

A GIS MODEL FOR INFRASTRUCTURE VULNERABILITY
AND ITS APPLICATION TO VOLCANIC HAZARDS
ON THE ISLAND OF HAWAI'I

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A Practicum

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ABSTRACT

This practicum is a partnership with the Hawaiian Volcano Observatory (HVO) and was conducted within the framework of vulnerability assessment. In short, a vulnerability assessment investigates the value, in quantity and cost, of infrastructural entities potentially lost in a modeled hazard event. This paper describes a vulnerability model that assesses the impacts of a lava flow to property and infrastructure on the Island of Hawai'i. Created using the ModelBuilder object programming capability of ArcGIS 10.3, the Lava Flow Vulnerability Model investigates four categories of potentially vulnerable infrastructure: streets, structures, agriculture, and critical infrastructure. Critical infrastructure losses are counted per category, and the remaining three components are assessed in terms of both physical quantities lost and the estimated costs associated with those damages. The model produces outputs in both tabular and spatial form. It is designed to function consecutively and seamlessly with HVO's existing lava flow inundation models. Furthermore, it returns results in minutes, significantly increasing the efficiency of the agency's vulnerability assessment process. The Lava Flow Vulnerability Model was generalized to create a second model with even greater versatility. This Hazard Vulnerability Model is adaptable to any locality and to other hazards that leave behind a damage "footprint"; thus, it has broad applicability across the realm of hazard and vulnerability studies.



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April 16, 2019

Dr. Rebecca Hawley
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Dear Dr. Hawley:

This letter is to acknowledge the contribution of Shauna Bladt's Thesis work titled, A GIS MODEL FOR INFRASTRUCTURE VULNERABILITY AND ITS APPLICATION TO VOLCANIC HAZARDS ON THE ISLAND OF HAWAI'I, a vulnerability model, to the U.S. Geological Survey's Hawaiian Volcano Observatory.

When I first began this line of research (2002), "assessing the economic impact (now termed vulnerability) of lava flows", some colleagues belittled my endeavor as outside the scope of geologic research. Now it seems that volcano science research has embraced vulnerability analyses as standard practice and there is a movement that vulnerability analyses should be included in a comprehensive hazards assessment for volcanoes.

Shauna's project has 3 main objectives:

1. Given the input of a hazardous event (e.g. lava flow), the model a) identifies property and infrastructure components threatened by the hazard and b) assesses the potential impact of the hazard scenario in terms of quantity lost (e.g. miles of road buried) and, when feasible, of the associated cost.
2. The model provides outputs in both tabular and spatial (map) form.
3. The model runs consecutively and seamlessly with HVO's existing models for lava flows and other volcanic hazards. That is, the vulnerability model operates as an extension to existing hazard models.

All three of the objectives, she attained, are substantial improvements over the way we used to conduct the vulnerability analysis. Originally, we would take the hazard footprint and intersect it with the infrastructure layers one by one. Export the tables to excel, enter our cost factor (the cost of road by type per mile) and tabulate the results.

When a volcano erupts emergency managers want to quickly identify the plausible downslope areas, their communities, and infrastructure in harm's way. With this information they decide how to deploy resources to cope with the event; plan evacuation(s) and allocate resources.

The vulnerability model (assessment) is intended to make asset allocation more efficient and effective and to facilitate emergency response activities. In the long-term, the assessments can show what is at risk in terms of critical infrastructure (i.e. power plants, etc....). Land-use planning is the most effective tool to mitigate lava flow hazards. Vulnerability models provide away for planners assess the economic impacts and if warranted to limit the exposure to lava flow hazards by moving critical infrastructure to less hazardous areas.

Ms. Bladt's model has greatly improved the efficiency of our vulnerability assessments by improving the work-flow, increasing the speed, reducing the possibility of human error (transcription), running seamlessly with our existing hazards models and compiling the results in tabular and map-based (GIS) products.

Another significant value added contribution was Shauna's addition of looking at land-use and configuring away to assess the economic impacts of losing agricultural lands. This was something we did not do in our model before!

We will use this model in all of our future assessments and I plan to share it with the Volcano Science Center to be used for all kinds of volcanic hazards!

Sincerely,

A handwritten signature in black ink that reads "Frank A. Trusdell". The script is cursive and fluid, with the first letters of each word being capitalized and prominent.

Frank A Trusdell
Geologist

LIABILITY STATEMENT

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1. Introduction

1.1. Background: Volcanoes of Hawai'i Island

The Island of Hawai'i is composed of five shield volcanoes (Fig. 1). Kohala has not erupted in over 60 millennia and is considered dormant. Mauna Kea, which last erupted 4000 years ago, is also dormant, and Hualālai, where the last recorded eruption took place in 1800-01, is active. The two most active volcanoes, Kīlauea and Mauna

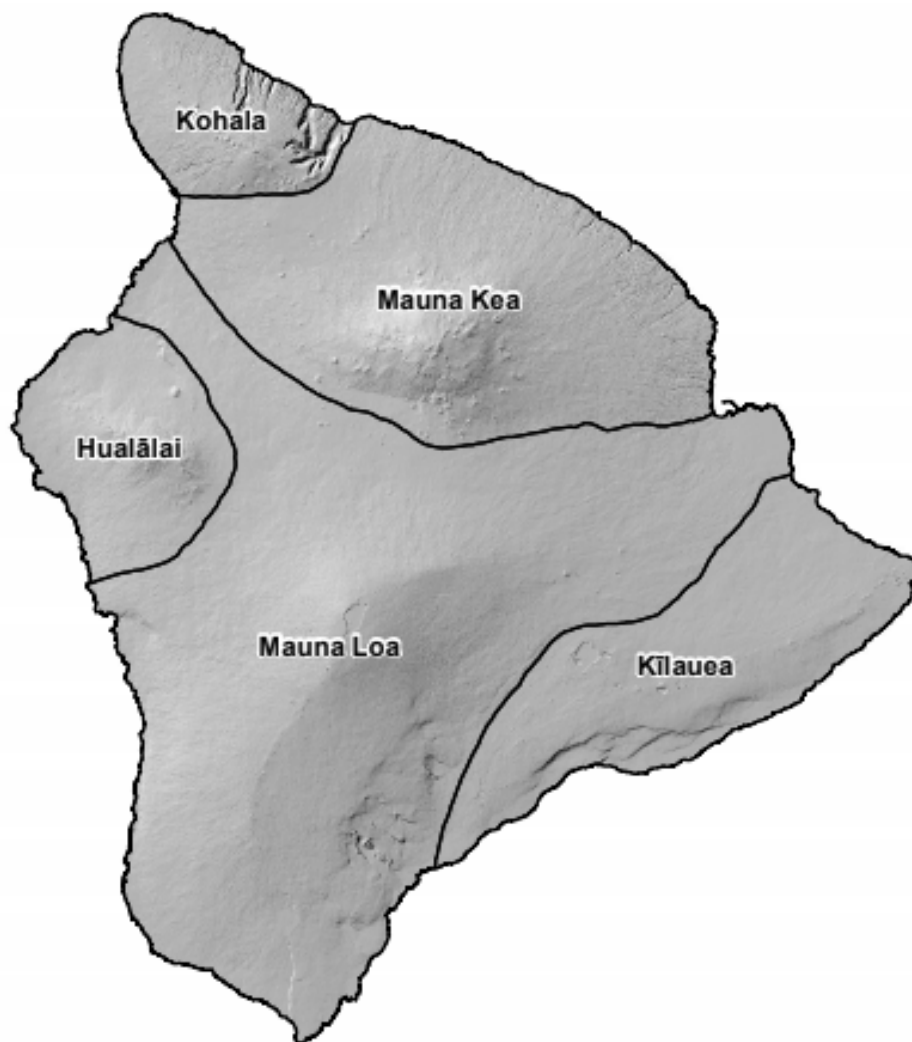


Figure 1: Volcanoes of the Island of Hawai'i. This figure is composed of a digital elevation model of the island (National Oceanic and Atmospheric Administration 2007) and volcano boundaries inferred from the limits of lava flow hazard zones (Wright et. al. 1992) digitized by the State of Hawaii Office of Planning.

