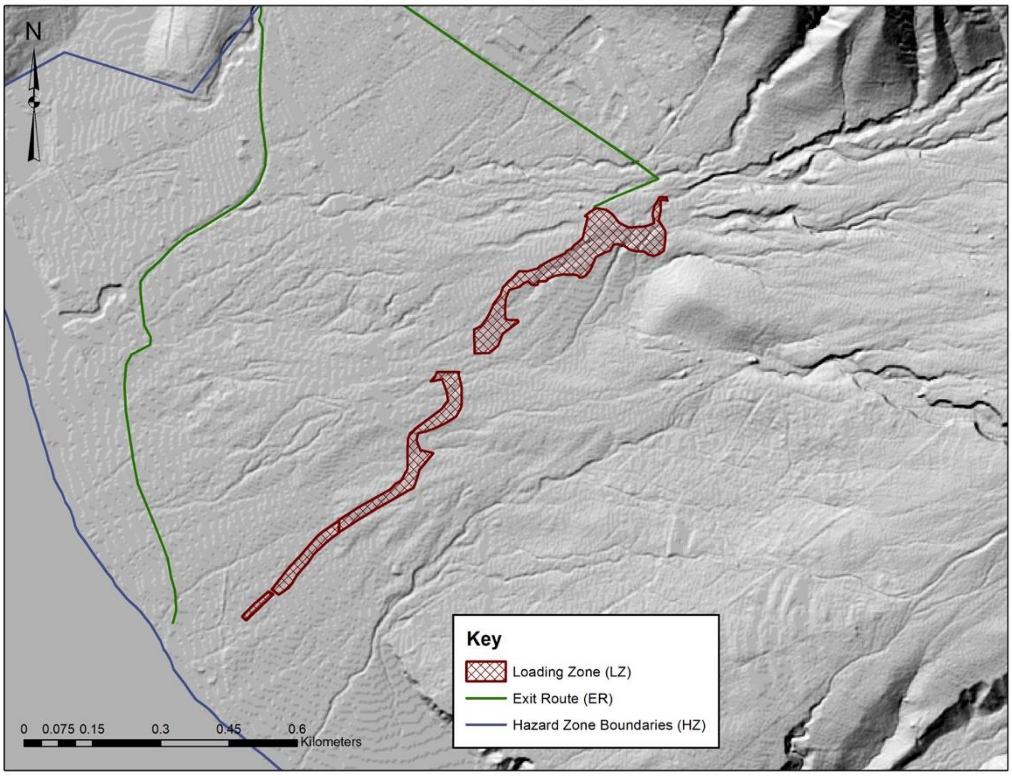
Site Specific Risk Assessment for Fort Ghaut, Plymouth area of the Soufrière Hills Volcano, Montserrat July 2020



Site map for proposed sand mining operations in Fort Ghaut, Plymouth used in the risk assessment

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Summary

A site-specific risk assessment has been undertaken for Sand Mining Operations in the Fort Ghaut, Plymouth area currently located within Zone V. This risk assessment is based on 1) the current (July 2020) hazard level, 2) best-available hazard data for pyroclastic flow and lahar hazards to this area, 3) exposure information provided by Government of Montserrat, and 4) an assumption of operations continuing for a one-year period. For both pyroclastic flows and lahar we determine the probability of inundation using a combination of historical observational data from Montserrat, flow simulations and statistical approaches.

The probability of the proposed site being impacted by lahar hazard (of at least moderate size) in the next one year is found to be close to 1.0 (i.e. ~100% likelihood). Risk to life from lahar hazards is calculated on the assumption that an event would be seen and recognised by persons on the ground and that appropriate action would and could be taken to self-evacuate from the flow path. For an individual working 56 hours per week at the site, the risk of fatality from such an event in the one-year period is found to be 0.00796 (~8 in a 1,000 chance) with a range from 0.0001 to 0.09547783 (i.e. 1 in a 10,000 to ~1 in 10 chance).

The probability of the proposed site being impacted by a pyroclastic flow in the next one year is found to be 0.0002-0.0012 (I.e. 1 in a 5,000 to 1 in 850 chance). Risk to life is calculated on the basis that a flow could feasibly occur with insufficient warning to allow for evacuation to a safe location, *and* that pyroclastic flows in the great majority of cases are lethal. For an individual, working 56 hours per week at the site, the risk of fatality from such an event in the one-year period is found to be in the range 0.000067 - 0.0004.

Background

1. Sand mining has been undertaken in the Lower Belham Valley of the Soufrière Hills Volcano (SHV) since 2010. At present, there are four companies undertaking sand mining in this area and over time this has resulted in depletion of the Lower Belham Valley sand resource. There is now a proposal to expand the areas available for sand extraction into a) Upper Belham Valley and b) Fort Ghaut in the vicinity of Plymouth, both of these sites are located within the current Zone V. The risk assessment for Upper Belham Valley has already been published (MVO Open File Report 20-03; Miller and Calder, 2020).
2. On 21 May 2020, a request was made to the Montserrat Volcano Observatory (MVO) from the Montserrat Land Development Agency (MLDA, on behalf of the Ministry of Agriculture) to undertake a quantitative assessment of volcanic risk to workers involved in sand mining in a specific area in the Fort Ghaut, Plymouth area within Zone V (see Figure 1). The locations of the proposed Loading Zone (LZ), and Exit Route (ER) were provided by the Montserrat Land Development Agency (MLDA).
3. MVO in collaboration with the Scientific Advisory Committee (SAC), is currently in the process of developing a new volcanic hazard assessment for the entire Zone V (a microzonation hazard map) which will consider multiple volcanic hazards. Whilst this hazard assessment is still ongoing, it is possible to use elements of the updated hazard assessment as data inputs for the current site-specific / activity-specific risk assessment undertaken here.

