A new model of volcanic surge for New Zealand (EQC grant 18/764)

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Summary

The propagation of particle laden volcanic currents such as pyroclastic surges and base surges can cause extensive damage to exposed populations and structures. Such currents occur frequently in the volcanic record and in New Zealand, but are relatively small and thus generally unpreserved in the geologic record. Being an extreme proximal hazard, the surge extent is crucial to estimate in order to determine exclusion/risk zones. While models exist to estimate the extent of surges, they are generally based on either very simple approaches that neglect important physical processes with limited dimensionality, or are highly complex and require extensive computational resources and estimation of uncertain parameters.

In this project, we propose a new method to modelling surge propagation that can be adapted and extended to more complex physics than simple (e.g. energy line) methods to provide first order approximations to surge extent, but without including computationally expensive physical details. This is achieved through use of a level set approach, where propagation of the surge is calculated from speed functions at the surge front. This method was demonstrated on three case studies: the 2012 Te Maari surges, the 2016 Whakaari/White Island surges and the Maungataketake surges in the Auckland volcanic field. First, an energy line method was reformulated using Bernoulli's theorem and used to identify areas of critical need and limitations to focus improvements. For the Te Maari case, different coefficients of α for the Energy Grade Line gave different fits for the surge extend perpendicular to and aligned with the estimated directions of the blast. The constraint of large scale topography in directing energy was seen to be important for the Whakaari case, where the runout was approximated better using an 'effective radius' approach, while the Maungataketake surge model did not show a good fit to the estimated extents, highlighting potential limitations in the energy line method. To improve upon this model, we took a potential flow approach to account for the effect of terrain relief acting as an energy sink for the surge. In case studies with low relief, the potential flow model had little effect. However, the high relief in the Te Maari case had the effect of limiting the extent of the surge to approximate the extents perpendicular to the blast, but with an underestimation in the direction of the blast. This demonstration shows the applicability of the new modelling approach, while also supporting implementation through model architecture that integrates geospatial libraries.

Introduction

Pyroclastic surges are damaging particle laden currents that propagate at high velocity from their explosive volcanic source, presenting a unique risk to New Zealand's population, infrastructure and economy. Owing to the extensive risk posed by surges, current contingency plans for volcanic activity within the Auckland Volcanic Field (AVF) call for the evacuation of a 3 to 5 kilometre radius from an erupting vent. Allowing for vent location uncertainty, this can result in the evacuation of more than 434,000 people in some AVF scenarios (Blake et al., 2017). Regardless of the resulting volcanic activity, mass evacuations on this scale will cause considerable economic damage and may take more time than an eruption warning could provide. However, the definition of an evacuation radius in this manner does not account for the potential eruption size or effect of topography on surge propagation. Geologic evidence may allow for improvements to evacuation radius estimates, however such evidence is sparse, and additional support may be needed to interpret the likelihood of events, particularly for those with larger runouts. Numerical or empirical models that link eruption properties to surge dynamics, runout and hazard can also be used as a support tool for defining evacuation zones. However, many currently available models are proven and calibrated to large eruptions, which may not be analogous to the small-volume surges often seen in New Zealand, where the effect of initial and boundary (terrain) conditions can be significant.

The velocity, runout and sedimentation of surges vary with the explosive energy and style of the eruption, surge volume and concentration, terrain characteristics and environmental conditions (Brand et al., 2014; Bursik and Woods, 1996; Lube et al., 2014; Valentine, 1987). The understanding of volcanic surges is an area of ongoing research with international importance, where current research is improving our scientific understanding of surge dynamics (Breard and Lube, 2017; Breard et al., 2016), developing advanced modelling tools (Dufek and Bergantz, 2007; Esposti Ongaro et al., 2007; Kelfoun, 2017), and establishing benchmarks to assess the performance and communicate the limitations and applicability of surge models. The need for physically justified, quantitative models of volcanic surges is well recognised and several models, varying in scale and detail, have been developed to help understand surge dynamics and provide useful information on surge hazard zones (Esposti Ongaro et al., 2007; Esposti Ongaro et al., 2016; Kelfoun et al., 2017; Malin and Sheridan, 1982a; Widiwijayanti et al., 2009). To be useful in a hazard assessment context, models need to balance computational cost (less-costly models will enable a greater exploration of surge scenarios, a probabilistic quantification of hazard and enable re-assessment of hazard during unrest (Lindsay et al., 2010; Sandri et al., 2012)), the full description of surge physics (models that consider all physical effects will be more accurate, but come at a high computational cost) and, the number and type of input parameters (a large number of a-priori unknown and/or calibrated parameters increases uncertainty). High detail, three-dimensional numerical models (Dufek and Bergantz, 2007; Esposti Ongaro et al., 2007) that simulate the multiphase interactions within a surge cloud currently offer the most complete description of surge physics, but come at a considerable computational cost, limiting their use in probabilistic hazard estimates and the breadth of sensitivity analyses to unknown or uncertain input parameters. A reduction in computational cost of surge modelling relies on the simplification of the surge physics (e.g. through depth-averaging (Doyle et al., 2010; Kelfoun, 2017)), but is then dependent on the calibration of averaging parameters to field observations, which are affected by epistemic uncertainty as a result of the averaging. The assumptions of these models and calibration processes effectively require expert inference, limiting the easy application and use as a hazard assessment tool by end users. Models and tools using empirical or semi-empirical relationships to delineate surge extent are more often favoured (internationally) by end users. These models have the benefit of being computationally and conceptually simple, fostering their use in hazard assessment, particularly during a crisis (Ogburn et al., 2014). However, these models greatly simplify the physics of pyroclastic surges, being designed and calibrated to large volume eruptions where boundary and terrain effects on runout, dynamics and sedimentation are minimal compared to the explosive energy and volume of the eruptions. In simple terms, these models assume the surge extent is governed primarily by exchanges between gravitational and kinetic energy. In reality, the exchange of momentum within a propagating surge is much more complex, being controlled by terrain characteristics, surge concentration and particle dynamics (Dufek, 2016). In large eruptions, these effects appear to be relatively small and simple energy exchange relationships work to a reasonable degree of accuracy. However, proportionally more energy will be dissipated through these effects in smaller surges, limiting their use when predicting the surge extent from smaller volume and energy eruptions. As a result, the extent of small volume surges, such as those expected from the AVF may be over-estimated by current simple models.

Despite their frequent occurrence, there are no models that operate at the speed and level of detail needed to delineate small volume surge hazard that also meets the end-user need for fast, robust hazard estimations. While globally important, this gap is very significant in the context of New Zealand's volcanoes, where small volume surges are a common feature. Small volume surges have occurred during most phreatomagmatic eruptions in the AVF, and were observed in the 2012 eruption of Te Maari and recent eruptions of White Island (2013, 2016). Furthermore, the academic literature contains a multitude of advances in hazard mapping techniques that are not represented in current mapping practices (Calder et al., 2015), as well as a refined understanding of surge dynamics that is not accounted for in the current surge modelling approaches.

This EQC research project aims to establish a new generation of modelling tools to support decision making in hazard assessment and emergency management. In this project, we aim to develop a new, robust and evidence based surge model, particularly suited to small volume surges, that can be used to support the assessment and delineation of New Zealand's surge hazard. This was achieved through development of a modelling framework, greater understanding of topography effects in surge models, adaptation of current models to account for relief and the ease of implementation with end users.