Loa, pose the greatest threat to the island's communities and their inhabitants. Kīlauea continually erupted lavas from its east rift zone from 1983 to September 2018 and is among the most active volcanoes in the world. Mauna Loa is the world's largest active volcano and has erupted thirty-three times since 1843 (Trusdell 1995), most recently in 1984 (Lockwood and Lipman 1987). The 1984 eruption of Mauna Loa produced a lava flow that came within 4.5 miles of the city of Hilo, the island's largest population center (Trusdell 2012).

Inhabitants of Hawai'i face a number of hazards associated with the island's volcanoes. The volcanoes are known to produce rare explosive eruptions, volcanic smog (vog), and damaging earthquakes, which can also trigger tsunamis (Trusdell 2012). However, the greatest hazard on the island is lava (Mullineaux et. al. 1987; Trusdell 2012; Trusdell and Zoeller 2017). Hawaiian volcanoes produce voluminous eruptions of basaltic lava that can last for years or even decades. Pu'u 'Ō'ō cone on the east rift zone of Kīlauea continuously output lavas for 35 years, beginning in January 1983 (U.S. Geological Survey 2017) and persisting until the spring of 2018 (U.S. Geological Survey 2018). In that time, the Pu'u 'Ō'ō eruption produced over 4 cubic kilometers of lava. Due to such eruptive output volumes, duration, and lava tubes, flows on Hawai'i are known to travel long distances and cover broad swaths of land. Pu'u 'Ō'ō lava inundated approximately 144 km² of the island's southeast flank (U.S. Geological Survey 2017). Flows from Mauna Loa have traveled more than fifty kilometers from their source vents (Trusdell 2012; Trusdell and Zoeller 2017). The destructive nature of lava coupled with large inundation footprints and high frequency of occurrence make lava flows particularly hazardous to the island's communities.

Meanwhile, Hawai'i has seen a great deal of population growth. The island (and county) of Hawai'i has a population of roughly 200,000 and has seen an 8.3% population increase since 2010, making it the fastest growing county in the state (U.S. Census Bureau 2017). Developmental pressure coupled with lower land prices motivates developers to build new infrastructure on the flanks of the island's active volcanoes despite the risks posed by volcanic hazards. It is estimated (Trusdell 2012) that \$2.3 billion in infrastructure was constructed on Mauna Loa's flanks alone between the volcano's 1984 eruption and 2002. Due to this growth, and because most of the island's communities are susceptible to lava flow inundation (Trusdell 2012) and other hazards, vulnerability assessment is a critical component of county planning and emergency management.

1.2. The Practicum Purpose: Modeling Infrastructure Vulnerability

The Hawaiian Volcano Observatory (HVO), part of the U.S. Geological Survey's Volcano Hazards Program, plays a critical role in the assessment of volcanic hazards and the threats they pose to communities on the Island of Hawai'i. HVO's mission is to study and monitor Hawaii's volcanoes to enable timely and accurate warning of hazardous events and increase awareness among Hawaii's residents (Trusdell 2012). HVO scientists serve as advisers to the County and State Civil Defense, which head emergency response efforts, as well as to the public. This practicum is a partnership with HVO and was conducted within the framework of vulnerability assessment. In short, this vulnerability assessment investigates the value, in quantity and cost, of infrastructural entities potentially lost in a modeled hazard event. The purpose of the

practicum was to construct an ArcGIS vulnerability model that assesses the impacts of a volcanic hazard event on infrastructure and property on the Island of Hawai'i.

This model is limited to an assessment of the exposure and physical vulnerability of infrastructure based on HVO's existing lava flow hazard models (see Section 2.3). Exposure is defined in this practicum as the presence of elements-at-risk within a hazard area. Hazard areas are provided by the existing lava flow models. Physical vulnerability is defined as the value, in quantity and/or cost, of infrastructural entities potentially lost in the modeled hazard event. Thus, the vulnerability of each element-at-risk is the product of its exposure and its value (see Fig. 2). This definition reveals two important traits of the model's approach. It performs a quantitative analysis of physical vulnerability, and it adopts the understanding that total losses of exposed entities are expected in the case of a lava flow.

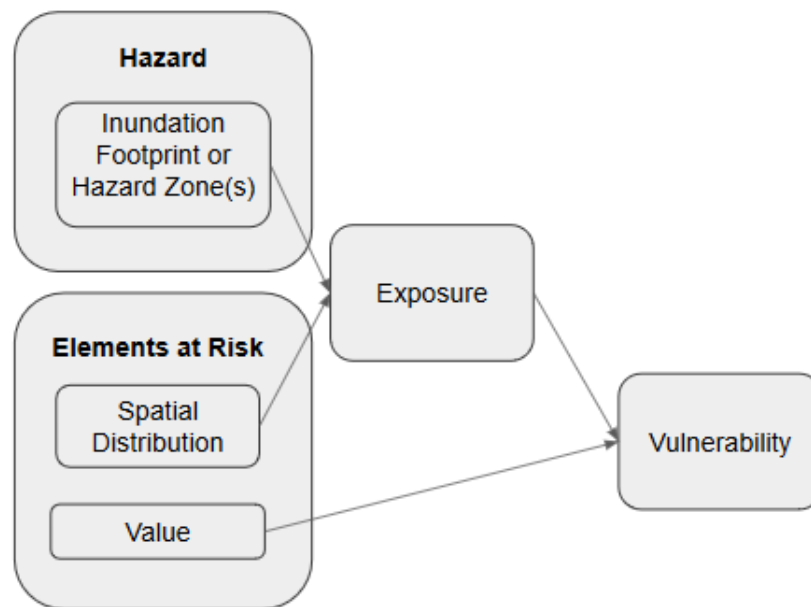


Figure 2: Progression of the Vulnerability Assessment Conducted in this Practicum, as described in Section 1.2.

1.3. Model Objectives

The model presented here meets all three of the following objectives:

1. Given the input of a hazardous event (e.g. lava flow), the model a) identifies property and infrastructure components threatened by the hazard and b) assesses the potential impact of the hazard scenario in terms of quantity lost (e.g. miles of road buried) and, when feasible, of the associated cost.
2. The model provides outputs in both tabular and spatial (map) form.
3. The model runs consecutively and seamlessly with HVO's existing models for lava flows and other volcanic hazards. That is, the vulnerability model operates as an extension to existing hazard models.

1.4. Practicum Scope

This paper delivers a vulnerability assessment limited to the study of Mauna Loa and Kīlauea volcanoes and regions threatened by their lava flows. It accounts for the most comprehensive sample of property and infrastructural entities threatened by Mauna Loa and Kīlauea as available data allows. Actual probabilities of lava flow occurrence are not estimated; thus, a full risk assessment is outside the scope of this practicum, which is limited to an assessment of exposure and physical vulnerability as defined in Section 1.2. However, the vulnerability model demonstrated herein is flexible enough to be applicable to lava flows and additional hazards in the Hawaiian Islands and around the world.

1.5. Project Justification

HVO's mission is to study and monitor Hawaii's volcanoes to enable timely and accurate warning of hazardous events and increase awareness among Hawaii's residents. The vulnerability model constructed during this practicum contributes toward the realization of that mission. It is an improvement upon the Observatory's prior GIS methodology for vulnerability assessment, a brute-force process in which vulnerability results were manually compiled for each infrastructure category (roads, bridges, schools, parcels, electrical substations, etc.), shapefile by shapefile, in a process performed separately from the models that predict hazard scenarios and corresponding threatened areas.

The new vulnerability model accounts for all property and infrastructure elements within a single model cycle and integrates seamlessly and consecutively with existing hazard models. In a matter of minutes, it accomplishes an analysis that requires hours, if not days, to complete manually; thus, it significantly improves the efficiency of HVO's vulnerability assessment system and process. This model's seamless and consecutive relationship to existing inundation models also improves the accuracy of its outputs, as there is less human involvement, and thus less potential for error, in the assessment process. Therefore, by improving the accuracy and efficiency of their vulnerability assessment system, this model contributes toward the fulfillment of the Observatory's mission to provide timely and accurate warning of hazardous events.