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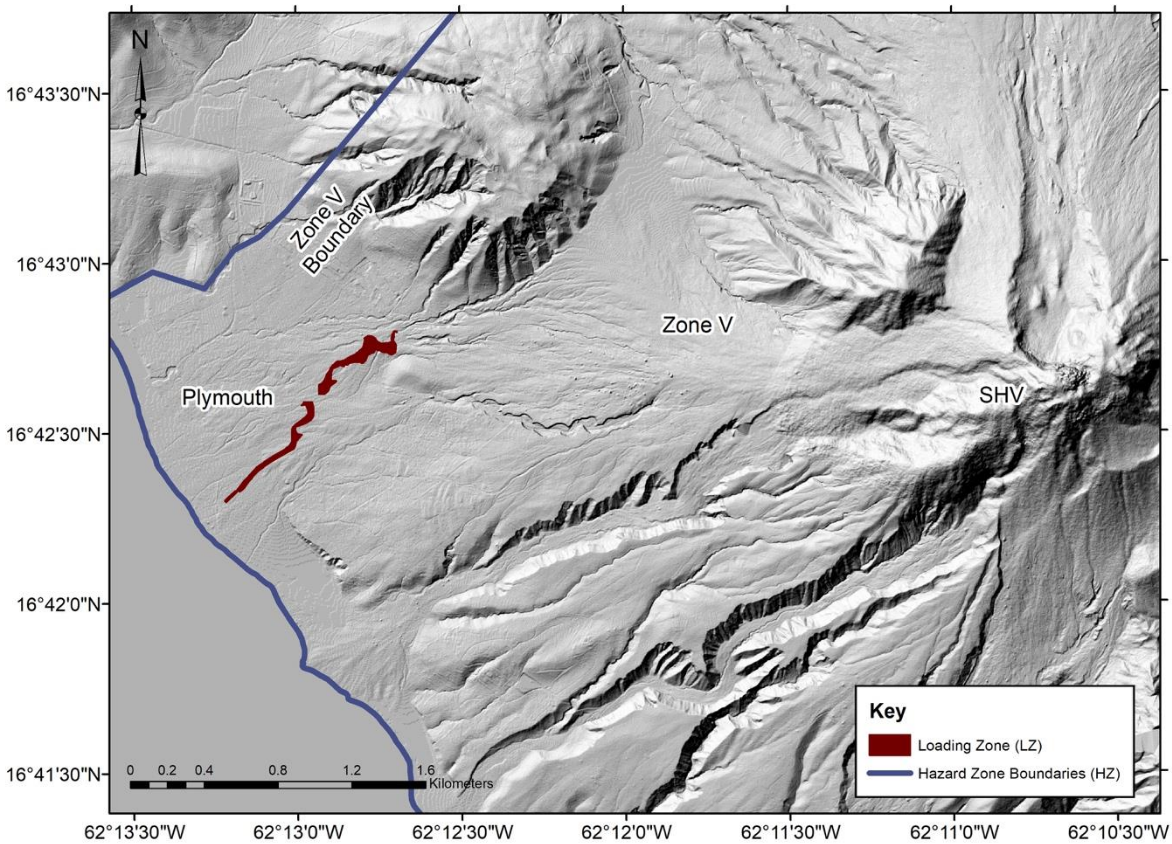
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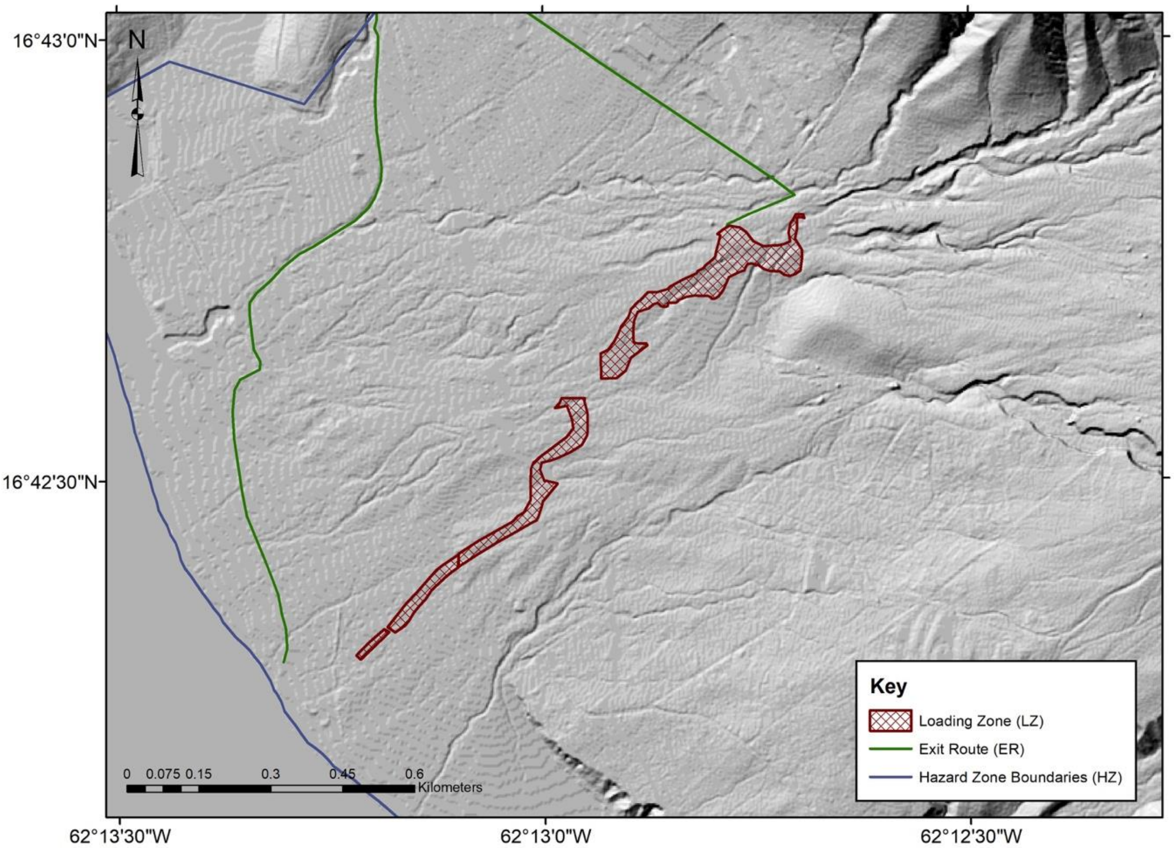
Loading Zone (LZ)
Hazard Zone Boundaries (HZ)

b)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Kilometers
Key
Loading Zone (LZ)
Exit Route (ER)
Hazard Zone Boundaries (HZ)

Figure 1: Location of proposed sand mining operations in the Fort Ghaut area used in the risk assessment a) location of the proposed site (Loading Zone; LZ) in relation to the Soufrière Hills Volcano (SHV) and within the Plymouth area, b) detailed view of the site. Loading Zone (LZ) coordinates (showing upper and lower portions), and Exit Route (ER) locations were provided by the Montserrat Land Development Authority (MLDA) of Government of Montserrat.

