experiments*
- G *Observational (ground based)*
- R *Observational (remote sensing)*
- E *Analytical / engineering calculations*
- J *Expert judgement*

Handling of multi-haz. impacts
- Listed *Multi-hazard interaction with 1+ hazard(s)*
- P *Other hazards in parallel, interaction not studied*
- I *Hazard studied in isolation*

Function availability
- V *Vulnerability functions*
- F *Fragility functions*
- D *Damage states*
- T *Critical thresholds*
- A *Anecdotal*

Fig. 4 Summary across built environment type (rows) and hazard (columns) combinations of impacts considering four areas, (1) (top left quadrant; blue) dominance of one or a few hazard intensity metrics (HIM) in accounting for the impact consequence, (2) (bottom left quadrant; red) types of studies undertaken, (3) (top right quadrant; green) handling of multi-hazard impacts, and (4) (bottom right quadrant; purple) status of quantitative and qualitative function development. In hazards, "edifice" refers to edifice formation (for example, vent opening, cinder cone formation), while "A.R." stands for acid rain. Darker colors indicate greater dominance of a single HIM (HIM quadrant), more sophisticated treatment (multi-hazard quadrant), or more rigorous quantitative study (remainder). Empty cells reflect no study. For HIMs, if one (dark blue) or two to three (blue) HIMs account for the majority of impact, the HIM is listed. Light blue corresponds to several or variable HIMs required, and a slash indicates that other factors, such as network design, are more important. Types of studies include laboratory experiments (L), observations on ground (O) or by remote sensing (R), analytical /engineering studies (E), or studies reliant on expert judgment (J). For multi-hazard handling, dark green corresponds to studies that consider the compounding effects of hazard impacts (M). For example, such a study might examine how the impact changes depending on whether tephra fall occurs before or after ballistics; if compounding impacts are considered, the other concerned hazard(s) are listed. Also, in the multi-hazard quadrant, medium green corresponds to several hazards considered in parallel (P), reflecting the multi-hazard nature of volcanic eruptions, but without consideration of compounding and cascading effects of hazards and impacts. Light green indicates hazards have only been studied in isolation (I). Finally, for function development, dark purple indicates existing fragility (F) and/or vulnerability (V) functions, purple indicates critical thresholds (T) and/or damage state scales (D) are established, and light purple indicates only anecdotal (A) or qualitative data is available. A single study will often contribute to several quadrants and can contribute several designations within the bottom two quadrants. Built-environment systems are often complex and so require bespoke approaches to assessing volcanic impacts; an absence of vulnerability model in this figure does not necessarily imply lack of knowledge on this topic. The studies contributing to this analysis are indicated in Supplementary Information

reducing road network functionality (Blake et al. 2016; Magill et al. 2013). Controlled laboratory experiments have been invaluable for identifying and validating thresholds at which functionality loss occurs for various asset types (e.g., Blake et al. 2017b; Wardman et al. 2012b; Williams et al. 2017).

Asset damage can occur with minimal to high hazard intensity. Several studies have proposed hazard-specific damage state scales, used to categorize observed damage and to forecast future damage given exposure (e.g., Hayes et al. 2019; Jenkins et al. 2015; Williams et al. 2020; Wilson et al. 2014a). Much effort has focused on identifying suitable hazard intensity metrics for various built environment and hazard combinations. This is possible for some combinations (e.g., residential building damage is well described by tephra loading) but has poor success for others (e.g., wastewater treatment plant design is a stronger control on damage than any tephra HIM). Interestingly, recent work documents that pyroclastic density currents (PDCs) and lava flows—generally considered binary impact hazards—can cause partial but incomplete damage of a structure (Jenkins et al. 2017, 2013).

Asset destruction studies have mostly been concerned with tephra, lava flows, PDCs, and lahars. There is no single mechanism of destruction—volcanic hazards can destroy through burial, removal, incineration, and collapse, among others. Cataloguing post-eruption damage has been invaluable in informing pre-eruption impact assessments, e.g., through fragility functions. However, there has been limited work on engineered solutions to reduce the likelihood of asset damage destruction (Willingham 2005; Zuccaro and Leone 2012); more emphasis is placed on hazard avoidance and/or redesign of infrastructure networks (Sword-Daniels et al. 2011).

While most volcanic hazards can cause destruction of the built environment, in terms of **life-safety concerns** it is more likely that people are killed by the volcanic hazard (unlike for earthquakes where collapsed buildings can be an important cause of fatalities). Buildings can in some situations decrease the severity of projectile and PDC exposure, offering some (unreliable) protection to inhabitants (e.g., Fitzgerald et al. 2017; Jenkins et al. 2013; Williams et al. 2019). However, buildings can also offer a false sense of security or compel individuals to remain behind and protect assets in the face of a life-threatening hazard. Life-safety concerns can also arise from disruption to critical service provision for vulnerable persons or from clean-up activities, such as falls from roofs (Brown et al. 2017; Wardman et al. 2012a).

Opportunities

Figure 4 provides a visual gap analysis (lighter/empty cells) highlighting opportunities for further study. Tephra impacts across the built environment and building impacts across the various hazards are comparatively well studied, while gas/acid rain and proximal hazard impacts to critical infrastructure have had limited examination.

While great strides have been made in understanding the causes and ramifications of impacts to the built environment, this knowledge has limited applicability without detailed asset data—a usable inventory of buildings and critical infrastructure networks populated with relevant up-to-date information. Such databases are very difficult to obtain/maintain but are required to correctly identify the range of damage in a post-eruption assessment and, importantly, to support assessments *before* or *during* a crisis to identify likely impacts and inform mitigative solutions.

Further, volcanic eruptions are multi-hazard events that can last seconds through to decades: there has been nascent work on multi-hazard and dynamic interactions, or cascading and compounding impacts (Fig. 4). The spatio-temporal dynamism of exposure and vulnerability also remains an important, but underdeveloped, research area.

Each eruption with documented impacts improves our fundamental understanding of how volcanic eruptions affect the built environment. However, this knowledge has not yet been translated into regulatory codes or widespread policy adoption beyond land-use avoidance. It may be that such risk management is inappropriate or cost prohibitive for the built environment in volcanic settings, but it is an area for future exploration and transdisciplinary study.

Future directions

In the next decade, we anticipate the continuation of studies applying similar methods as described in Approaches, leading to more robust observational datasets and an enhanced understanding of the causes, ranges, and ramifications of impacts. Particularly, we expect validation, refinement, and/or calibration of the quantitative relationships between hazard intensity and impact.

In addition, we anticipate several important growth areas:

1. Expanded role of **big Earth data and data science** to fully exploit **satellite and UAV technologies; stakeholder, media, and crowdsourced data** for asset inventories; rapid hazard and damage mapping; and loss estimation.
2. **Higher spatial and temporal resolution modeling**, considering eruption narratives, multi-hazard interactions, cascading and compounding events, systemic response and dynamic changes in exposure and vulnerability.
3. **Transdisciplinary collaborations** exploring the role of engineering, policy, insurance, crisis management, and habitability considerations to improve the lived experience of volcanic eruptions in the context of the built environment.
4. Development of more **evidence-based mitigative solutions**, applicable in pre-, syn-, and post-eruptive settings.

The international volcanological community has a critical role in reducing the societal damage that can be caused by volcanic eruptions. As part of this role, we encourage consideration of a funded, rapid, international response team with a mandate to offer evidence-based information and support concerning the impacts of volcanic eruptions to the built environment.

The last 20 + years has been an era of remarkable growth in knowledge concerning impacts of volcanic eruptions on the built environment. We look forward to continued momentum and discoveries over the next decade and more.

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