2. Literature Review

2.1. Framework: Vulnerability Assessment

Vulnerability assessment is a key component of risk assessment, a common tool used in studies of natural and manmade hazards and their potential impacts to affected communities. The goal of a risk assessment is to investigate the potential for damage to property and services in a particular area due to a predicted hazard (Wilson et. al. 2014). Geographic information systems are crucial tools in risk assessment studies, as they provide the advantageous abilities to efficiently explore great numbers of hazard scenarios (van Westen 2013) and manage the large geodatabases required to track and store the volumes of information utilized in risk analyses. GIS risk assessment models, such as the U.S. Federal Emergency Management Agency's Hazus software (FEMA 2018), predict the extent of a modeled hazard and calculate the losses expected to result from the hazard event. These losses can be assessed in terms of lives, infrastructure, and functionalities of networks such as transportation and communications systems. The Hazus software includes tailored risk assessment methodologies for earthquakes, floods, hurricanes, and tsunamis that provide loss estimates in both spatial and tabular media (FEMA 2018). However, it is important to note that the program lacks an assessment methodology specific to lava flows. Developed with ArcGIS, Hazus demonstrates the modern risk assessment framework and is the national standard for natural hazard risk modeling (van Westen 2013).

The development of the modern framework for risk assessment reflects a recent shift in the field of disaster management from the reactive approach of response and recovery to a much more proactive focus on risk reduction and mitigation (van Westen

2013). This widely accepted risk assessment framework (Dominey-Howes and Goff 2013; Wilson et. al. 2014; Biass et. al. 2013; Scaini et. al. 2014; van Westen 2013) involves a process that investigates three components of risk: hazard, exposure, and vulnerability (Fig. 3). The first step of the risk assessment, then, is the hazard assessment, wherein a potential hazard is identified. The characteristics and parameters that determine the hazard's spatial extent and intensity are estimated. Hazard analyses typically draw upon an inventory of previous hazard events in the study area and establish patterns in their extents, intensities, frequencies, and consequences. Environmental factors - such as geology, hydrology, topography, and soil and vegetation types - that influence the hazard's spatial extent and severity gradient, are considered. The final parameters accounted for in hazard analyses are

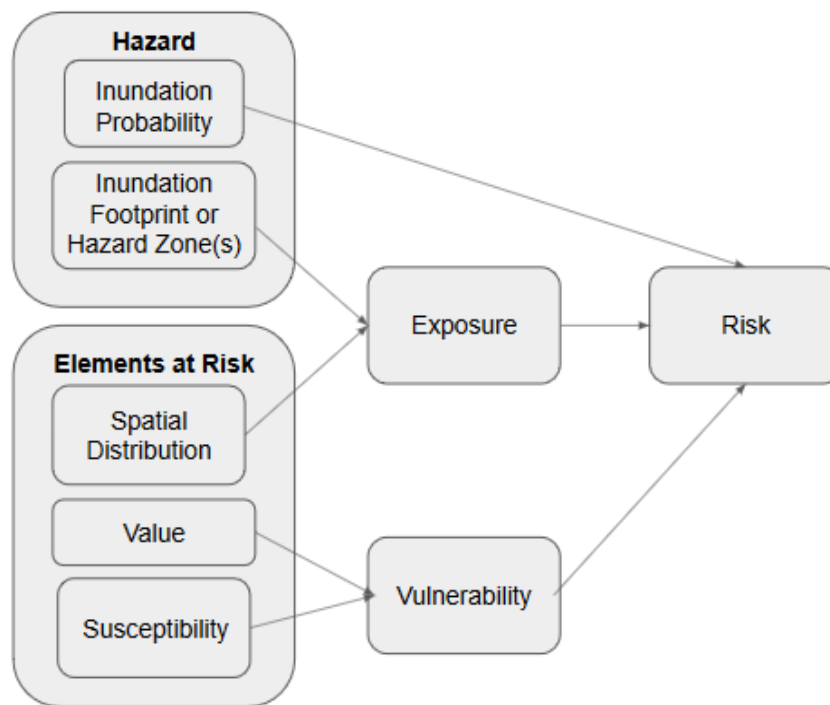


Figure 3: General Progression of a Risk Assessment, as described in Section 2.1.

the locations of triggering factors. A volcanic vent is one example of a triggering factor, which constitutes the origin of the potential hazard (van Westen 2013). Once hazard characteristics are determined, a number of hazard scenarios are modeled. In a GIS setting, these models produce map features displaying one or more hazard areas, which are geographic areas that the hazard is likely to impact. The hazard area can be an inundation “footprint” that depicts the extent of a hazard of a particular type originating from a single trigger point (Alcorn et. al. 2013; Trusdell et. al. 2017). Alternatively, simulated hazard scenarios from many origin points are often utilized to divide the study area into hazard zones (Favalli et. al. 2009; Trusdell and Zoeller 2017; Favalli et. al. 2012). The goal of zone mapping is to delineate hazard zones based on inundation probability, types, severities, and/or frequencies of the studied hazard (van Westen 2013). Lava flow hazard assessment methodologies developed and employed at HVO are discussed in Section 2.3.

Once the hazard analysis is complete, the second component of risk assessment begins. This is the exposure assessment. Exposure is defined as the degree to which elements-at-risk come into contact with the hazard. Thus, in order to evaluate exposure in a GIS setting, a database of existing elements-at-risk within the area of study is needed. Relevant data may include spatial information on populations, habitats, property, agricultural lands, and infrastructure such as buildings, roads, and utility networks. Critical facilities like hospitals and fire stations are particularly important to include in this database. Land use data are commonly utilized to assess elements at risk, as they reveal building types and agricultural lands, and provide insight as to where populations may be concentrated. Elements-at-risk can be quantified with physical

counts (e.g. number of residences), dimensional measurements (e.g. length of road), or monetary values (van Westen 2013). They are often represented in vector format as a collection of feature classes that each demonstrate the spatial distribution of a specific entity type (FEMA 2018). Alternatively, for imagery or land use data, a raster representation of elements-at-risk can be obtained by superimposing a grid on the image or land use raster and calculating the percentage of or area within each grid cell occupied by a particular entity type (Favalli et. al. 2009; Favalli et. al. 2012). An exposure map is produced in GIS by an overlay of the hazard zone or inundation footprint upon a collective map of the elements-at-risk (Wilson et. al. 2014; Dominey-Howes and Goff 2013; Alcorn et. al. 2013; Jenkins et. al. 2017).

Concurrent with or following the exposure assessment is the third component, the vulnerability assessment. The definition of vulnerability, and thus the scope of the vulnerability assessment, is widely disputed (van Westen 2013; Scaini et. al. 2014). Some studies (Biass et. al. 2013; Scaini et. al. 2014; Alcorn et. al. 2013; van Westen 2013) use a systemic definition of vulnerability. Systemic vulnerability is the susceptibility of communities and the entities within them to impact from hazards based on physical, social, economic, and environmental factors and the interdependencies of these factors. Physical vulnerability is the likelihood that infrastructure will be damaged when exposed to a hazard. Social vulnerability encompasses the traits of a person or population, such as age, education level and disability status, that may influence their ability to respond to a hazard. Economic vulnerability is the potential for a hazard to damage a community's income, impact its earning potential (future losses due to cessation of economic activity), interrupt imports and exports, etc. Environmental

vulnerability explores the capacity of an ecosystem to tolerate a hazard over time and space. The final element of systemic vulnerability is territorial vulnerability, which is a weighted average of the other four elements that accounts for their interconnectedness within the at-risk community. Each component of systemic vulnerability is assessed qualitatively (van Westen 2013). That is, each element-at-risk is assigned a high-to-low index or indicator for each of physical, social, economic, and environmental susceptibility. A weighted average of these indicator values is taken for each entity in order to assign it a territorial, or overarching, vulnerability score.

Other studies (Heesen et. al. 2014; Diefenbach et. al. 2015; Alberico et. al. 2015) focus on a thematic approach limited to the element of physical vulnerability. While this approach cannot match the thoroughness of a systemic vulnerability assessment, it is far more efficient and still supports the identification of infrastructure that may benefit from mitigation measures, prioritization of risk reduction resources, and quantification of potential damages and losses of infrastructure in hazard scenarios (Wilson et. al. 2014; Diefenbach et. al. 2015). Physical vulnerability can be assessed qualitatively in a process similar to the systemic vulnerability assessment described above. Typically in these thematic physical vulnerability studies, susceptibility themes are chosen first. Second, numeric vulnerability indicators are assigned to each theme to represent levels of susceptibility within that theme. For example, one theme might encompass a building's level of structural soundness, and another the degree to which the building is shielded by topography and other structures. Finally, each theme is assigned a weight, and a weighted average of all the assigned indicators across all themes is calculated, resulting in a global vulnerability indicator. In GIS, a thematic vulnerability assessment is

conducted using spatial multi-criteria evaluation (SMCE) (van Westen 2013). An SMCE analysis using vector data requires that feature classes representing elements-at-risk have attribute fields that contain the vulnerability indicators. The global vulnerability indicator is obtained with a field calculator or a model programmed to perform the necessary weighting and averaging operations. The vulnerability assessment can also be accomplished using raster data. Each theme has its own raster, in which cell values reflect the indicators of that theme. Spatial analysis tools are then employed to weigh and average the cell values and produce an output raster with cell values indicating the global vulnerability score for each cell.