Conditions for the Risk Assessment

4. It is important to stress that the risk assessment presented here is undertaken specifically for the current level of volcanic activity, i.e. low-level volcanic activity (Hazard Level One), associated with the current pause in eruptive activity. In the event of a change in volcanic activity level, such as a re-start in the eruption, lava extrusion, gas venting or an explosive event, the outcomes of this risk assessment will no longer be valid.
5. This risk assessment considers hazards from pyroclastic flows and lahars, the most frequent and life-threatening volcanic hazards associated with the Fort Ghaut area. As it stands it explicitly does not consider other volcanic hazards related to ballistic projectiles (bombs) from explosive eruptions of the volcano, tephra (ash and lapilli fall), or gas hazards. The risk assessment also does not include environmental or man-made risk or any other kind of risk other than those explicitly stated.
6. This risk assessment is based on conditions of little or no warning of pyroclastic flows or lahars occurring. i.e. it is based on no provision of early warning or risk mitigation strategies by MVO or other bodies. We take this approach because currently there is no capacity for lahar early warning and we consider (conservatively), that pyroclastic flows from lava dome collapse could feasibly occur with no detectable precursory activity.
7. This risk assessment is undertaken on the basis of information about the working operations as provided to MVO from MLDA via the 'Data requirements for site specific risk assessment form' (Appendix 1). The outcomes only pertain to risk associated with exposure of personnel, not damage to or loss of equipment or machinery used in the operations. In the event of a change in the exposure level of workers i.e. change in number of workers involved, duration within the loading zone or access routes, or activities, the outcomes of this risk assessment will no longer be valid and there would need to be a re-assessment of the risk. The risk assessment is undertaken for a one-year period based on volume and extraction rate estimates, see paragraph 29. We also include values for a five-year risk assessment period in order to facilitate comparison with the risk assessment undertaken for the Upper Belham Valley (MVO Open File Report 20-03; Miller and Calder, 2020). It should be noted however that the exposure values for the Upper Belham Valley are different to those in this risk assessment.
8. Once the MVO in collaboration with the SAC, has completed the new volcanic hazard assessment for Zone V (the microzonation hazard map), we recommend a revision of this risk assessment should be undertaken, as we will be in a position to include assessments from other associated hazards including that related to ballistic projectiles.

Volcanic Hazards relevant to the Fort Ghaut area

9. The main volcanic hazards of relevance to the site include: 1) pyroclastic flows and associated ash cloud surges from lava dome collapse; 2) lahars (mostly rain-triggered mudflows); 3) pyroclastic flows and associated ash cloud surges from eruption column

collapse during explosive eruptions; 4) tephra fall from explosive eruptions (including the fallout of ash, pumice and small dense lithic fragments); 5) ballistic projectiles from explosive eruptions; and 6) volcanic gases.

10. For the purpose of this risk assessment only hazards from pyroclastic flows (lava dome collapse) and lahars are considered. These are considered to be the two principal life-threatening volcanic hazards that could impact the Fort Ghaut area. While currently, the activity at the volcano is low, the volcano is still a potential source of these hazards. Although the likelihood of such events occurring is low, both pyroclastic flows from lava dome collapse and lahars could feasibly occur, and they could do so with little or no warning.
11. The conditions and mechanisms for pyroclastic flow generation are different now to those during the eruptive period. During periods of active dome extrusion, the first order control for pyroclastic flow generation is lava extrusion and associated dome instability. In the absence of dome growth, during pauses, or post-eruptions, other mechanisms come into play. Lava domes can collapse years, decades or millennia, after volcanic activity is over, due to intense rainfall, seismic activity, and/or weakening by hydrothermal activity and developing structural instabilities as the dome cool. Therefore, pyroclastic flows could still feasibly occur at any time, with little or no warning, posing a threat to people working in, or visiting, Zone V.
12. Pyroclastic flows descend the flanks of volcanoes at high velocity. They commonly travel at speeds of 10-60m/s and can inundate wide areas. As such, people working at the site, would only have tens of seconds to move out of the way of a pyroclastic flow if one were to occur with no warning, and assuming that they could see that a flow event had initiated from the summit of the volcano. As the volcano is often shrouded in cloud, clear site of activity at the summit, should not be assumed. To evacuate from a pyroclastic flow, workers would need to remove themselves from the Plymouth area entirely and/or evacuate from zone V (several hundred meters to a few km), which is unlikely to be feasible in the short lead-time that would be available.
13. Lahars triggered by intense or prolonged rainfall can remobilise previously deposited volcanic material long after eruptions have ceased. The large dome collapse event in February 2010 generated a pyroclastic deposit fan that continues to be gradually incorporated into lahars during rainfall events. Depending on the level of water saturation of the ground, lahars can develop quite quickly during a period of intense rainfall. Particular caution should be observed during the rainy season, though such events can occur at any time during the year.
14. Lahars are high velocity water-based flows. They travel at speeds of approximately 5-30m/s. Commonly, people are alerted to lahars by hearing them approaching or seeing their initial phases in the drainage channel. As such, people working at the site, would only have tens of seconds to move out of the way of a lahar flow if an event were to occur with no warning. In the upper reaches above Plymouth, lahars are only likely to inundate the central channel area, and therefore effective evacuation might involve moving only a few 10’s metres away. It should be noted that previous work on lahar at SHV has for the most part been focused on the Belham Valley, the nature of lahar hazard in the Fort Ghaut, Plymouth area is less well understood and so we use the Belham Valley as a proxy to supplement this information.
15. Although feasible, we consider it unlikely that either a pyroclastic flow, or a lahar would occur in the Fort Ghaut area with little or no warning. MVO monitors volcanic

activity 24/7 and staff are always present in the operations room if people have entered Zone V using authorised channels. We consider it likely that MVO would recognise precursory activity that could indicate volcanic activity, including pyroclastic flows might occur. Lahars occur when there is heavy rainfall or there has been a prolonged period of increased rainfall in a source region (often on the higher topographic areas). Lahars triggered in upper reaches can impact lower areas that have not experienced rain directly. We do note however that at this time MVO does not operate real-time monitoring of rainfall or lahar event triggering in order to provide lahar warnings. These warning signs and the processes to recognize them, whether personal or institutional, would provide some means to risk mitigation, that would work to reduce the risk to life as determined by this assessment. However, these cannot be quantified, and as such this risk assessment does not directly take them into account. We note that a range of risk mitigation strategies could be put into place to reduce risk, including (but not limited to) those outlined in the proposed safety plan, and that this should be fully explored through discussion with MVO, DMCA and any institution / company with responsibility for activities in this area, refer to paragraph 39.