Objectives

Objective I. A modelling framework for surge hazard

From the perspective of risk to property and life, delineation of the surge extent is most critical. For life safety, uncertainties in eruption size, energy, individual location and actions make it infeasible to delineate a 'safe' area that may be within the surge extent. When considering the effect of surges on buildings, a number of actions may cause damage (e.g. pressure, chemical effects, sedimentation, inundation; Spence et al., 2004), however, the dominant action causing most damage is generally dynamic pressure, i.e. the lateral force applied to structures by the moving blast of a surge. Studies (Jenkins et al., 2013; Mead et al., 2017) have demonstrated that buildings are, in general, not resilient to high-density (compared to air) lateral loads such as those experienced in pyroclastic surges. For example, estimated dynamic pressures from the surge modelling (Brand et al., 2014) show dynamic pressures greater than 15 kPa within 2-4 km of the vent, and < 5 kPa within 6 km. Such pressures have been shown to cause significant damage to buildings at pressures as low as 1-2 kPa (Jenkins et al., 2013). Given the significant of surge extent (and propagation which is proportional to dynamic pressure), our primary objective is to develop a surge modelling framework that tracks the extent and propagation of surges. Other properties of pyroclastic surges (e.g. concentration, temperature, particle size distribution and sedimentation) are not required to be explicitly tracked, except in the role they play to determine surge propagation and extent.

Tracking the motion of a surge front is a non-trivial, challenging task due to changing topology of the interface, dependence and feedback between frontal velocity, physical properties and location of the front (Sethian, 2001). Our modelling framework uses a level set method where, instead of explicitly estimating the surge boundary with time, the surface is implicitly tracked through the calculation of a signed distance function that expresses the distance from any location in the computational domain to the interface (Aghakhani et al., 2016; Hilton et al., 2015; Sethian, 2001). By capturing the distance to the surge front across the domain, rather than the front itself, this method avoids complications with front merging, splitting and backwards propagation. Setting ϕ as the signed distance value, where negative values indicate the cell is 'behind' the propagating front, positive values are 'ahead' of the propagating front and the surge front is the isoline where ϕ = 0, surge propagation can be modelled as:

$$\frac{\partial \phi}{\partial t} + s|\nabla \phi| = 0 \qquad (1)$$

Note this approach is applicable in any number of dimensions, with the isosurface simply being one dimension fewer than the signed distance domain. In this study we focus on mapping surge propagation in plan view (i.e. Northing and Easting on a map). In the level set formulation the signed distance (ϕ) changes according to a speed function, denoted as *s* in equation 1. The speed function (*s*) can have any computable definition that expresses the frontal velocity of an interface (i.e. normal velocity). In most simple functions used here, the speed function is a linear mapping of front morphology (e.g. surge curvature) and/or external variables such as topography and gradient. These methods are well established for interface capturing in fluid dynamics (Sethian and Smereka, 2003), including jump conditions, shocks and detonation waves (Osher et al., 2004), and have a demonstrated capacity to track moving interfaces dominated by complex physics using empirical formulations for frontal propagation (Hilton et al., 2016; Rhee et al., 2006; Sethian and Adalsteinsson, 1997).

Despite this ability to simulate complex phenomena, the approach has a limited computational cost (Adalsteinsson and Sethian, 1995) while also remaining conceptually simple to implement speed functions.

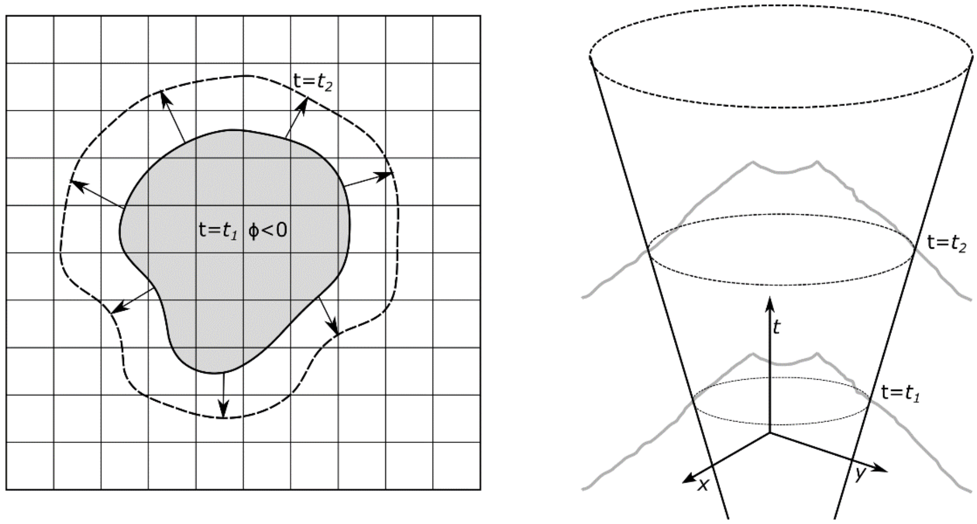

Figure 1. Illustration of the proposed fast marching level set method for volcanic surge propagation. The surge boundary (left, grey) is defined at any time *t* as the location where the signed distance function ϕ equals 0. The advance of the front to time = t_2 is controlled by a speed function, shown for a linear, monotonically advancing relationship (i.e. similar to energy line approximations) on the right. Geometrically, the propagation of these functions can be thought of as a three dimensional shape with dimensions *x, y*, and time.

In this research we have adapted the level set modelling framework SPARK (Hilton et al., 2015; Miller et al., 2015), originally developed to simulate bushfire behaviour. Bushfires exhibit similar levels of complexity to surges, but with a similar simplification of impacts (i.e. bushfire area and front is focus), and lessons from bushfire front tracking can be applied with few necessary adaptations to pyroclastic flow physics. Using an already developed simulation tool has many benefits, leveraging a greater pool of development resources and supporting implementation through the use of modern software engineering principles. SPARK is built upon the QT C++ toolkit and CSIRO Workspace (Workspace, 2014) multiplatform tools, for which there already exists a suite of tools (Mead et al., 2015; https://github.com/stuartmead/volcanoplugin) specifically for volcanic hazard assessment.

The software interface is shown in Figure 2 and demonstrates some key features of the modelling framework. Box 1 (top left) shows sample scripts used to define the surge speed (*s* in equation 1). This demonstrates the simplicity of development for a surge model within the level set framework, ensuring models can be created, adapted or modified in response to ongoing scientific research. Note this example took only 6 lines of simple code to define a surge model. In box 2 (bottom left) the interface for interacting with simulation results is shown. In addition to outputting results as geospatial vectors or rasters, the simulation tool allows for direct visualisation and interaction with the results to support rapid evaluation, prototyping and evaluation of surge models. Box 3 shows the technical 'backend' of the solver workflow. In most end-user cases, this would be hidden behind a graphical user interface (GUI), but the workflow framework allows for easy extension and adaptation for workflows