Physical vulnerability is also commonly assessed in a quantitative manner (van Westen 2013; Trusdell et. al. 2017; Favalli et. al. 2012). A quantitative analysis of physical vulnerability determines for each class of elements-at-risk a tangible potential loss measured in a quantity, such as a count of entities lost, a sum of acres destroyed, or the predicted monetary value of repairs to and replacement of the infrastructure. In a geographic information system, a quantitative assessment of physical vulnerability relies on the presence of data like building values and land areas in addition to the vulnerability indicators for those elements-at-risk. Each quantity value is weighed by a vulnerability indicator and then the weighted quantities are tallied using statistical analysis tools. In the case of a lava flow, total loss of exposed entities is expected (Favalli et. al. 2012; Jenkins et. al. 2017). Thus, in this practicum, vulnerability indicators are assumed to equal 1 and the quantitative physical vulnerability of an element-at-risk is defined as its value in quantity and/or cost. With the hazard, exposure, and

vulnerability components accounted for, an analyst may proceed with the risk assessment.

Risk analysis adds a component of probability to the exposure and vulnerability assessments. Risk is the probability of occurrence of damages and losses resulting from the intersection of the natural hazard with vulnerable entities (van Westen 2013). To complete the overarching risk assessment, risk is calculated as the product of the exposure and vulnerability variables (Dominey-Howes and Goff 2013; Wilson et. al. 2014; Biass et. al. 2013; Scaini et. al. 2014). A high degree of exposure coupled with a high vulnerability yields the greatest probability of damage and loss, and thus the greatest risk to exposed entities. In a GIS-based risk assessment, the risk per element is determined by an overlay of the exposure and vulnerability variables using spatial analysis and geoprocessing tools. The result is the typical risk map, a raster or polygon surface that reflects the spatial distribution of risk to a number of different areas or entities. Some studies (Favalli et. al. 2009; Fourneir d' Alba 1979; Favalli et. al. 2012) incorporate the probability of the hazard's occurrence into the risk assessment. In this methodology, risk is defined as the product of hazard, vulnerability, and the value of the threatened infrastructure. Some researchers take the risk assessment process a step further by analyzing risk across multiple trigger points. The product of this "reverse" risk assessment is a vector or raster surface of potential trigger points, such as volcanic vents, where the value at each trigger point is the sum of the calculated risk to all localities or entities in the path of a hazard originating from that location (Favalli et. al. 2009). This expanded methodology is particularly useful for studies of volcanic risk because it yields a map that details the total risk to property and infrastructure from an

eruption originating at any or all points on the surface of the volcano. While the typical risk map is most useful for long term planning, this reverse map is ideal for fast consultation and decision making during a particular hazard event (Favalli et. al. 2012). Hazard probabilities were not estimated during this practicum; thus, a full risk assessment was not performed. The model is limited to the assessments of exposure and physical vulnerability in the form of quantities lost and associated costs. Created within the framework of vulnerability assessment, it builds upon the broad foundation of HVO's volcano hazard studies.

2.2. History and Hazards of Hawai'i Island's Volcanoes

HVO published its first hazard assessment of Hawaiian volcanoes in the mid-1970s (Mullineaux and Peterson 1974). This paper discusses a number of volcano-related hazards to which the Hawaiian Islands are prone, focusing primarily on Mauna Loa and Kīlauea. It explores the likely extent, frequency, and severity of these hazards. Mullineaux and Peterson produced accompanying maps dividing the islands of Hawai'i and Maui into various lava flow hazard zones. In the thirty years since, the Observatory has continued to expand on this work, revising and refining the boundaries of these hazard zones (Mullineaux et. al. 1987; Heliker, 1990). The final revision (Wright et. al. 1992) partitions Hawai'i into nine hazard zones depicting potential for lava flow inundation in various parts of the island (see Fig. 4). The boundaries of these hazard zones are defined based on proximity to the summits and rift zones of the active volcanoes, distribution of historical flows, and topography. GIS analysis was integrated into the Observatory's hazard assessment methodology in the mid-1990s, in a process that used the spatial distribution of past lava flows to calculate probabilities of

occurrence at particular localities and rates of coverage for various flow scenarios on the flanks of Mauna Loa (Kauahikaua et. al. 1995). The constantly-morphing topography and behavior of Hawaii's volcanoes and continuing expansion of the island's communities demands ongoing revisions of these hazard assessments. See Section 2.3 for a detailed discussion of HVO's modern lava flow hazard assessment methodologies, including the modeling of single lava flow paths and the development of lava flow inundation zones for Mauna Loa and Kīlauea.

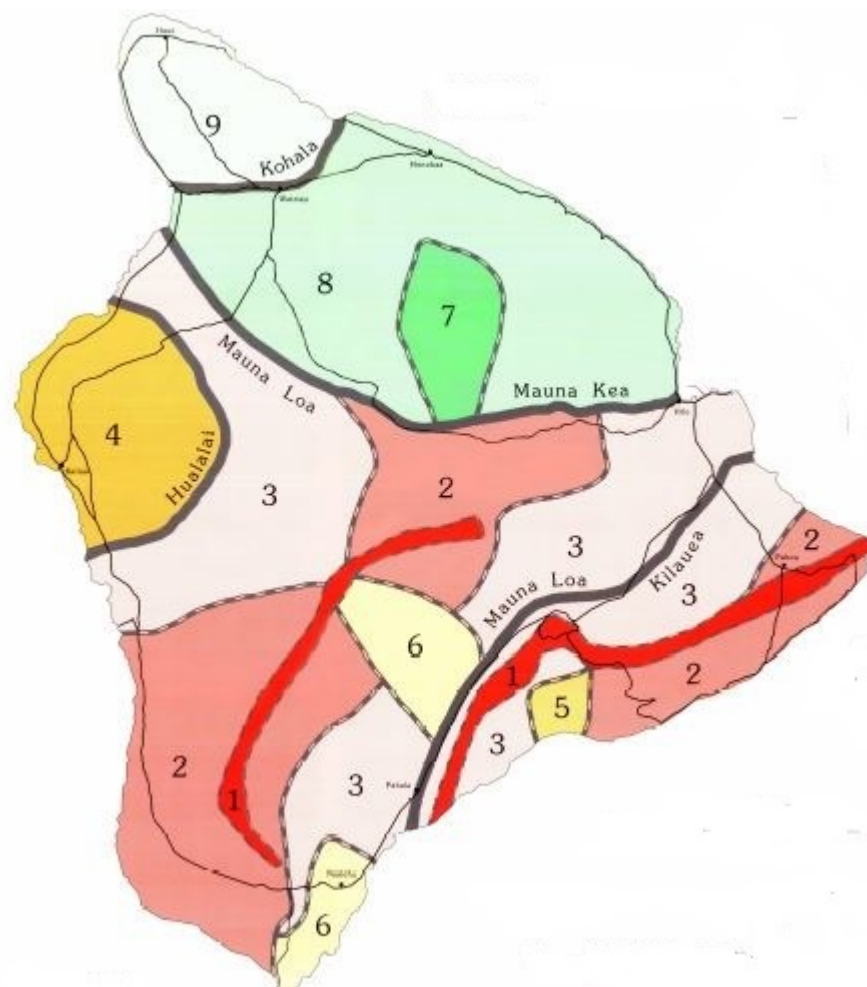


Figure 4: Lava Flow Hazard Zones on Hawai'i Island. Zone 1 faces the greatest hazard, and Zone 9 the smallest. Hazard zone 1 illustrates the summit calderas and rift zones of Mauna Loa and Kīlauea. Solid black lines are volcano boundaries. Dashed lines are hazard zone boundaries. Major roads and communities are also shown (from Wright et. al. 1992).

