Decision making under uncertainty during volcanic crises: the 2011 eruption of El Hierro, Canary Islands.

Rosa Sobradelo[1,2], Joan Martí[2], Christopher Kilburn[1] & Carmen López[3]

[1] Aon Benfield UCL Hazard Centre, UCL, Gower Street, London WC1E 6BT, UK (r.sobradelo@ucl.ac.uk).
[2] CSIC-Barcelona, Institute of Earth Sciences "Jaume Almera", Group of Volcanology, Spain.
[3] Observatorio Geofísico Central, Instituto Geográfico Nacional, Parque del Retiro, Madrid, Spain.

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1. Introduction

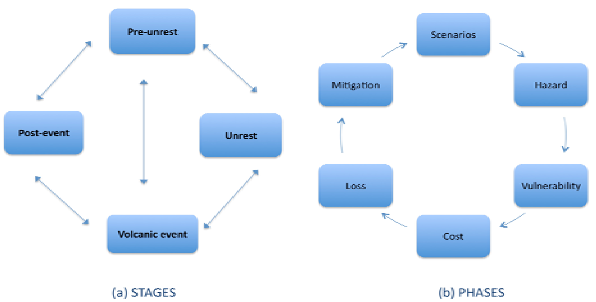
Understanding the potential evolution of a volcanic crisis and its impact are crucial for designing effective mitigation strategies. Here we present a new model BADEMO (Bayesian Decision Model) that applies an objective and flexible probabilistic approach to managing volcanic crises in real time, and apply it to the 2011 eruption of El Hierro, in the Canary Islands. The model quantifyies the uncertainty associated with specified mitigating actions as an emergency evolves, and serves as a mechanism for improving communications between scientists and decision makers.

Previous analyses of volcanic hazards have focussed on the event-tree approach, introduced by Newhall and Hoblitt (2002). These assess the probability of occurrence of an eruptive scenario. BADEMO goes a step further by combining these probabilities with evaluations of the associated vulnerability, potential loss and cost of mitigation.

2. The 2011 El Hierro eruption, Canary Islands, Spain

El Hierro is the most westerly of the Canary Islands (*below*). Following almost three months of unrest, a submarine eruption began on 10 October 2011 about two km south of the coastal town of La Restinga (Lopez et al, 2012). The eruption was the first on El Hierro for at least 200 years and the first in the Canary Islands for 40 years.

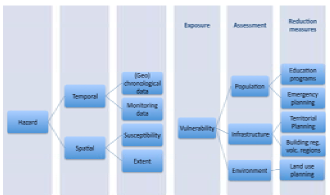
Owing to the long repose interval, local decision makers were unfamiliar with responding to a volcanic emergency. Unfamiliarity increased the subjective uncertainty in evaluating alternative mitigating strategies, notably whether to evacuate La Restinga, to halt fishing near the island, or to do nothing until additional information was obtained. The emergency has thus provided an ideal case for retrospectively testing BADEMO's capability for improving the objective analysis of emergency strategies.

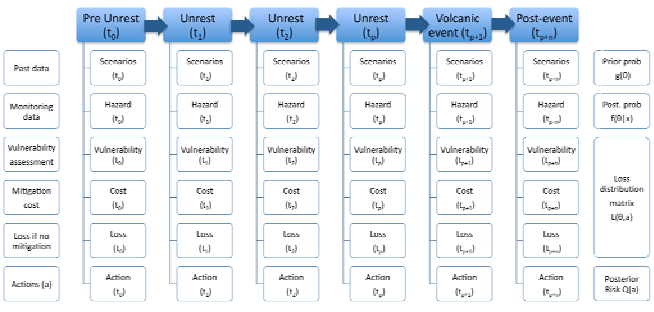


(a) STAGES (b) PHASES

(a) The effective management of a volcanic crisis analyses the conditions before and after an eruption, in addition to the volcanic unrest itself.

(b) The process of reaching a decision during an emergency can formally be divided into six phases grouped as: Scenarios (Deterministic), Hazard (Probabilistic) and Vulnerability, Cost, Loss and Mitigation (Informational).

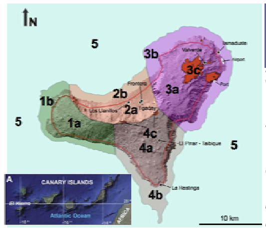




The key information for managing a volcanic crisis can be represented as an event tree. The trunk consists of stages that describe the approach to an eruption and subsequent recovery. Each stage acts as a node to support branches describing the components required to evaluate costs and benefits of potential mitigating actions.