16. If impacted directly, pyroclastic flows are commonly lethal to human life. For the purpose of this assessment, we consider that the probability that pyroclastic flow will be lethal to those exposed (severity factor), is equal to 1.0. Implicit in this severity factor is that the immediate efforts of those exposed to evacuate, under conditions of no warning, are unlikely to allow enough time to exit the impact zone.
17. If impacted directly by a lahar the chances of survival can be significantly better than for pyroclastic flows, although globally they are still one of the largest causes of death around volcanoes. Lahars in valleys are also typically more laterally constrained and may therefore be easier to escape from. From a global perspective the probability that lahar will be lethal to those exposed (severity factor) has been estimated to be in the range 0.1 to 1.0 if those exposed are caught unaware (Newhall, 1982). However, we note that lahars on Montserrat are modest in size and extent, and that most lahar flows that have been examined in detail (those located in the Belham Valley) are considered of low-concentration. For the purpose of this assessment, we undertook an expert elicitation in order to obtain a more appropriate severity factor for the particular conditions of lahars in Montserrat. As such, for lahar hazard in the Fort Ghaut area of Montserrat the severity factor is estimated at 0.00833 (~8 in a thousand chance), with the range of uncertainty from 0.0001 – 0.1. These values represent the probability that a lahar on Montserrat would be lethal, and they also implicitly incorporate the likelihood that a person has the ability to see and recognise an event, and could take appropriate action to move out of the way of the lahar. This estimate does not include any early warnings that could be given by MVO, or any mitigation strategies that could be employed at the company or institutional level, such as choosing not to work in rainy conditions.

Lahar Hazard Information

18. The MVO lahar database covers the ten-year period since the last major dome collapse at SHV, 17 January 2010 to 31 March 2020 (MVO Open File Report 20-02; James and Miller, 2020). It includes all the lahar events that have been recorded by MVO. The recording and recognition of events is contingent on visual or seismic observations

and is therefore biased depending on site accessibility and seismic network distribution. It should be noted therefore, that this database represents a minimum number of events during this time period and that in particular there have likely been many more smaller volume events that are not identified on the seismic records.

19. The magnitude (volume) of individual lahars can be estimated from the seismic signal durations. The volumes are calculated using flow rates in the Belham valley during the period 2001-2004 (Barclay et al., 2007) using the formula V = t x Q, where V=Volume, t=Time, Q=Discharge rate. The flow rate is dependent on the channel type, with flow rates in the rage of 15 – 45 m^3/s for braided, multi-channel flows and flow rates in the rage of 60-90 m^3/s for the largest, single channel, valley filling events (which are uncommon). Given the uncertainty in channel type for events in the database, volumes are calculated using minimum (15 m^3/s), average (30 m^3/s), and maximum values (45 m^3/s).
20. Three categories of lahar events for Montserrat are identified i) Minor: 0-30,000 m^3 – short, flash events that are confined to channels, but could almost reach the sea in this area; ii) Moderate: 30,001-100,000 m^3 – events that would generally extend down to the sea iii) Major: 100,001 m^3 and above – events that are likely to be more widespread and will extend to the sea.
21. Lahar hazard footprints are calculated using the computational modelling tool LAHARZ (Schilling, 1998), the most widely used tool for understanding potential lahar inundation zones. Three, nested, lahar hazard footprint have been determined using the upper limit volumes from each of the three size categories of lahar (Figure 2). Note that LAHARZ uses a simplified model for lahar flow that does not consider how individual volumes, flow rates and sediment content fluctuate as the lahar moves downstream and as such these footprints should be considered a guide rather than a prediction of spatial distribution of lahar inundation. Furthermore, this assessment has been undertaken using the DEM from 2010 (MVO Open File Report 15-01; Stinton, 2015) and changes in topography that have occurred since this time will not be accounted for in the flow modelling and resulting footprints.
22. The probabilities of occurrence of lahar events for the one-year period of assessment are based upon recurrence rate estimates for each lahar size category as captured in the lahar database. These recurrence rates are therefore contingent on the level of completeness and caveats as noted above (see paragraph 18). The probabilities used for this risk assessment consider only moderate and major category events, due to clear underreporting of the smallest magnitude events. Further details on the lahar database, probabilities and modelling can be found in MVO Open File Report 20-02 (James and Miller, 2020).
23. The hazard assessment indicates that the probabilities of inundation by lahar flow in the parts of the LZ over the next one-year period is approximately equal to one (see Tables 1, 2). However, from the modelled lahar inundation areas (Figure 2) we note that for the most part this hazard is restricted to the upper portion of the LZ. Only a small area of the lower portion of the LZ overlaps with the possible lahar inundation area, as the two channels either side would direct the flow. It should be noted that the southern portion of the LZ, whilst for the most part is out of the predicted inundation zone, has a location which is set between two possible lahar channel routes, such that an event could isolate this area, making evacuation out of the area via land impossible and stranding workers.

Lahar Category	*Volume Range (m^3)*	*Recurrence Rate in Five (5) years (average volume)*	*Probability of Occurrence in Five (5) years †*	*Probability of Occurrence in One (1) year †*	*Number of Events Per Year*	*Average recurrence rate of average volume event (days)*
*Minor	0-30,000	4.94	0.99	0.63	0.99	369
Moderate	30,001 – 100,000	33.10	1.00	1.00	6.62	55
Major	100,001 +	13.34	1.00	0.93	2.67	137

Table 1: Likelihood of lahar inundation at the Loading Zone (LZ) for three categories of event
N.B. Largest event in the database (18/04/2010) has an estimated average volume of 648,000 m^3 and an estimated maximum volume of 972,000 m^3

* Number of minor category events is a significant underestimate (estimated at ~13% of actual events) due to the sensitivity threshold of event detection using the seismic network. For the purposes of the risk assessment we consider events of Moderate and Major categories only. Furthermore, small events are not likely to be life-threatening.

†Probabilities here are rounded to two decimal places; probabilities cannot be equal to 1, but in this instance, they are so close to 1 that they can be considered as 1.