Mauna Loa is the primary focus of modern hazards research at HVO, as its location, sheer size, and the frequency and severity of its historical eruptions make it the most dangerous volcano and the greatest threat to life and property on the Island of Hawai'i (Rubin 2016). Rising more than 4000 meters above sea level and comprising roughly 50 percent of the island's land area, Mauna Loa stands among the largest and most active volcanoes in the world. Over the past three millennia, Mauna Loa has erupted on average once every six years, and 33 eruptions have been recorded since 1843. Researchers have identified three primary eruptive regions on Mauna Loa: the summit caldera, called Moku'āweoweo; the northeast rift zone; and the southwest rift zone (Trusdell 2012; Tilling et. al. 2010). Eruptions of Mauna Loa typically commence within Moku'āweoweo, where fissures produce lava fountains that feed lava flows. In half of summit eruptions, vents remain within the summit area and lava flows leaving the caldera generally travel less than 10 kilometers. However, the other fifty percent of Moku'āweoweo eruptions involve the eventual migration of eruptive vents down either of Mauna Loa's rift zones. The northeast rift zone (NERZ) slopes gently and is relatively remote, and lava flows originating within the NERZ take weeks to months to reach populated areas (Trusdell 2012). On the contrary, Mauna Loa's southwest rift zone (SWRZ) has steeper slopes and is proximal to communities in the island's South Kona and Ka'ū districts. Consequently, lava flows originating in the SWRZ can reach these communities within hours. Thus, risk of inundation and subsequent loss of infrastructure in populated areas is significantly higher for SWRZ eruptions than for those from the NERZ. Radial vents, defined as eruptive sites outside the caldera and rift zones, are also known to occur, but are much less predictable and can open much lower on the

volcano's slopes, and thus much closer to population centers, than the primary vents in the summit and rift zones (Trusdell 2012). Four radial vents have formed on the island in the last 200 years, favoring the volcano's northwest flank (Lockwood and Lipman 1987). While future eruptions of Mauna Loa are inevitable, the volcano has remained quiet since the 1984 eruption that sent lava within 4.5 miles of the city of Hilo. However, Kīlauea, Mauna Loa's southern neighbor, has been far more active in recent history.

Kīlauea is the youngest of Hawaii's volcanoes and constitutes the southeasternmost portion of the island. At 1247 meters above sea level (USGS 2018a), it rises to one third the height of Mauna Loa, but shares the same volcanic structure. Like its bigger neighbor, Kīlauea has three primary eruptive regions: a summit caldera and two rift zones oriented northeast and southwest (Tilling et. al. 2010). The historical record of volcanic activity on Kīlauea begins with oral documentation of an explosive and deadly eruption that occurred in the summit region in 1790 (Rubin 2016). However, explosive eruptions are rare on Kīlauea, which is far better known for its relatively docile and sustained eruptions of lava. One such eruption, beginning in 2008, produced a well-known lava lake within the summit's Halema'uma'u Crater (Wright and Klein 2014). This molten lake endured for nearly a decade, drawing countless visitors to Hawai'i Volcanoes National Park until its withdrawal and disappearance in the spring of 2018. Kīlauea's southwest rift zone has not erupted since 1974 and has not produced a significant lava flow since 1919 (Macdonald et. al. 1983). The land downslope of the southwest rift is sparsely populated, further reducing, but not eliminating, the risk its eruptions pose to proximal communities and infrastructure.

However, in stark contrast, the east rift zone (ERZ) has seen a high frequency of activity for the past half-century, producing eruptions of lava an average of once every 1.5 years between 1955 and 1983 (Macdonald et. al. 1983) and continuously through September 2018 (USGS 2018b). The high lava flow hazard in the area of Kīlauea's east rift is coupled with elevated vulnerability. Development in the island's Puna district has placed a large number of residents and elements-at-risk within a few miles of - and in some cases directly upon - the rift zone. A 1960 eruption of the lower ERZ destroyed most of the town of Kapoho (MacDonald 1962), and in 1990, the town of Kalapana and surrounding subdivisions fell victim to lava flows produced by the Pu'u 'Ō'ō-Kūpaianaha eruption on the upper ERZ (Tilling et. al. 2010). The remarkable timeline and output of the eruption at Pu'u 'Ō'ō is summarized in Section 1.1. The inundation of Kalapana resulted in the loss of more than 180 structures, with the cost of damages totaling \$61 million (Oregon State University 2018). The district of Puna once again faced widespread loss of property and infrastructure in the wake of the summer 2018 eruption of Kīlauea's lower ERZ. Losses from this eruption are further explored via vulnerability assessment in Section 4.2.

2.3. Lava Flow Hazard Assessment Methods of the Hawaiian Volcano Observatory

HVO volcanologists have studied a great number of summit and rift zone eruptions of Mauna Loa and Kīlauea, and radial vents on Mauna Loa, in pursuit of one critical question: when a particular vent erupts, what areas are threatened by its lavas? In answer to this question, the researchers have developed two hazard assessment methodologies for lava flows, both implemented with ArcGIS models. The first method (Trusdell et. al. 2017) delineates the most likely footprint of a single lava flow (Fig. 5).

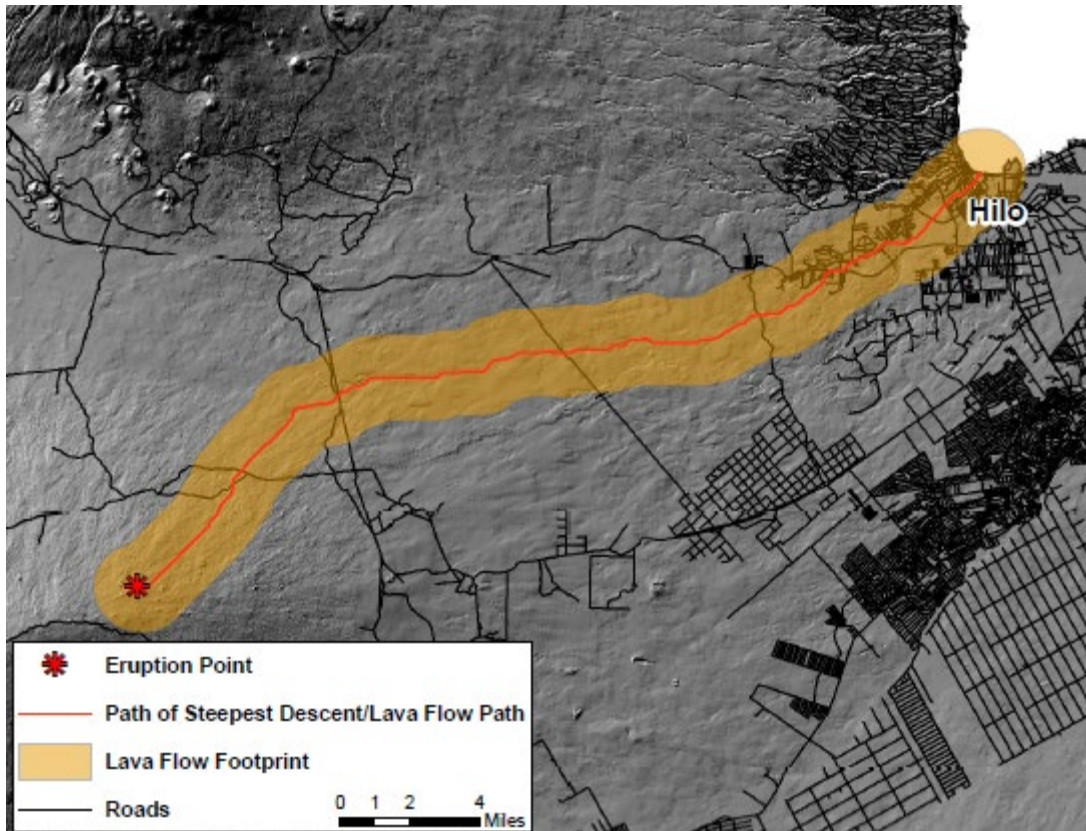


Figure 5: Results of the Single Eruption Path Method, as discussed in Section 2.3. The three vector outputs are superimposed upon a digital elevation model of Hawai'i Island (National Oceanic and Atmospheric Administration 2007) and a Hawai'i roads shapefile (Trusdell and Lockwood 2017).