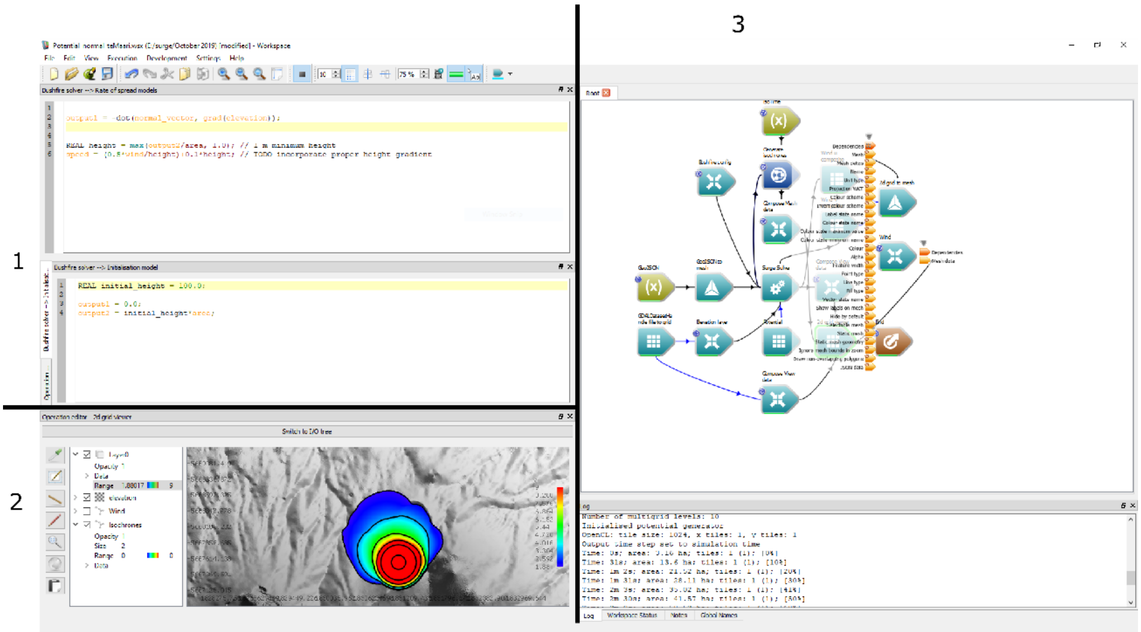

Figure 2. Demonstration of the level set modelling framework, SPARK, adapted (using scripts in box 1) for use with pyroclastic surge modelling. Box 2 shows the output of a simulation, using interactive tile maps. Box 3 shows the 'backend' workflow used to generate the model output.

(including the addition of other software libraries) in order to meet other needs (e.g. the simulation output could trigger a RiskScape hazard assessment, or an input distribution of potential could be calculated within the workflow to drive thousands of simulations for a risk assessment).

Objective II. Testing the role of terrain effects through real-world events

To aid the development of surge models relevant for New Zealand, we chose three case studies representative of typical surges in New Zealand and with characteristics that can be used to test currently available (i.e. published) simple surge delineation approaches. The three case studies are:

6th August 2012 Te Maari surge

The 6th of August 2012 eruption at Tongariro volcano consisted of a sequence of events. First, a failure of the western flank of Upper Te Maari generated an ~700,000 m^3 debris avalanche that travelled down the Mangatipua Stream (Procter et al., 2014). This was followed by a sequence of explosions (detected through infrasound sensors) that produced overlapping ballistic and surge deposits (Lube et al., 2014). Four of these explosions released most of the eruption energy and are presumed to have produced the pyroclastic density currents (Jolly et al., 2014). The surges deposited 338,000 m^3 of volcaniclastics across an area of 6.1 km^2. The deposit pattern (Figure 3) is elongated in the West and East directions, with the deposit travelling much less distance in the North and South directions. Topographic effects likely had a role in constraining the southern extent of the surge, however the Western and Eastern deposit lobes indicate topographic effects had a smaller effect in this direction, as surges surmounted cliffs and several ridges between 25 and 70 m high. The maximum extent of the surge (distance from Upper Te Maari Crater) is ~2.5 km in the West and East lobes, while travelling 0.5 km South ('uphill') and ~1.6 km North. The surge was also highly mobile for its eruption energy and volume, with a similar mobility to other blast-like surges (Lube et al., 2014), and the origin is hypothesised to be from the East-West oriented fissure, which may account for the observed directionality. The high mobility, complex eruption dynamics and steep, irregular topography present a surge case study that is typically hard to model with very simple techniques, but where input uncertainty may also hamper very detailed, computationally expensive simulation tools.

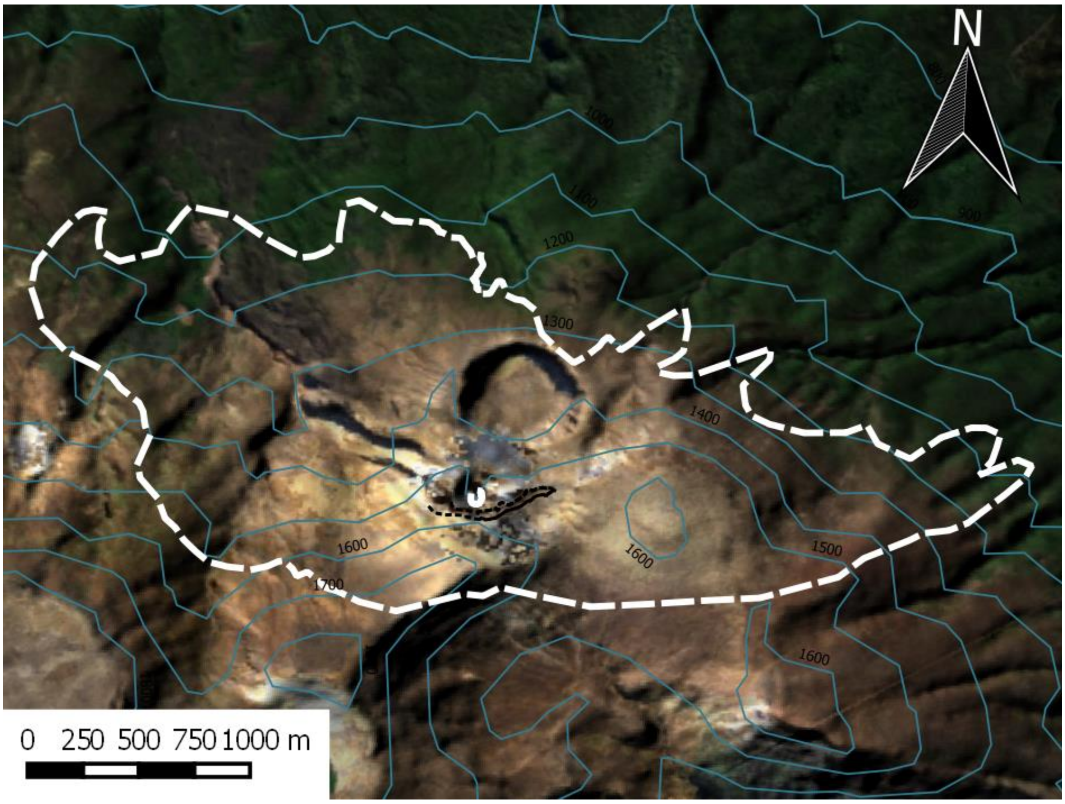

Figure 3. Overview of the 2012 Te Maari surge/blast. Dashed white line represents surge extent, black lines indicate the West (dashed) and East (solid) fissures from which the surge is hypothesised to originate. Basemap: LINZ NZ 10 m Satellite Imagery

Maungataketake Base Surges

Deposits of the Maungataketake tuff ring in the Auckland volcanic field have previously been used to assess surge dynamics and hazard for Auckland (Brand et al., 2014). The ~83 - 92 ka Maungataketake eruption emplaced a series of base surges in the first phase of the eruption from shallow explosions (Agustín-Flores et al., 2014). The surge deposits contain remnants of Podocarp trees, interpreted as being snapped due to the high dynamic pressure of the surges. Modelling by Brand et al. (2014) suggests this surge travelled ~2.25 to 2.35 km radially from its vent.