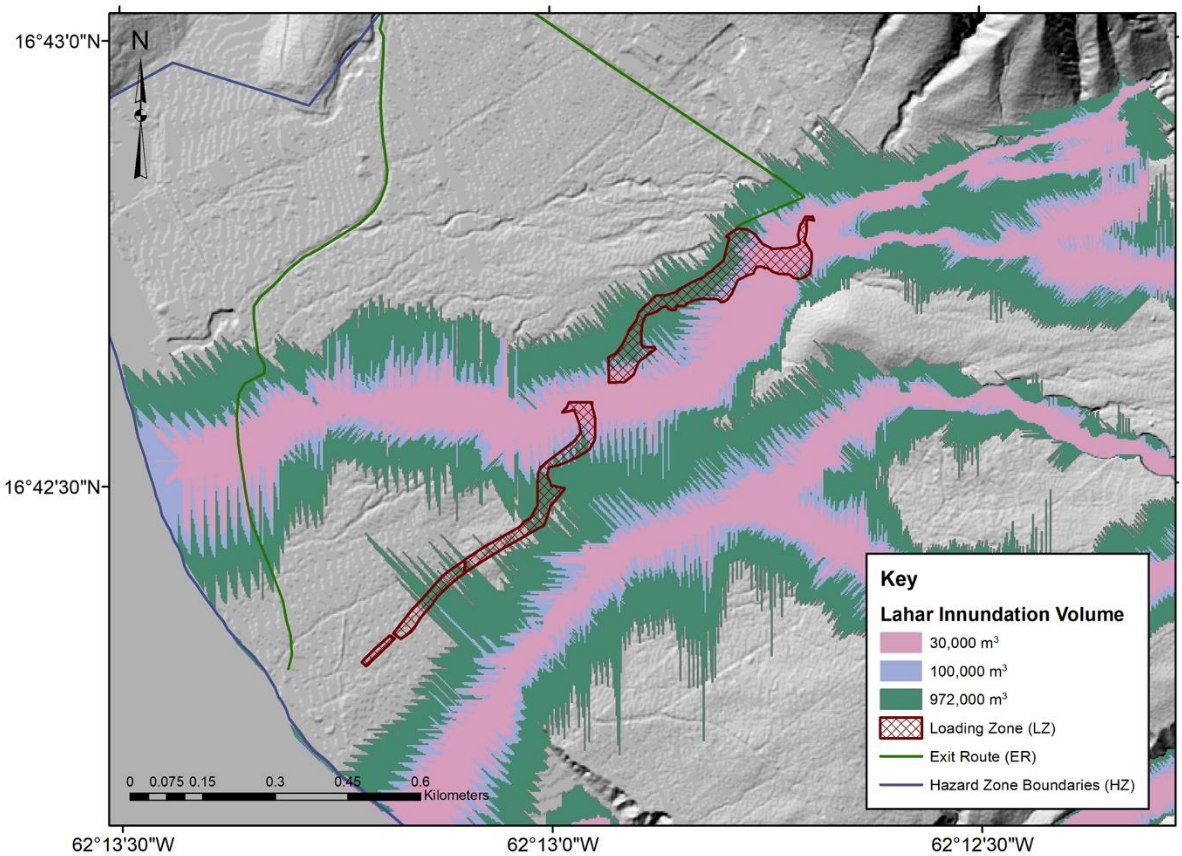


Figure 2: Potential lahar inundation areas in the Fort Ghaut, Plymouth area. The lahar hazard footprints are calculated using the computational modelling tool LAHARZ (Schilling, 1998) using the upper limit volumes from each category of lahar. Loading Zone (LZ) coordinates, and Exit Route (ER)

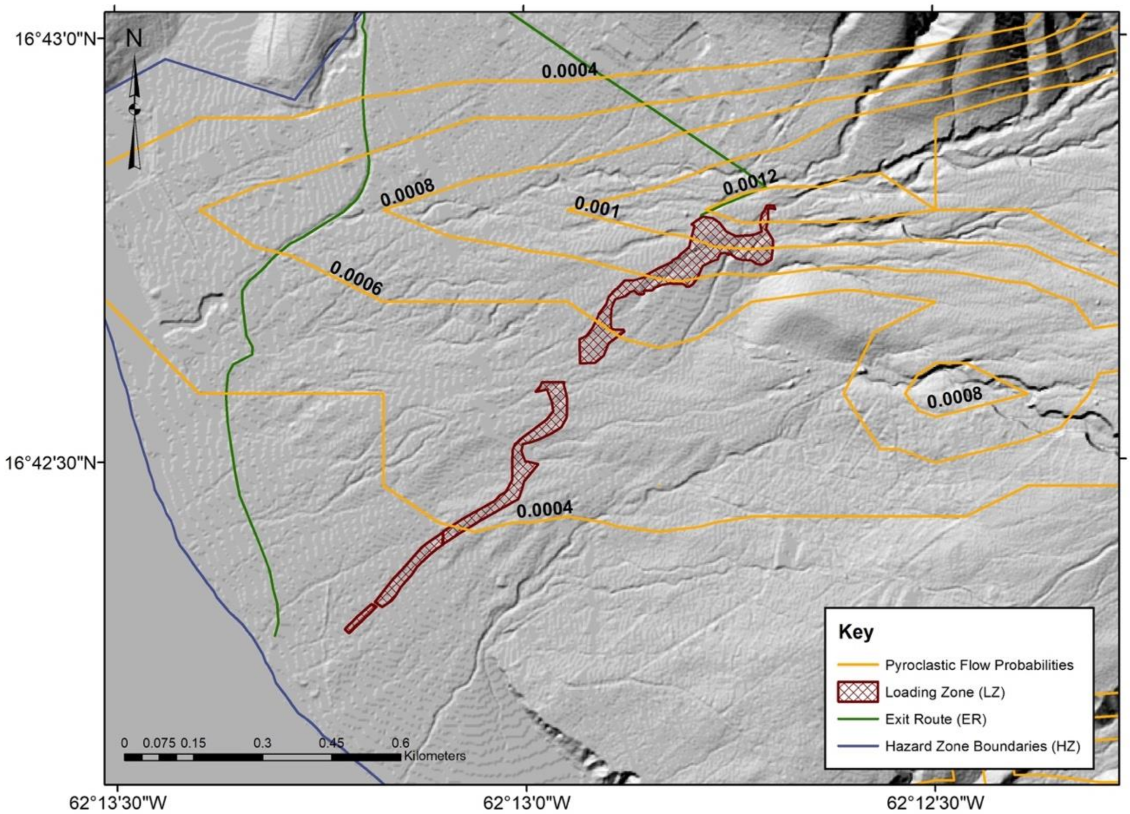
locations were provided by the Montserrat Land Development Authority (MLDA) of Government of Montserrat.