The second method (Trusdell and Zoeller 2017) is derived from the first and uses multiple flow paths to produce one or more lava inundation zones (Fig. 6). Both lava flow hazard assessment methods and the GIS models they utilize were developed by HVO geologists prior to the start of this practicum. However, the lava flow impact assessments performed by these two models comprise the critical first step in the vulnerability assessment described herein (Fig. 2).

The first and simplest lava flow hazard assessment method (Trusdell et. al. 2017) calculates the most likely path of a single lava flow originating from a particular vent. Based on topography and the behavior of past flows in the area of the chosen vent, a two-dimensional flow footprint that represents the probable area of lava inundation in

the modeled eruption is produced. This method is an aggregation of two major processes. First, a polyline flow path is created by determining the line of steepest descent from the source vent to the ocean. Second, since lava flows have surface area, a buffer is applied to the steepest descent line to simulate flow width and produce the two-dimensional flow footprint. The linear flow path is calculated using a single eruption path model that combines ArcMap's hydrology toolset and the Cost Path tool.

To run the single eruption path model, inputs of an eruption site and a digital elevation model (DEM) are required. The eruption model uses the hydrology toolset to obtain flow direction and flow accumulation rasters from the elevation data. Hydrology tools are appropriate for modeling lava flows because lava, like water, is gravity driven and will generally follow the steepest descending topography (Favalli et. al. 2009). The flow direction raster records the cardinal direction from each cell to its steepest downslope neighbor(s). The flow accumulation raster, created from the flow direction raster, displays for each output cell the combined flow from all cells feeding into that cell. The flow direction and flow accumulation rasters are utilized by the Cost Path tool to consecutively identify each cell on the path of steepest descent between the specified eruptive vent and the island's shoreline. The final step of the single eruption path method is the application of a buffer to the line of steepest descent, which produces the two-dimensional lava flow footprint (Fig. 5). The width of the buffer is an average of the widths of past lava flows in the vicinity of the simulated flow, as determined from geologic mapping.

The second and more complex lava flow hazard assessment method (Trusdell and Zoeller 2017) also calculates lines of steepest descent over a DEM from a vent

system to the ocean. However, this second method considers multiple eruptive scenarios, and instead of a lava flow footprint, it establishes one or more inundation zones (Fig. 6). A lava inundation zone is defined as the full area that could possibly be overrun by lava from a particular vent system, such as a segment of a rift zone. Its boundaries are determined based on the topography surrounding and downslope from the vents and the limits of recent and prehistoric coverage of lava flows from that rift segment. It is unusual for a lava inundation zone to be fully covered by a single eruption; additionally, the threat from erupted lava is equal throughout all areas of the inundation zone. It is important to note that lava inundation zones are separate and distinct from the lava flow hazard zones shown in Fig. 4 and discussed in Section 2.2. Hazard zones are divisions of the island ranked by level of potential for lava inundation, while each lava inundation zone simply shows the area at risk for lava coverage from a particular rift segment or summit caldera. Inundation zones are not ranked like hazard zones.

Similar to the single eruption path method, HVO's method for creating lava inundation zones consists of two processes. During the first process, a number of steepest descent lines originating from the user-specified vent system are simulated to define a general area at risk for inundation. The second process specifies the boundaries of the risk area and delineates the inundation zone. The first process of the inundation zone method uses the same hydrology and cost path analyses employed in the single eruption path method to model lines of steepest descent across a DEM. However, instead of the eruption point used to simulate a single flow path, the lava origin is a linear feature that defines a series of vents, typically comprising a segment of

a rift zone. The model can be cycled through any number of iterations to produce the desired number of steepest descent lines from random locations along the linear origin. The set of descent lines simulated by the model offer a visual of the area to which lava flows from the rift segment pose a hazard. A greater number of descent lines yields a clearer picture of the area at risk from the modeled vent system.

The second process of the inundation zone methodology utilizes an inverted DEM to detect ridgelines which, according to the DEM modeling, are natural barriers to lava flows and thus define the extent of the inundation zone. The inverted DEM becomes the input for a second set of iterations of the steepest descent model utilized in the first process. However, on the inverted DEM, the least cost paths follow the lines of highest terrain, not steepest descent, back to the rift segment, and the locations of ridgelines are revealed. Finally, the ridgelines, the rift segment, and the coastline become the boundaries of a polygon that defines an inundation zone. Geologic maps of past flows from the modeled vent system are used to verify the accuracy of the inundation zones, and in rare cases, zones are adjusted to include parts of these flows that fall outside the original zone boundaries. Using this methodology, HVO geologists have mapped lava inundation zones covering the entirety of Mauna Loa (Trusdell and Zoeller 2017; see Fig. 6) and the lower east rift zone of Kīlauea. Flow footprints and lava inundation zones are the results of the two GIS hazard assessments for lava flows employed at HVO, and either can function as the hazard input for the vulnerability models designed in this practicum.

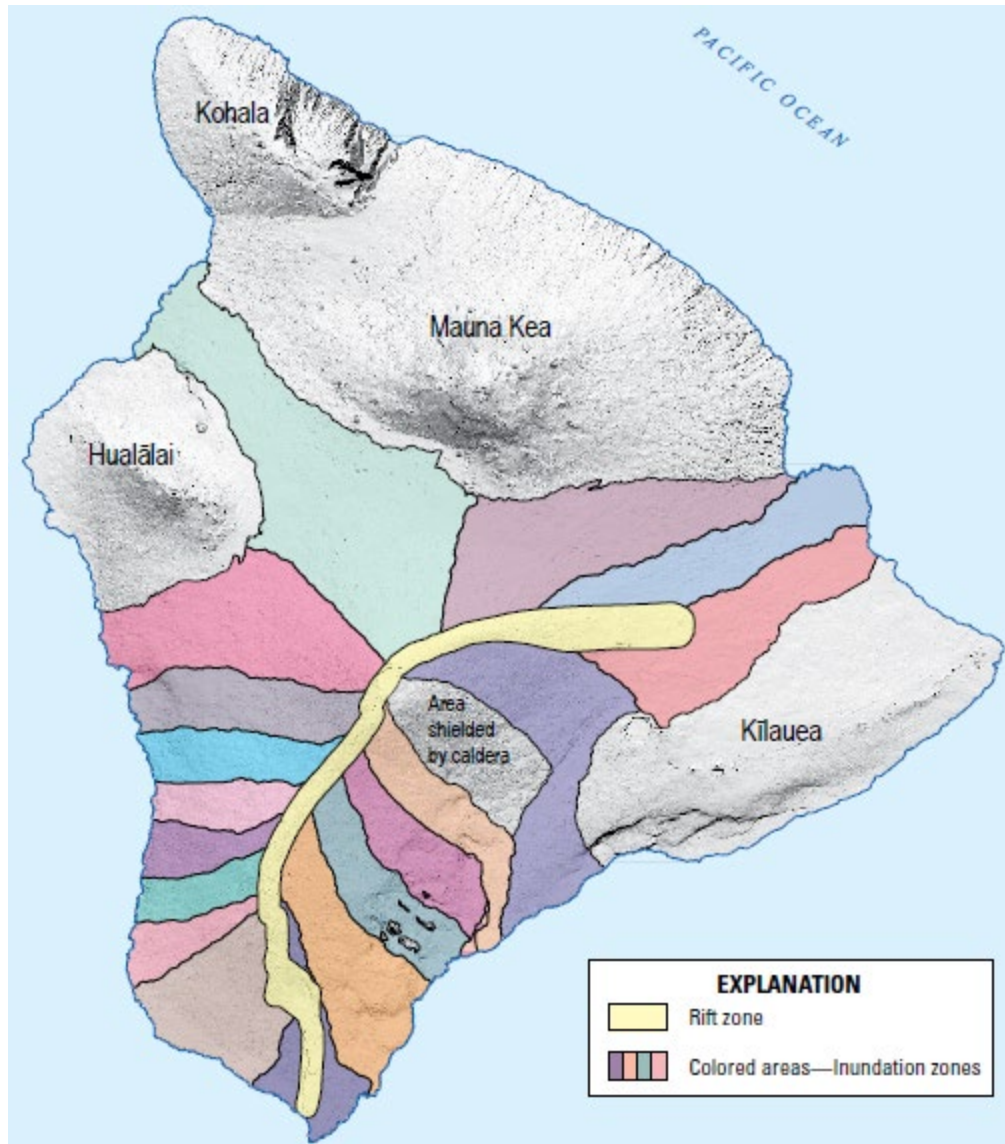


Figure 6: Lava Flow Inundation Zones for Mauna Loa. The rift zone polygon encompasses the summit caldera and the southwest and northeast rift zones of the volcano. Each inundation zone represents the area that can be inundated by the rift segment or vent system above it. From Trusdell and Zoeller 2017.