Despite being less documented than the other surge case studies, this event is valuable to model in order to understand the comparative performance of new surge approximations within the Auckland Volcanic Field. The low, undulating topography (average slope ~1°) also provides a data point to assess conditions where topography has a lesser effect compared to internal surge dynamics.

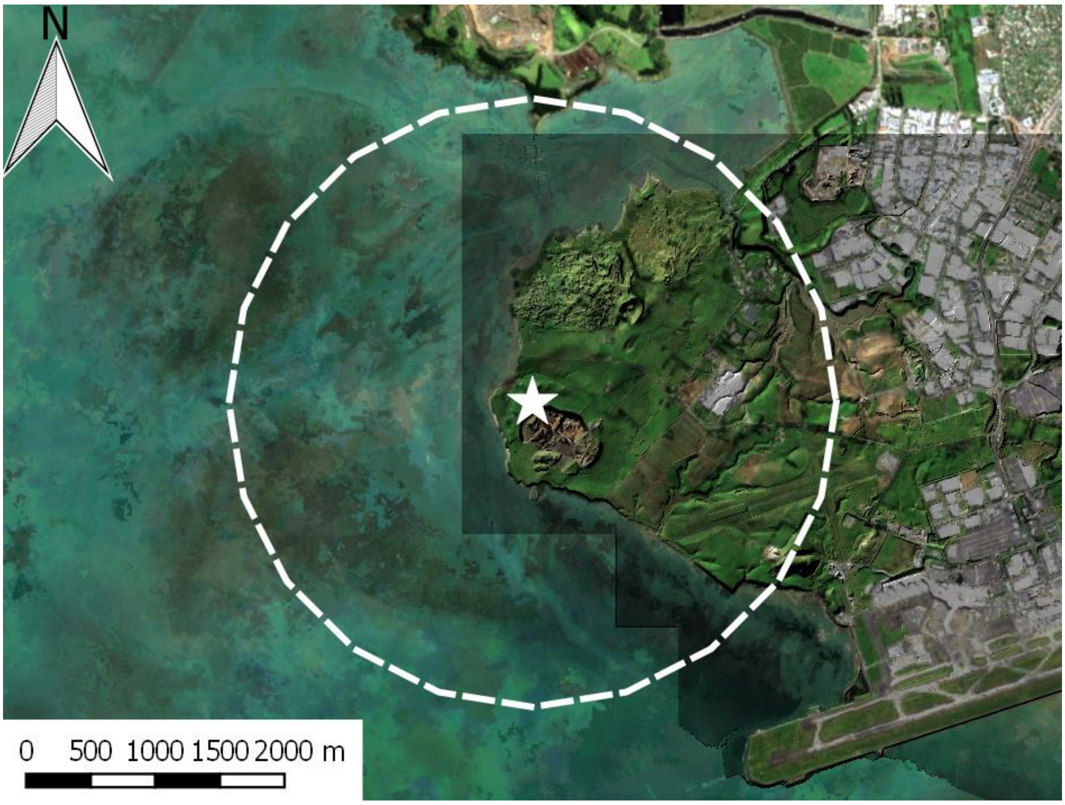

Figure 4. Overview of the ~82-92ka Maungataketake base surge. Dashed white line represents the surge extent estimated from modelling (Brand et al., 2014), star indicates presumed location of the vent from Agustín-Flores et al. (2014). Note the surge is unlikely to have propagated exactly radially, but is extrapolated as an axisymmetric current based on 1-dimensional modelling. Basemap: LINZ NZ 10 m Satellite Imagery and Auckland 1 m LiDAR.

27 April Whakaari/White Island Surges

Pyroclastic surges are a frequent eruption phenomena at White Island/Whakaari. Surges occurred in the 2013, 2016 and presumably the 2019 event (Kilgour et al., 2019). Here, we focus on the 2016 event, which was well documented with both geophysical instruments (Walsh et al., 2019) and geologic evidence. At around 10PM on the 27th of April 2016, an eruption consisting of 6 distinct explosions, detected from an array of instruments (Walsh et al., 2019), occurred at White Island. This generated a number of phenomena and hazards, with an ash deposit was emplaced up to ~700 m from the inner crater. The presence of sheared marker posts (used for repeat levelling surveys and gas flux measurements) and the deposit similarity to the previous 2013 surge suggests this deposit was mostly emplaced by a low energy pyroclastic surge (Kilgour et al., 2019). Access limitations prevented an exact determination of deposit volume, but the extra-crater deposit was estimated to be ~13,200 m^3, covering an area of 331,000 m^2 with an estimated initial velocity of 11 ms^{-1}. However, the inner crater wall was likely to have a strong topographic constraint on the surge, preventing much of the surge volume from propagating out of the crater rim. On the basis of analogue modelling, Kilgour et al. (2019) estimated the total surge volume to be ~65,000 m^3. The steep topography was also responsible for directing the surge towards the east, rather than radially.

The directionality of this surge (constrained by large topographic features), role of smaller scale topography (i.e. the crater rim) and reliable data provides a case study well suited to the objectives of our model.

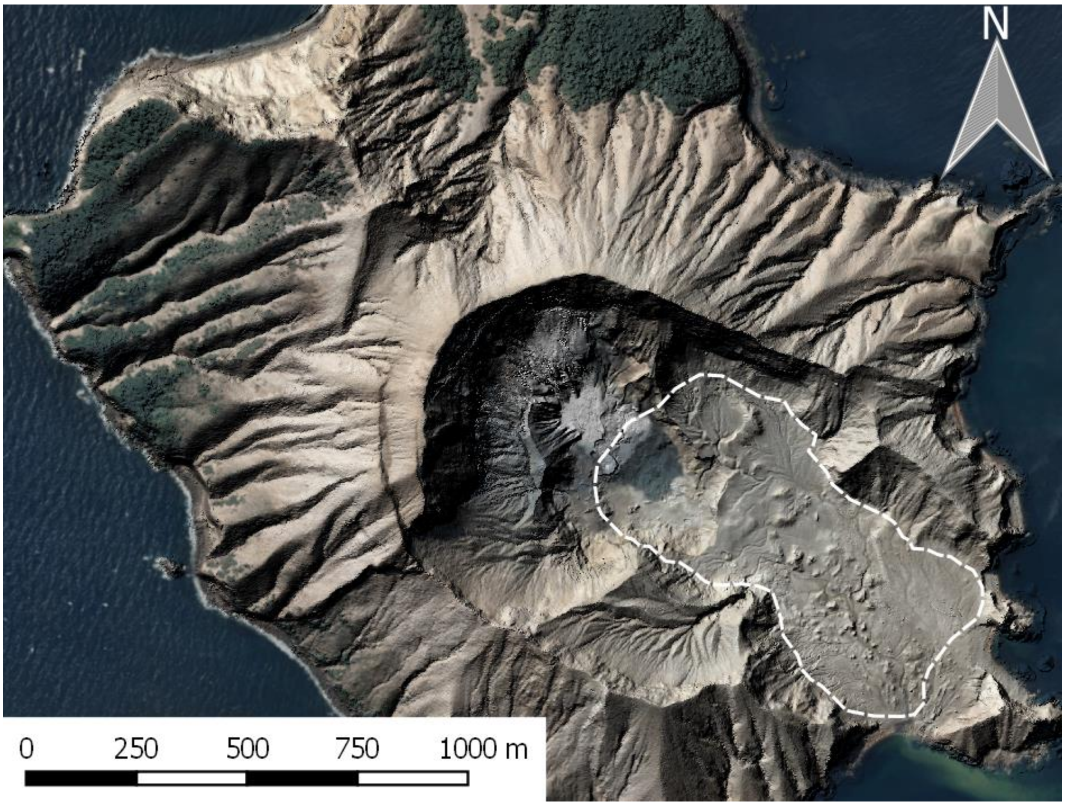

Figure 5. Outline of the the 2016 Whakaari/White Island base surge. Dashed white line represents the surge extent estimated from isopach at 5 mm thickness (Kilgour et al., 2019). Basemap: LINZ Bay of Plenty 0.3 m Aerial Imagery and Digital Surface Model from Walsh et al. (2019).