Pyroclastic Flow Hazard Information

24. Since the first pyroclastic flow generated in March 1996 there have been more than 900 events recorded with runout distances over 1 km. Most of these were the result of lava dome collapse events, but some events were generated by eruption column collapse associated with explosive events.
25. The last phase of dome growth ended on 11 February 2010 after an explosion removed about 20% of the dome. Sporadic, small dome collapse pyroclastic flows and rockfalls generated by degradation of the remaining dome and crater area occurred until 2013, and have subsequently phased out almost entirely. No pyroclastic flows have been recorded in the quiescent period from 2013–2020. However, the large lava dome remaining at the summit presents a continued threat from dome-collapse hazard. Indeed, collapses of lava domes are known to occur years, decades or millennia, post-eruption and are therefore a plausible hazard scenario, whose risks must be taken into account.
26. We use a probabilistic hazard assessment for pyroclastic flows for SHV which has been recently undertaken by Calder and collaborators (Spiller et al., 2020, In press). That work presents a new probabilistic approach for forecasting pyroclastic density currents from lava dome collapse that takes into account lava dome eruption durations, as well as extended periods of relative quiescence. The approach was specifically developed for, and tuned to, the current situation at the SHV and utilizes the existing database of historical pyroclastic flow events at SHV. The hazard analysis considers probabilistic scenarios for flow volume and initial direction, and can determine probabilities of inundation for different forecast windows of interest. The statistical forecasting model developed is based on considering a very low-frequency background level of activity that is balanced with the chance that activity has already completely ceased or will cease at some point in the future. The statistical model is then combined with a simulation-based strategy to assess the impact of pyroclastic flows on a specific area of interest from flows corresponding to different scenarios (e.g., flow volume, initial direction). The spatial distribution of the pyroclastic flow inundation areas are modelled using flow simulations undertaken in TITAN2D (Patra et al., 2005) and by combining 1000s of scenario simulations.
27. The outcome of the work presented in Spiller at al., 2020 is the development of a probabilistic hazard map for pyroclastic flow inundation over the next one-year and five-year periods which represents a defensible, evidence-based approach to pyroclastic flow forecasting during this period of post-eruption unrest. The hazard assessment indicates that the probabilities of inundation by pyroclastic flow for the entire LZ over the next one-year period is in the range 0.0002 to 0.0012 (see Figure 3a). We note that for this one-year timeframe the lower portion of the LZ falls entirely in the 0.0002 to 0.0004 range, whereas the upper portion has a range from 0.0004 up to 0.0012, with only a very small region sitting in the 0.0012 range. For the five-year period the hazard assessment indicates that the probabilities of inundation by pyroclastic flow in the LZ is in the range 0.001 to 0.004 (see Figure 3b). In this instance we note that the majority of the lower portion of the LZ falls into the zone delineated by the 0.001 contour, whereas the upper portion falls within the 0.002 – 0.003 contour

range with only a small portion sitting within the 0.004 contour. Further details on the pyroclastic flow statistical analysis and modelling can be found in Spiller et al., 2020 (In press).

a)



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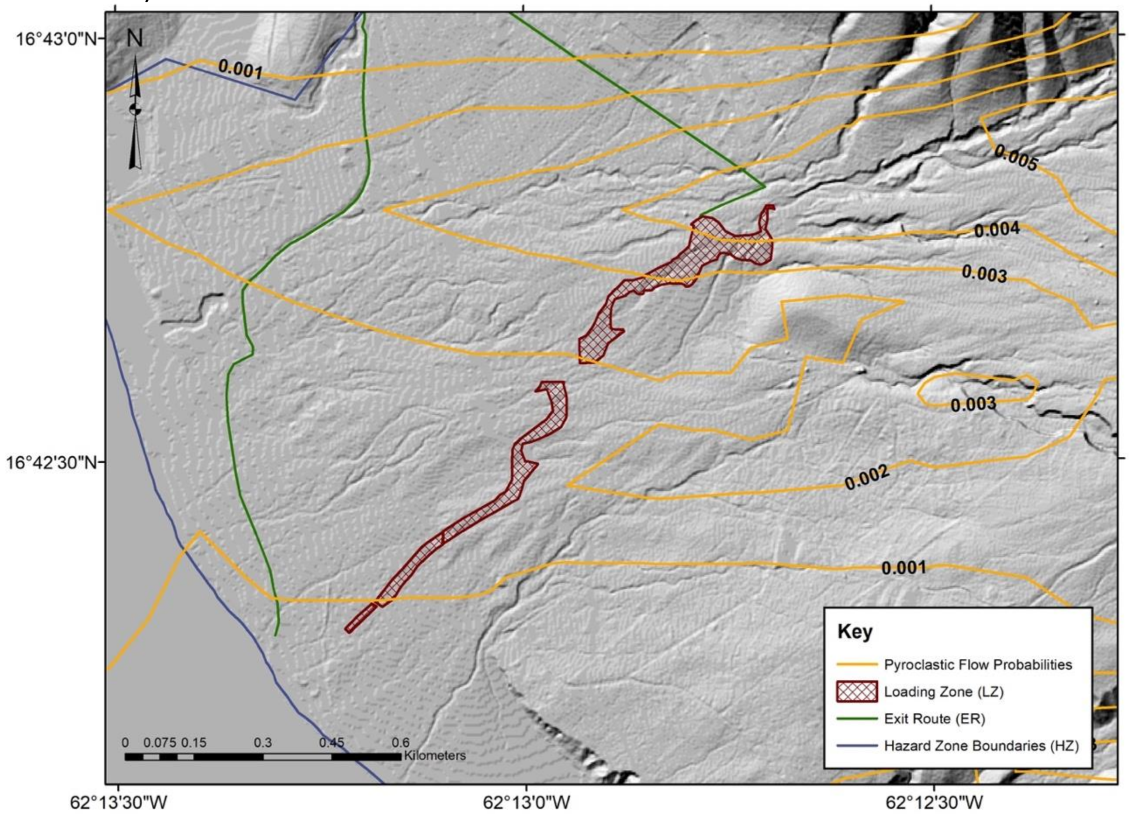

Figure 3: Probabilities of pyroclastic flow impact areas in the Fort Ghaut, Plymouth area for a) a one-year timeframe and b) a five-year timeframe. The spatial distributions are modelled by combining flow simulations undertaken in TITAN2D (Patra et al., 2005) with the statistical analysis of historical events. Loading Zone (LZ) coordinates, and Exit Route (ER) locations were provided by the Montserrat Land Development Authority (MLDA) of Government of Montserrat.