3. Methods and Practicum Chronology

3.1. Lava Flow Vulnerability Model Methodology

Constructed using the ModelBuilder capability of ArcMap 10.3, the Lava Flow Vulnerability Model assesses physical vulnerability in terms of the values - in quantities and/or costs - of infrastructural entities potentially lost to a simulated lava flow. Its process begins with the implementation of the single eruption path model discussed in Section 2.3, which is imbedded within the Lava Flow Vulnerability Model. The single eruption path model produces a lava flow footprint polygon and displays it on a map along with the eruption point. The lava flow footprint is then applied to four imbedded vulnerability submodels, each of which assesses values of expected losses for a different category of elements-at-risk. The four submodels cover the vulnerabilities of structures, streets, critical infrastructure, and agriculture. The basic anatomy of a submodel consists of input parameters, processes that act upon those parameters, and outputs produced by those processes (Fig. 7).

Three types of input parameters are required for each submodel: the lava flow footprint, infrastructure data, and value parameters. Infrastructure data are the feature classes that record the spatial distribution of elements-at-risk and data tables that contain additional information about them. Value parameters have two purposes in the model; they enable the user to choose desired units for calculated values or specify the field(s) in an attribute table that contain the data to be input to a particular process. The model's processes utilize ArcMap tools to serve four major functions. They clip the infrastructure data with the lava flow footprint to identify elements-at-risk exposed to the flow, correct geometry errors produced by the clipping process, categorize exposed

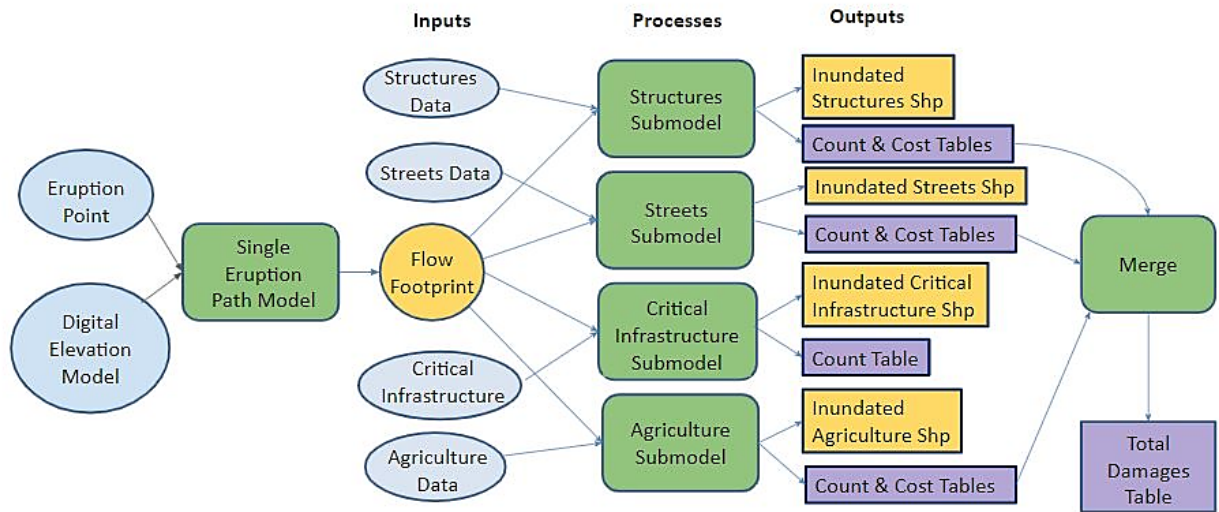


Figure 7: Summary of Components and Processes of the Lava Flow Vulnerability Model described in Section 3.1. Inputs are shown as ovals, processes in rectangles with rounded edges, and outputs in traditional rectangles. Connecting arrows indicate the progression of the model. Refer to Appendix A for detailed diagrams and documentation of the Lava Flow Vulnerability Model.

features, and perform statistical analyses on those infrastructure categories to generate counts and cost estimates. The submodels are chains of ArcMap tools where the output of one tool becomes the input of the next tool in a sequence. The final outputs of each submodel consist of one or more inundated infrastructure shapefiles, which are displayed in an ArcMap document, and some combination of count and/or cost tables. The output inundated infrastructure shapefiles contain the entities exposed to the lava flow. Count and cost tables summarize the values of losses in quantities and damage costs, respectively.

Critical Infrastructure is the most complex of the four submodels. The term critical infrastructure refers to structures, networks, and systems so vital that their destruction or incapacitation would be detrimental to public health and safety, the economy, or security. Entities that meet these criteria include but are not limited to bridges, fire and police facilities, power plants and electric substations, hospitals and urgent care centers, assisted living facilities, schools, financial institutions, and major transportation

hubs like airports, harbors, bus terminals and train stations. The first phase of the critical infrastructure submodel is iterated over all feature classes in a feature dataset. This iterated subprocess adds a category field to the attribute table of each feature class to record critical infrastructure type, clips the feature class with the lava flow footprint, and converts any non-point features to point features. This addition of the category field and conversion to point features are necessary steps because, in the second phase of the critical infrastructure submodel, all features are merged into a single output point shapefile containing all inundated critical infrastructure entities. The second output of the critical infrastructure submodel is a count table that records the number of inundated entities in each category.

The Structures submodel clips parcel or building features with the lava flow footprint to produce a shapefile showing inundated structures, a count and cost table that displays losses by structure class, and a totals table that summarizes the total count and cost of the affected buildings. The Streets submodel clips polyline street features with the flow footprint and employs a table of values by road type to yield an inundated streets polyline shapefile and two output tables. The first is a classified count and cost table that records for each road type the length of roads buried and the cost of those damages. The second is a summary table that records the total length of roads buried across all categories and the total cost of street losses. The Agriculture submodel utilizes land value data and agricultural parcels categorized by crop type. The agricultural parcels and land value data are clipped by the flow footprint and then spatially joined to produce a shapefile of inundated agricultural lands and two combined count and cost output tables. The first table records inundated area and associated

costs for each crop category. The second is a summary table that reports the total area of inundated agricultural lands and the total cost of agricultural losses.

The Lava Flow Vulnerability Model displays the eruption point, flow footprint and the output shapefiles obtained from all four submodels on a map and adds all categorized count and cost tables to the map document's table of contents. Finally, the vulnerability model merges the summary tables from the Structures, Streets, and Agriculture submodels to produce a single lava flow damages table that appears in the map document's table of contents and reports the following: total number of lost structures, total cost of lost structures, total length of inundated streets, total cost of street losses, total area of inundated agricultural lands, total cost of damage to agriculture, and a grand total cost of damages to infrastructure, which is the sum of the costs of structure, street, and agricultural losses. In the end, the Lava Flow Vulnerability Model yields eleven outputs. These are the eruption point, the flow footprint, four inundated infrastructure shapefiles, three combined count and cost tables, the categorized critical infrastructure count table, and the summary table that records total damages to infrastructure in the lava flow scenario. Visual examples of the Lava Flow Vulnerability model's outputs appear in Section 4.1 of this paper. Refer to Appendix A for flow diagrams demonstrating the progression of the Lava Flow Vulnerability Model and its submodels, and detailed descriptions of input data, value parameters, tools, and model outputs.

3.2. Tasks and Timeline of the Practicum Project

The vulnerability models presented in this paper were completed over the course of a sixteen week internship at the Hawaiian Volcano Observatory during the winter and

spring of 2018. Work on the project was composed of three major tasks. These tasks included the gathering of relevant data and assembly of an infrastructure geodatabase, the construction of the Lava Flow Vulnerability Model as described in Section 3.1, and the generalization of the Lava Flow Vulnerability Model to create the Hazard Vulnerability Model (Fig. 8), which assesses physical vulnerability of infrastructure using the inundation footprint of any hazard. These three major tasks were not completed in their given order. Instead, progress alternated among them, and they were accomplished more or less simultaneously. Refer to Appendix C for a practicum timeline, which serves as a detailed log of hours worked and progress made over the course of the practicum.