To demonstrate the implementation of a surge propagation model in the new framework and elucidate some important features desirable in an improved model, we reformulate the well known energy line model (Malin and Sheridan, 1982a; Sheridan and Malin, 1983) into speed function suitable for the level set. This requires a reassessment of the energy grade line approach from base assumptions of Bernoulli's theorem.

Energy grade line approaches

Bernoulli's theorem for steady, incompressible and frictionless flow forms the basis of energy line approaches to delineate pyroclastic surge extent (e.g. Malin and Sheridan, 1982a; Sheridan, 1979; Sheridan and Malin, 1983; Tierz et al., 2016a). The total mechanical energy (measured as 'pressure head') of such a flow is the sum of potential, kinetic and 'pressure' energies. With p as pressure, ρ density, g gravity, V velocity and z as the height above a datum, the total energy of the system at any point is

$$\frac{p}{\rho g} + \frac{V^2}{2g} + z = c \quad (2)$$

Using an open-channel assumption (i.e. pressure is atmospheric at all points), and neglecting ρ for the moment, the energy grade line (*EGL*) expresses the total energy as a height above the datum:

$$\frac{V^2}{2g} + z = EGL \quad (3)$$

A converse expression for the hydraulic grade line (*HGL*) is commonly used in Bernoulli flow analyses is $\frac{p}{\rho g} + z = HGL$, but simplifies to *z* under open-channel assumptions. It can be seen that the difference between the *EGL* and *HGL* is $\frac{V^2}{2g}$. This value is typically called the *velocity* head (e.g. Körner, 2017), with units of metres, as it is the difference in *z* between the energy and hydraulic grade line. Assuming surges are truly ground-hugging (Malin and Sheridan, 1982b), the velocity head is simply the difference between the *EGL* and terrain. **Error! Reference source not found.** (top) shows a graphical approach to the energy grade line model in a frictionless flow. In this model, the initial energy input h_{v0} and point *A* is suggested (Sheridan, 1979) as the height (i.e. energy) added from the 'gas thrust' zone of an eruption. Thus, the *EGL* is $z_A + h_{v0}$, where z_A is the elevation at point A (vent). Under the frictionless assumption, the velocity head (h_v) at any point is equal to the difference between the EGL and elevation at that point. This means that, while energy is equal for all locations (and therefore the surge propagates infinitely in flat terrain), h_v, and therefore velocity ($V = \sqrt{2gh_v}$) differ according to the terrain. For example, in Figure 6 (top) $h_{vC} > h_{vD} > h_{v0}$; $h_{vB} = 0$, and the surge propagates when h_v is greater than 0.

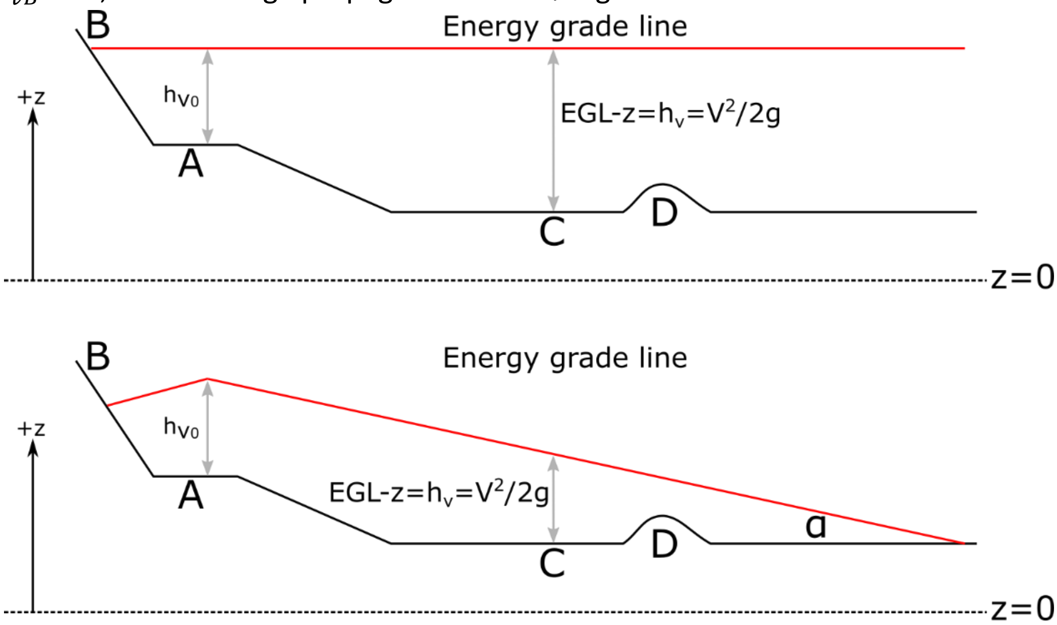

Figure 6. (top) Energy grade line approach under frictionless assumptions, **(bottom)** energy grade line under a linear energy dissipation approach.

A more realistic case where energy loss occurs can be modelled by a reducing EGL over distance (analogous to head loss) or any other parameter. The simplest approach ('energy cone') is to use the Heim coefficient (Sheridan and Malin, 1983), shown in **Error! Reference source not found.** (bottom). Here energy loss decreases by $\tan(\alpha)$. The EGL can then be expressed as

$$EGL = (z_A + h_{v0}) - r\tan\alpha \tag{4}$$

where *r* is the distance from source (i.e. *A*). Other approaches to decreasing EGL over distance can be used, but are typically more complicated (e.g. Esposti Ongaro et al., 2016).

Implementation

Two approaches to reduction of the energy line are implemented in the level set framework. One approach calculates the straight-line distance (radius) from the vent, reducing the initial energy, resulting in a velocity head of:

$$\frac{V^2}{2g} = h_{v0} + z_A - r\tan\alpha - z_{x,y} \tag{5}$$

A potential improvement to the calculation in equation 5 is to estimate the reduction in energy using an 'effective radius', $r_e = \sqrt{\frac{area}{\pi}}$, with a velocity head of:

$$\frac{V^2}{2g} = h_{v0} + z_A - r_e\tan\alpha - z_{x,y} \tag{6}$$

Results of energy grade line approaches

The energy line speed functions (equations 5 and 6) were applied to each case study to identify areas of critical need and limitations that may be improved upon, both in objective III and future work. For each case, we assumed an initial energy input (h_{v0}) of ~0.1 the height of the plume (i.e. following a similar approach to Tierz et al., 2016b) and evaluate the model fit, identifying the potential source of errors to improve upon.