Operational Activity Information (Personnel Exposure)

28. The number/type of exposed elements (personnel only) provided by MLDA along with approximate timeframes are provided in Table 2. Exposure information used in the risk assessment to include:

Exposure Category (personnel)	*Number of People in Category*	*Number of Days Per Week*	*Number of Hours Per Day*	*Number of People Hours Per Week*
Fixed Loaders	4	7	8	224
Truck Drivers	10	7	8	560
Safety Officer	2	7	8	112

Table 2: Categories of exposed personnel in the LZ for mining operations. N.B. We assume a maximum of 56 hours per week that a person is in the LZ. Working on the assumption of zero tolerance for fatality we take this maximum level of exposure into account for the purposes of the risk calculations.

Timeframe of Risk Assessment

29. An estimation of the time needed (in years) to complete mining at the proposed site was determined based upon estimated volume of potential source material in the LZ and the historic mining rates. This timeframe is relevant, because the risk to life estimates need to be undertaken for specific time windows.
30. The MVO estimates that there is approximately 445,700 m^3 of potential source material in the area defined as LZ (~341,200 m^3 in the upper portion and ~104,500 m^3 in the lower portion). This maximum potential volume is based on determining the differential volume between the digital elevation model (DEM) of 1995 and that of 2010 – i.e. the pyroclastic material accumulated in the LZ between those years (this assumes that all the material present is potential source for sand mining).
31. An estimation of the time needed to extract this volume is based upon tonnage of sand from previous exports in the last 10 years from the Lower Belham Valley, obtained from the Montserrat Port Authority, an assumed density of the sand of 1.5-1.8 g/cm^3 and a rate of extraction based on recorded export dates. Using a ten (10) year average we calculate 3.5 to 4.2 years to complete extraction of the entire LZ; taking the most recent year exports (which is the highest), we calculate 1.7 to 2.0 years to complete extraction of the entire LZ.

Risk to Life for Workers in the Loading Zone from Lahar Hazard

32. Based on the SHV lahar database, and considering only events of moderate or major category, we estimate 9.29 lahar events occur in an average one-year period and 46.44 lahar events occur in an average five-year period. Such events are relatively

frequent at the SHV, with this average of 9.29 events occurring per year, the probability of one or more events of moderate or major category occurring in the next one-year period is very close to one i.e. essentially 100% likelihood of occurrence. More details on determination of the lahar recurrence rates, can be found in MVO Open File Report 20-02 (James and Miller, 2020).

33. If a person is located within the lahar inundation region (Figure 2) when such an event occurs, we make the assumption for the purpose of this assessment that the probability that the event will be lethal (i.e. the severity factor), is approximately 0.00833 with a range from 0.0001 to 0.1. Implicit in this severity factor is that a person is able to recognise and move out of the path of the hazard quickly enough to avoid exposure as well as the direct life-threatening physical impacts.
34. For an individual who is working in the LZ for 56 hours per week (out of 168 total hours per week) they are potentially exposed for ~33% of their total hours per week. If someone were to be located in the LZ 24x7 over a one-year period we estimate that they would be potentially exposed to 9.29 moderate or major lahar. For a worker that is exposed only during a period of 56 working hours per week we estimate that over a one-year period they would be potentially exposed to 3.1 lahar. Using the value of 3.1 moderate or major lahar occurring in a one-year period gives a probability of being exposed to at least one lahar in the one-year timeframe of 0.9547783. For an individual working 56 hours per week in the LZ for a period of one year, the risk to life due to lahar hazard is therefore calculated as 0.00796 with a range from 0.0001 to 0.09547783. By comparison, over a five-year period we estimate that being located in the LZ for 24x7 they would potentially be exposed to 46.44 moderate or major lahar. Therefore, for a worker that is exposed only during a period of 56 working hours per week over a five-year period we estimate that they would be potentially exposed to 15.5 lahar. Using the value of 15.5 moderate or major lahar occurring in a five-year period gives a probability of being exposed to at least one lahar in the five-year timeframe of 0.9999998 (close to 1). For a period of 5 years, the risk to life due to lahar hazard is therefore calculated as 0.00833 with a range from 0.0001 to 0.09999998 (Table 3).

Exposure Category (Personnel)	Number of People in Category (exposure)	Number of Hours Per Week per individual (exposure)	Probability of lahar hazard impacting the LZ (five year)	Probability of lahar hazard impacting the LZ (one year)	Probability of being exposed to at least one lahar during working hours (five year)	Probability of being exposed to at least one lahar during working hours (one year)	Probability of fatality if impacted (severity factor)	Individual Risk to Life (Probability of Fatality) Due to Lahar Flow hazard (five year)	Individual Risk to Life (Probability of Fatality) Due to Lahar Flow hazard (one year)
Fixed Loaders	4	56	1.000	0.9999075	0.9999998	0.9547783	0.00833 (0.0001 – 0.1)	0.00833 (0.0001 - 0.09999998)	0.00796 (0.0001- 0.09547783)
Truck Drivers	10	56	1.000	0.9999075	0.9999998	0.9547783	0.00833 (0.0001 – 0.1)	0.00833 (0.0001 - 0.09999998)	0.00796 (0.0001- 0.09547783)
Safety Officer	2	56	1.000	0.9999075	0.9999998	0.9547783	0.00833 (0.0001 – 0.1)	0.00833 (0.0001 - 0.09999998)	0.00796 (0.0001- 0.09547783)

Table 3: Estimated probability of fatality due to lahar hazard for workers in the LZ during the one-year and five-year timeframes.

Risk to Life for Workers in the Loading Zone from Pyroclastic Flow Hazard

35. At SHV, based upon the combined statistical and flow modelling approaches developed in Spiller et al, (In press), the probability of a pyroclastic flow impacting the site in the next one-year period is in the range 0.0002-0.0012 and for the next five-year period is in the range 0.001-0.004.
36. If a person is located within the pyroclastic flow inundation region (Figure 3) when such an event occurs, we make the reasonable assumption that the probability that the event will be lethal (i.e. the severity factor), is equal to one. Implicit in this severity factor is both the likely inability to move out of the path of the pyroclastic flow quickly enough to avoid exposure as well as the direct life-threatening physical impacts.
37. For an individual who is working in the LZ for 56 hours per week (out of a total of 168 hours per week) workers are only exposed for ~33% of their total hours per week. For an individual working 56 hours per week in the LZ for a period of one year, the risk to life due to pyroclastic flow hazard is therefore calculated as ranging from 0.000067 to 0.0004. For a period of five years, the risk to life due to pyroclastic flow hazard is calculated as ranging from 0.000333 to 0.001333 (Table 4).