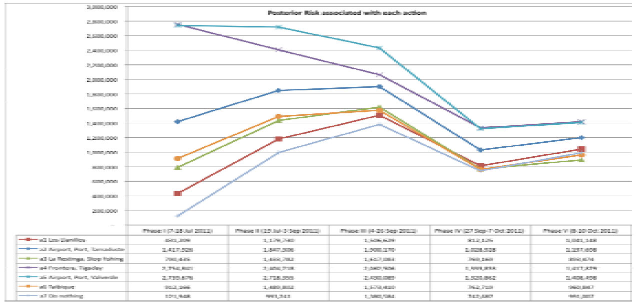
Bayesian Inference is used to compute the expected loss (or posterior risk), *Q(a)*, for each action, as the sum of the losses from different states of nature (scenarios) weighted by their probabilities of occurrence: $Q(a_k) = \Sigma\, L(\theta_i, a_k) \cdot f(\theta_i | x_{ij})$

The principal steps of BADEMO are:
(1) Identify the scenarios to be evaluated and their corresponding prior probabilities, g(θ).
(2) Using available data (e.g., from expert elicitation, existing models and monitoring data) estimate the conditional probability function, h(x|θ) and compute the posterior distribution f(θ|x).
(4) Define the loss distribution L(θ, a) associated with each action *a* and scenario, as a function of damage, indirect economic losses and vulnerability (e.g., population and infrastructure at risk).
(5) For each action calculate the expected loss *Q(a)*, with respect to the different scenarios.



Eruption scenarios and their probabilities at El Hierro. The eruptive products considered in Scenarios s1 to s8 are lava flows, ballistic ejecta, ash fallout and pyroclastic density currents.

Outcome	Scenario Zone	VEI	Prior HASSET	Posterior Probabilities Phase I (7-18/7 2011)	Phase II (19/7-3/9 2011)	Phase III (4-26/9 2011)	Phase IV (27/9-7/10 2011)	Phase V (8-10/10 2011)
Eruption <200m deep or near coast	s1 (SW-1b)	2, 3, 4	0.23	0	0	0.04	0.09	0
	s2 (NW-2b)	2, 3, 4	0.19	0.02	0.09	0	0	0
	s3 (NE-3b)	2, 3, 4	0.36	0	0	0	0	0
	s4 (S-4b)	2, 3, 4	0.15	0	0	0.09	0.34	0.57
Subaerial eruption	s5 (SW-1a)	2, 3	0.23	0	0.05	0.06	0.09	0
	s6 (NW-2a)	2, 3	0.19	0.02	0.19	0.21	0	0
	s7 (NE-3a)	2, 3	0.36	0	0	0	0	0
	s8 (S-4a)	2, 3	0.15	0	0.04	0.22	0.28	0.28
s9 Other (including submarine eruption >200m deep)			0.08	0.95	0.63	0.38	0.21	0.15



3. BADEMO applied to the 2011 emergency at El Hierro

BADEMO combines the hazard and risk factors that decision makers need for a holistic analysis of a volcanic crisis (*above left and centre*). The island was divided into five zones, based on the relative probability of a zone containing the location of a new vent and of being affected by an eruption in an another zone (*above right*). The potential cost of an eruption to each zone was estimated from a modified form of the cost-benefit analysis of Woo (2007). BADEMO was then applied to different episodes of the emergency, in order to identify the preferred mitigating strategies using only the information that had been available during each episode.

BADEMO quantified the losses expected from (a) taking no action, (b) evacuating Restinga and (c) halting fishing near El Hierro. The results showed that the cost of taking no action was consistently similar to or less than the costs of the alternative responses (*above right*). Options (b) and (c) were implemented during the emergency. In the end, the eruption had no direct impact on Restinga and so the option of "no action" preferred by BADEMO would have emerged as being the most cost-effective.

4. Conclusions

1. BADEMO provides objective criteria to identify response strategies with the lowest potential cost. The evaluation is dynamic and accommodates changes in (a) interpretations of unrest data and (b) local vulnerability (e.g., due to the movement of communities) as an emergency evolves.
2. BADEMO is particularly useful at volcanoes with long repose periods, where decision makers are unlikely to be familiar with the consequences of volcanic unrest and eruption.
3. BADEMO can be applied retrospectively to evaluate previous emergency responses and to identify opportunities for improving future strategies.
4. BADEMO presents the outcomes of different scenarios in a form that can readily be understood by decision makers unfamiliar with volcanic unrest.

References. Newhall CG, Hoblitt RP (2002) Bull Volcanol 64:3-20. López C, et al. (2012) Geophys Res Lett 39: DOI: 10.1029/2012GL051846.
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Aon Benfield UCL Hazard Centre

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