Simulated results for Te Maari simulations are shown in Figure 7. The top image shows the surge extent (colours indicate scale of the velocity head) calculated using the speed function in equation 5 with an α of 22°, which shows a reasonably approximation of the extent of laterally directed surges (East and West); the bottom image shows the surge extent with an α of 35°, where the Northern and Southern extents of the surge show an improved match. Figure 8 shows simulation results from the White Island case study, comparing the use of equation 5 (top, straight line radius) and equation 6 (bottom, effective area radius). In this case, use of an effective radius shows an improved match to the maximum extent of the surge in the South East direction compared to a straight line approximation. Figure 9 shows the surge model applied to the Maungataketake case study. This surge propagates almost asymmetrically, with topography having a limited effect. No portion of the surge reaches the modelled extent of Brand et al. (2014), even at low α values, unless the eruption energy was much larger, i.e. of a similar scale to the Te Maari eruption (Figure 9, bottom).

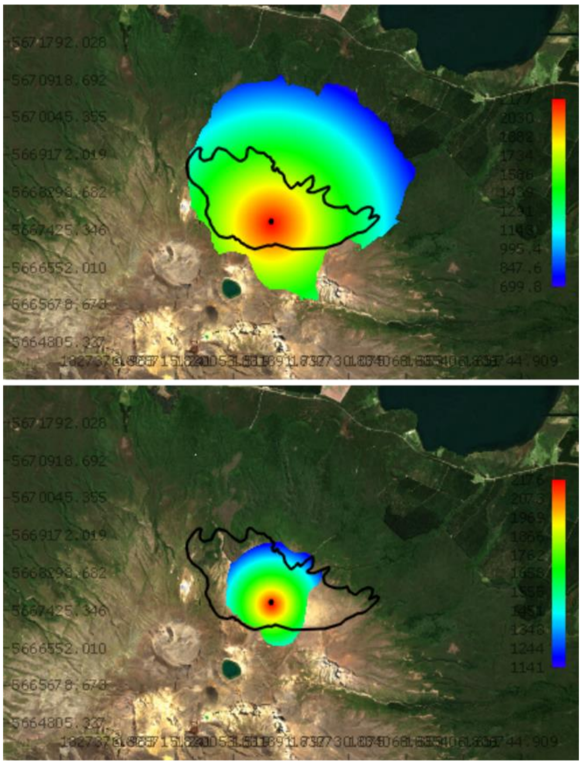

Figure 7. (top) Energy grade line surge propagation for Te Maari case study with α = 22°, **(bottom)** energy grade line surge propagation for Te Maari case study with α = 35°.

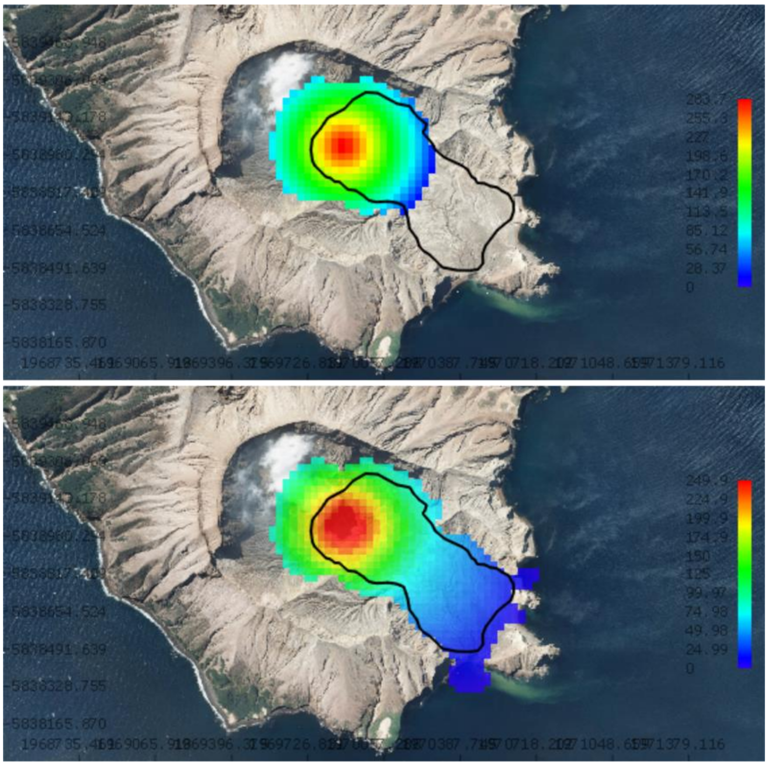

Figure 8. (top) Energy grade line surge propagation for White Island case study with α = 35° using equation 5, **(bottom)** energy grade line surge propagation for White Island case study with α = 35° using equation 6.

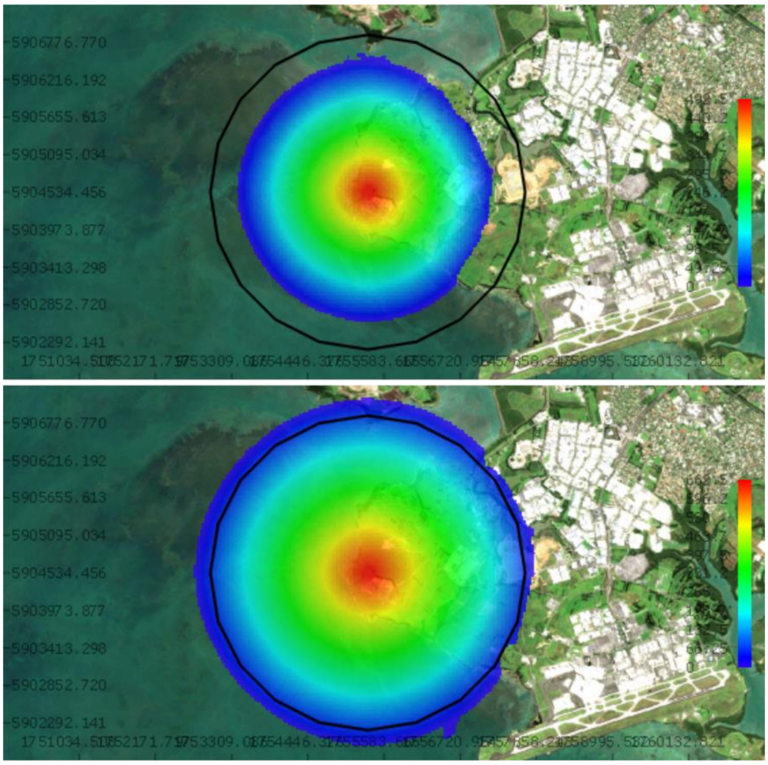

Figure 9. (top) Energy grade line surge propagation for Maungataketake case study with α = 15°, **(bottom)** energy grade line surge propagation for Maungataketake case study with α = 15° using an energy (h_{v0}) similar to the Te Maari case.

The examples shown here highlight several key considerations when modelling small volume surges using these simple approaches. The difference in best fit angles for the Te Maari case (Figure 7) show the importance and influence of directionality in blast-like surges. The difference in mathematical approaches for the Whakaari/White Island case between the straight line radius (Figure 8 top, equation 5) and effective radius (Figure 8 bottom, equation 6) show the influence of large topographic controls that direct energy towards a preferential direction. The application to Maungataketake highlights limitations in simple approaches and lack of data, where the lack of fit may be caused by inadequate representations of surge physics, eruption energy or both.