Exposure Category (Personnel)	Number of People in Category (exposure)	Number of Hours Per Week per individual (exposure)	Probability of PDC hazard impacting the LZ (five year)	Probability of PDC hazard impacting the LZ (one year)	Time exposure factor (out of 168 hours)	Probability of fatality if impacted (severity factor)	Individual Risk to Life (Probability of Fatality) Due to Pyroclastic Flow hazard (five year)	Individual Risk to Life (Probability of Fatality) Due to Pyroclastic Flow hazard (one year)
Fixed Loaders	4	56	0.001-0.004	0.0002-0.0012	0.333	1	0.000333-0.001333	0.000067-0.0004
Truck Drivers	10	56	0.001-0.004	0.0002-0.0012	0.333	1	0.000333-0.001333	0.000067-0.0004
Safety Officer	2	56	0.001-0.004	0.0002-0.0012	0.333	1	0.000333-0.001333	0.000067-0.0004

Table 4: Estimated probability of fatality due to pyroclastic flow hazard for workers in the LZ during the one-year and five-year timeframes.

38. Taking a conservative assumption of zero tolerance for any fatality to occur in the LZ during operations it is best to consider the individual maximum level of exposure (56 hours per week) when determining the risk to workers in the LZ.
39. The values presented in tables 3 and 4 do not account for organized mitigation strategies and actions, as these cannot be quantified for the purposes of the risk assessment. However, we do consider that strategies such as having a safety lookout and constant radio contact would help to reduce the risk to workers in the LZ. Appropriate mitigation measures should be undertaken by all organisations with a responsibility for activities in this area and we recommend the development of a joint strategy through discussions with MVO, DMCA, and other relevant institution or

company in addition to any individual safety plan. Here we outline a (non-exhaustive) list of possible risk mitigation actions that could be considered:

a. Initial and ongoing training and familiarization of workers to the volcanic hazards and risks posed to the LZ including recognition of potential warning signs and appropriate actions to take
b. Development and regular practice of both self- and organized- evacuation strategies that are tailored to lahar and PDC hazard, and accounting for both warning and no-warning scenarios. To include strategies via sea in case of possible stranding of personnel
c. Designation of a Health and Safety Manager who would be located at the LZ who will also provide a lookout function
d. Identification of a suitable location for a lookout function that also provides suitable and reliable communications to both MVO and to workers in the LZ
e. Development of a tested communication strategy to include constant contact with MVO
f. All workers to have a direct communication link to both MVO and the lookout / safety officer that is tested under working conditions e.g. increased noise, disruption etc.
g. Development of clear criteria or trigger points for when operations should cease due to heavy rain (which on occasion may not be observable in the LZ directly)
h. Development of monitoring strategies that could potentially provide early warnings to workers in the LZ, particularly in the case of lahar
i. Wearing of appropriate safety equipment and clothing

Limitations of this Risk Assessment

40. It should be recognised that there are generic limitations to risk assessments of this kind. The present assessment is based on a limited amount of field and volcano observatory information as well as on a review of, and approaches used in, previous published research outputs.
41. The outcome of this assessment relies on the judgement and experience of the MVO and its Director in evaluating conditions at the volcano and its eruptive behaviour. Some data in this report were taken or derived from preliminary work on hazard assessment that is ongoing and as yet unpublished.
42. It is important to be mindful of the intrinsic unpredictability of volcanoes, the inherent uncertainties in the scientific knowledge of volcanic behaviour, and the implications of this uncertainty for forecasting and decision-making. There are a number of sources of uncertainty, including:

- Fundamental randomness in the processes that drive volcanoes into eruption, and in the nature and intensities of those eruptions.
- Uncertainties in our understanding of the behaviour of complex volcano systems and eruption processes (for example, the relationships between pyroclastic flow runout distance, channel conditions and topography, and the physics of pyroclastic flows and surges and/or lahars).
- Data and observational uncertainties (e.g. incomplete knowledge of the actual valley shape and interfluve topography and conditions, material properties

inside pyroclastic currents, the uncertain nature of future eruption intensities, dome collapse geometries and pyroclastic flow and/or lahar volumes etc).

- Simulation uncertainties, arising from limitations or simplifications involved in modelling techniques, and the choices of input parameters.

43. This report and documents from the SAC which may have been used for this report may contain certain "forward-looking statements" with respect to the contributors' expectations relating to the future behaviour of the volcano. Statements containing the words "believe", "expect" and "anticipate", and words of similar meaning, are forward-looking and, by their nature, all forward-looking statements involve uncertainty because they relate to future events and circumstances most of which are beyond anyone's control. Such future events may result in changes to assumptions used for assessing hazards and risks and, as a consequence, actual future outcomes may differ materially from the expectations set forth in forward-looking statements in this report. The contributors undertake no obligation to update the forward-looking statements contained in this report.
44. Given all these factors, the authors of this report and the contributors of information it contains directly or indirectly believe that they have acted honestly and in good faith, and that the information provided in the report is offered, without prejudice, for the purpose of informing the GoM of the risks that might arise over the next 5 years, from volcanic activity in Montserrat in the area of Fort Ghaut, Plymouth. However, the state of the art is such that no technical assessment of this kind can eliminate uncertainties such as, but not limited to, those discussed above. Thus, for the avoidance of doubt, nothing contained in this report shall be construed as representing an express or implied warranty or guarantee on the part of the contributors to the report as to its fitness for purpose or suitability for use, and the authorities and parties to which this report is given must assume full responsibility for decisions in this regard. The MVO and authors accept no responsibility or liability, jointly or severally, for any decisions or actions taken by GoM, HMG, or others, directly or indirectly resulting from, arising out of, or influenced by the information provided in this report, nor do they accept any responsibility or liability to any third party in any way whatsoever. The responsibility of the contributors is restricted solely to the rectification of factual errors.

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Appendix A: Parameters for the risk assessment were provided to MVO from MLDA via the attached form - Data requirements for site specific risk assessment form