Objective III. Develop a new surge model that accounts for energy loss due to terrain

One benefit of the new surge modelling framework using the level set method is the extendibility to account for different phenomena (e.g. those identified previously) that may be important when modelling the impact of surges. This project has established the usability of the modelling framework for future research, presenting an opportunity for the further development of evidence-based, generic empirical relationships to describe surge propagation. In this objective we demonstrate one such extension possible with the level set framework: an approach to refine the extend and propagation of energy line methods by accounting for small-scale terrain effects. The velocity head in Energy Grade Line approaches (see previous) varies with topography, however the EGL is insensitive to topographic obstacles. This is a significant simplification, as flows are known to change their criticality/thickness in response to obstacles such as ridges (Woods et al., 1998). This modification to the energy line approach proposes to account for this effect using potential flow theory.

Using the same Bernoulli's assumptions as in the energy line method, we also apply an assumption of irrotational flow (i.e. flow does not rotate in z-x and z-y plane), meaning a velocity potential (ψ) can be defined,

$$\vec{V} = \nabla\psi \tag{7}$$

also satisfying the Laplace equation due to the incompressibility assumptions,

$$\nabla^2\psi = \frac{\partial^2\psi}{\partial x^2} + \frac{\partial^2\psi}{\partial y^2} = 0 \tag{8}$$

Which, as a linear equation allows for the superposition of simple flow fields (e.g. sources, sinks, vortices and doublets.

The ability to superimpose simple fields into the energy grade line, enabled through the additional assumption of irrotationality has many viable applications to surge modelling. For example, directionality or surges from multiple explosions along a fissure can be included through the addition of varied potential sources or constant flow fields. For the effects of terrain (which occur in out-of-plane to our modelled extent), we assume the perturbations to velocity head are small, meaning the velocity potential can be defined as an addition to the local velocity (for example, Siegel, 1976), where the difference in potential is proportional to the gradient of the terrain, in the normal direction to the flow front:

$$\nabla^2\psi = -n \cdot \nabla b \tag{9}$$

Where *b* is the elevation of the terrain, and the negative sign is to denote the terrain gradient as an energy sink.

Simulation results for the Te Maari and Whakaari studies using this potential flow terrain correction are demonstrated in Figure 10. The potential flow correction appears to have a minimal effect on the Whakaari and Maungataketake surges (Maungataketake case not shown), but changes the result significantly for the Te Maari case, where sharp relief (i.e. ∇b) has a large effect on constraining the flow. By comparison, the scale of relief (1 to 10's of metres) is much smaller than the thickness of the surge in Whakaari and Maungataketake cases. This indicates these surges were less influenced by small scale topographic gradients. It is notable however that the potential flow formulation still exerts an influence on the surge propagation, as shown by the vectors in in Figure 10 (bottom) where the constriction in topography induces a forcing against the surge direction.

The application to Te Maari highlights some important advantages over simple energy line approaches: by accounting for the relief, surge propagation has been limited for the same parameters (compare to Figure 7 top) in the Northern and Southern extents, which were previously over-estimated. The Eastern and Western extents are now under-estimated, also being limited by steep topographic gradients. This under-estimation demonstrates the influence of the directed blasts in these general directions (see Lube et al., 2014), which could

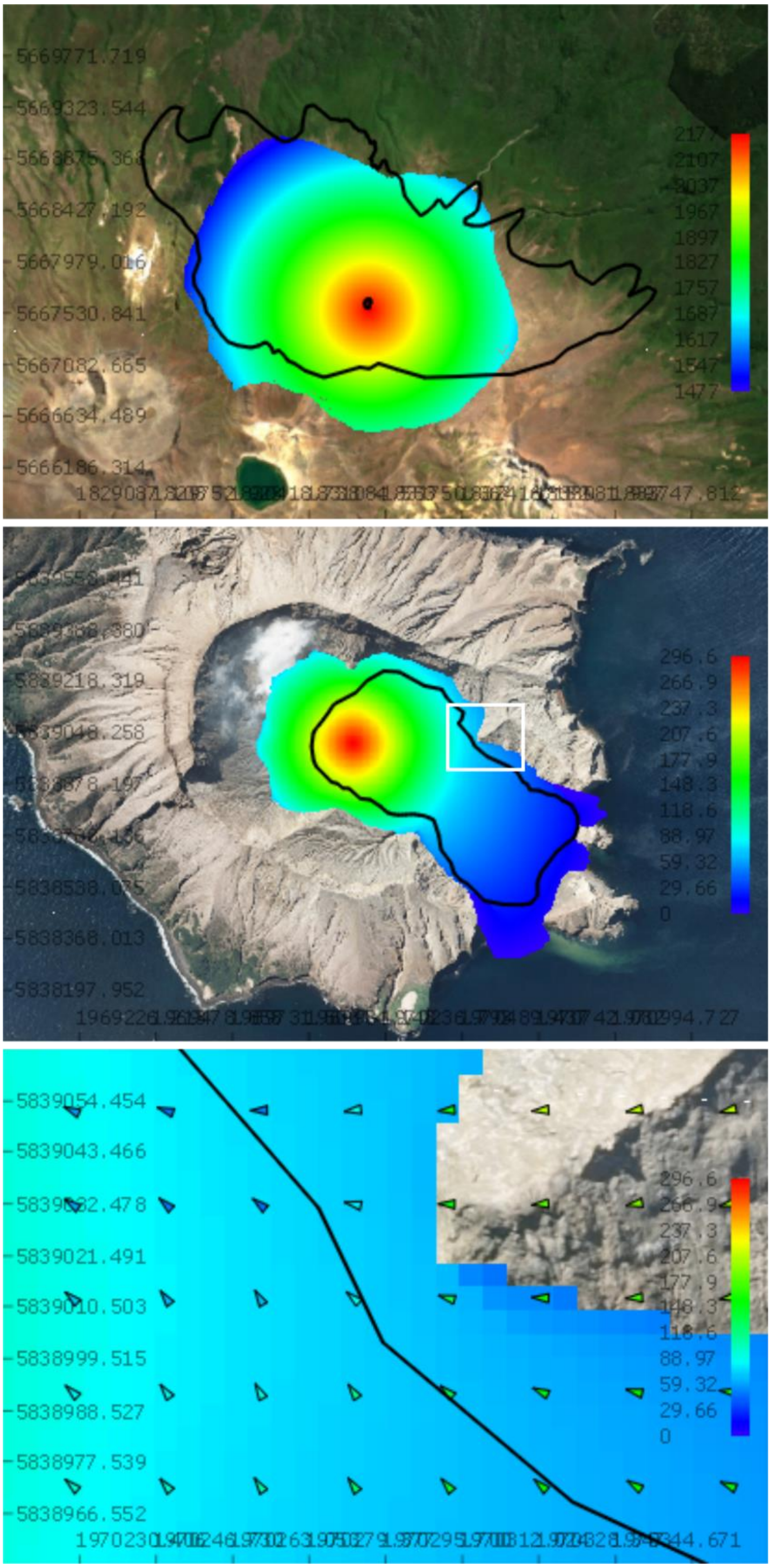

Figure 10. (top) Energy grade line surge propagation for Te Maari case study with α = 22° using the potential flow terrain correction, **(middle)** energy grade line surge propagation for White Island case study with α = 35° using equation 6 and potential flow correctin. **(bottom)** zoom of boxed area in middle showing vectors that act as a sink to surge energy.

also be accounted for using a similar potential flow formulation used in this objective to add a forcing term to the topographic skink term.

Objective IV. Implementation of new model

The reformulation of current simple surge propagation approaches into the level set modelling framework has many benefits for effective use both in the scientific community and for end users.

- The model is built on the extendable Qt and CSIRO Workspace frameworks (see Figure 11), which include geospatial components (GDAL, netCDF) and is extended to many open libraries to enable efficient pre- and post- processing of simulation results, including (e.g.) export to RiskScape. Additional operations are also continually being developed through aligned funding and from other communities (e.g. https://github.com/stuartmead/volcanoplugin).
- The creation of models, or adaptation of models into the level set framework requires only a few, simple lines of C-like code describing propogation speed of the front. This reduces the overhead and requirement of model development to account for specific phenomena or new findings in surge propogation physics.
- The use of the potential flow concept to account for the influence of relief requires no additional parameters, meaning useability is not affected by the addition of extra physics. This is a significant advantage, meaning models are generalised and less calibration and tuning is required in application.

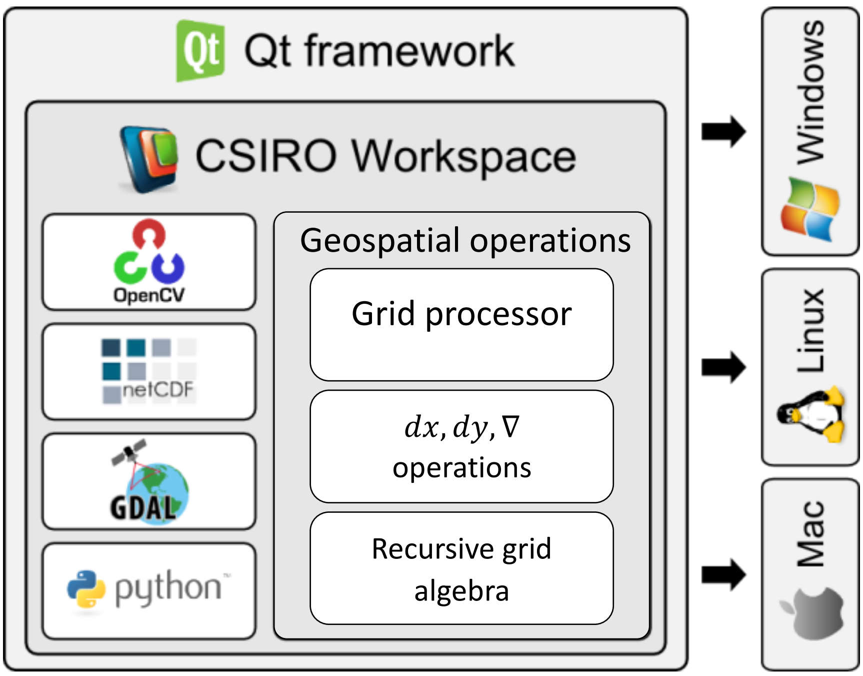

Figure 11. Architecture underlying the level set simulator and surge modelling framework. Built on the multi-platform Qt framework and CSIRO Workspace scientific workflow tool enables leveraging of open libraries (e.g. OpenCV, netCDF, GDAL) and already build components (e.g. Geospatial operations from other funded projects).

Supporting this objective, the modelling framework, conceptual overview and benefits of the projects' approach was presented at the 2018 DEVORA forum (http://www.devora.org.nz/presentations_and_posters/). A scientific publication describing the modelling framework, and demonstrating applications is also in preparation to summarise the use of this framework for end users.

Conclusions and key findings

This EQC project has supported the development of a new approach to modelling pyroclastic surges within New Zealand.

- A level set method (Sethian and Smereka, 2003) was adapted from the bushfire modelling framework SPARK (Hilton et al., 2015; Miller et al., 2015) to track the frontal propagation of volcanic surges.
- A current simple surge model (Energy Line model) was adapted to the level set formulation using Bernoulli's theorem. This was applied to three New Zealand examples: the 2012 Te Maari surge/directed blast, the 2006 Whakaari surge and the estimated Maungataketake surge extent.
    - For the Te Maari case, different coefficients of α for the Energy Grade Line gave different fits for the surge extend perpendicular to and aligned with the estimated directions of the blast.
    - The constraint of large scale topography in directing energy was seen to be important for the Whakaari case, where the runout was approximated better using an 'effective radius' approach.
    - The Maungataketake surge model did not show a good fit to the estimated extents in Brand et al. (2014), highlighting potential limitations in the energy line method.
- Accounting for the effect of relief in surge propagation, we modified the EGL method with a potential flow model, restricting the frontal velocity proportional to the terrain gradient normal to the flow. In case studies with low relief (e.g. Whakaari and Maungataketake), the potential flow model had little effect. However, the high relief in the Te Maari case had the effect of limiting the extent of the surge to approximate the extents perpendicular to the blast, but with an underestimation in the direction n of the blast. This fit is potentially a representation of the surge extent if the surge energy was not directed through the East-West fissures. A future application of the new modelling framework could be to include the effects of directionality as a potential flow source.

Impact

This new modelling framework has expanded the capability for modelling surges from either simple, limited physics approaches or highly expensive computation simulations to add a modelling technique that includes additional physical principles for a limited computational cost. The new approaches show an improved estimation of surge extent for some cases, particularly where relief is high. This has a potentially high impact in terms of reducing risk to volcanic hazards, as better quantified, rapid calculation of extents may reduce the uncertainty in risk estimation. The new framework also lays the foundation for future work, with modern software engineering approaches enabling better integration with end user tools and the ease of model creation streamlining the process from scientific discovery to application.

Future work

Several avenues of future work have been identified in this study and will be explored through collaborations developed with CSIRO (Dr. James Hilton) and in future funded work. In addition to preparation of a scientific publication based on this project future avenues of study are:

- The addition of other surge propagation models (e.g. one purely driven by potential flow, using 'box' models (Esposti Ongaro et al., 2016), or Bernoulli energy approaches (Woods et al., 1998)) is being explored to fully test the limits and applicability of the level set framework.
- Exploration of the potential flow concept to identify the possibility of including additional source/forcing/sink terms that describe, in simple terms, additional physical processes during an eruption, such as surges with directionality constraints.
- Future work is also needed to identify the initial energy and extent of small volume surges, as some results (e.g. Maungataketake) do not appear to fit well to currently implemented models. More information on smaller surges may better constrain the source of these errors.

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Outputs and Dissemination

DEVORA 2018 – “Modelling small base surges” http://www.devora.org.nz/download/1444/

“Volcano plugin” https://github.com/stuartmead/volcanoplugin - Plugin for Workspace framework containing some simple approaches to surge modelling and tools for modelling volcanic hazards (co-developed with funding from EQC and previous sources).

List of key end users

- **GNS Science:** Hazard model that may be applicable for delineation of exclusion zones
- **Department of Conservation:** Model that is particularly relevant for hazards along Tongariro volcanic centre
- **Ruapehu Alpine lifts:** Potential end-users of modelling products, particularly for lahars generated by surges.
- **DeVORA/Auckland City Council:** To identify potential surge extents for use in emergency management group plans.