The task of assembling a geodatabase of elements-at-risk for the island of Hawai'i was crucial to this project. The database serves as a spatial library of the island's infrastructure and the source of most inputs to both models. A geodatabase was the chosen format for storage of the infrastructure data for two reasons. First, the geodatabase is a powerful and efficient organizational tool capable of storing large quantities of data that exist in a variety of formats. Second, some vulnerability model processes utilize tools that require their inputs to be in a geodatabase. The iterator employed by the critical infrastructure submodel is a prime example of such a tool. The data stored in the infrastructure geodatabase are organized into three database subsets called feature datasets. The created datasets are Roads, Critical Infrastructure, and Land Divisions and Boundaries. These feature datasets and their contents are shown in Fig. 9.

The infrastructure data collected during this practicum came from four sources;

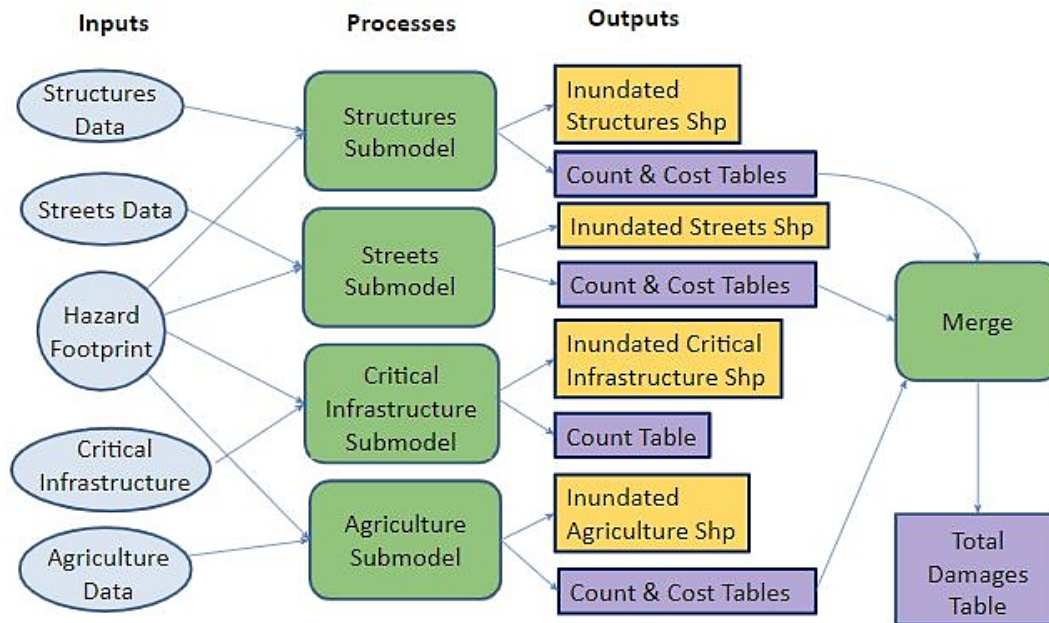


Figure 8: Summary of Components and Processes of the Generalized Hazard Vulnerability Model described in Section 3.2. Inputs, processes, and outputs are denoted in the same manner as those in Fig. 7 above. Refer to Appendix B for a detailed diagram and documentation of the Hazard Vulnerability Model.

these are the Hawaiian Volcano Observatory (HVO), the State of Hawaii Office of Planning, the U.S. Department of Homeland Security (DOHS), and the Pacific Disaster Center (PDC). The data retrieved from HVO and the online databases of the State of Hawaii Office of Planning and the DOHS are free and available to the public (State of Hawaii 2018; U.S. DOHS 2017; Trusdell and Lockwood 2017). The State of Hawaii and DOHS shapefiles were downloaded from their sources. Then, each file's metadata was imbedded within the file's item description before the files were imported to the infrastructure geodatabase. Data from the Pacific Disaster Center were obtained by HVO prior to the start of the practicum. Also pre-practicum, the single utilized HVO file, a roads shapefile, was compiled at the Observatory. In some cases multiple shapefiles contained overlapping data. For example, a handful of hospital facilities were present in the both the Hospitals feature class and the Skilled Nursing Facilities feature class. The attribute tables of such data files were visually compared, and duplicate data were

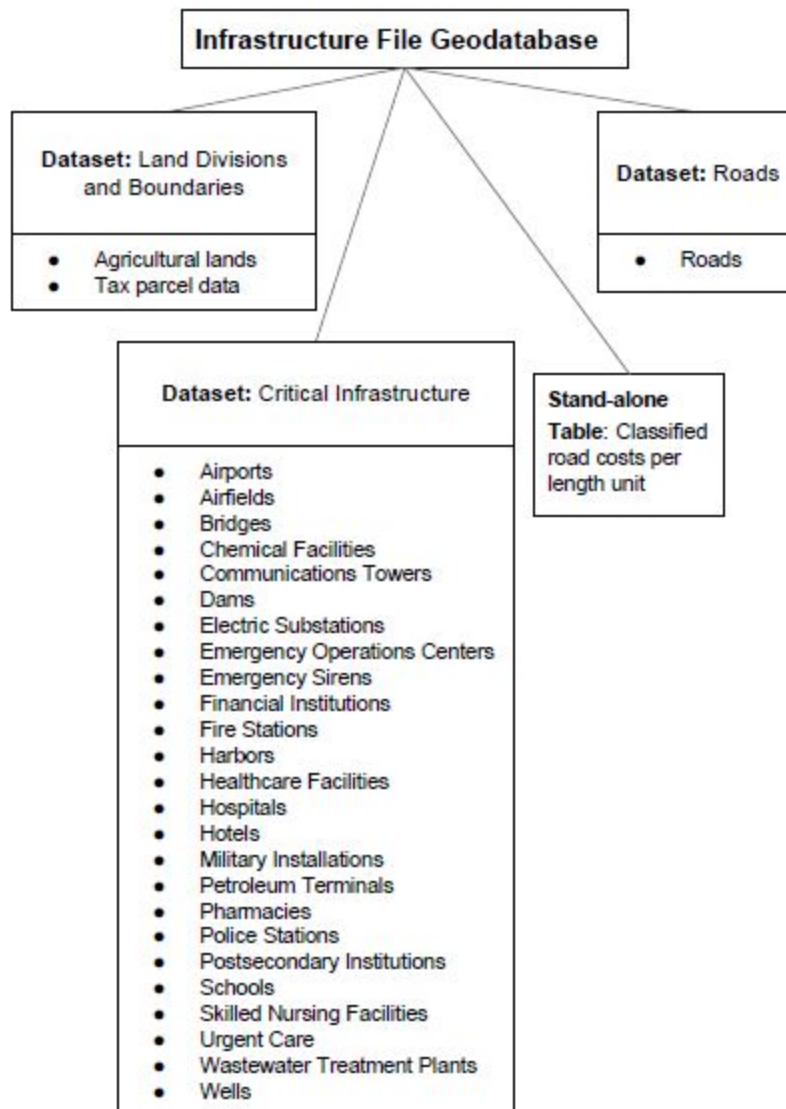


Figure 9: Organizational Structure of the Infrastructure Geodatabase for the Island of Hawai'i, as constructed during this practicum. The geodatabase contains three feature datasets and a stand-alone road costs table. Bullet points denote individual feature classes within each dataset. The results discussed in Sections 4.1 and 4.2 were obtained using the data in this geodatabase.

eliminated. Duplicate records within the same dataset were found with ArcMap's Find Identical tool, verified by inspection, and manually eliminated. The inclusion of metadata and elimination of duplicates were forms of data quality control. Quality data are necessary to obtain accurate model outputs and produce meaningful interpretations of those results.

In the midst of geodatabase assembly, the task of constructing the Lava Flow Vulnerability model began. The Streets submodel came together first. It was built around the Mauna Loa lava flow scenario explored in Section 4.1. It used Hawaii-specific data tables and feature classes, and input values (e.g. cost per unit length) were entered into processing tools as constants, not parameters. The Structures, Critical Infrastructure, and Agriculture submodels were constructed in a similar manner and in the order given. Then, the submodels were generalized to function with any input lava flow scenario and any infrastructure data. This generalization required all input tables and feature data to be set as parameters, or variables, in Modelbuilder. For many tools it was also necessary to change constants to value parameters, which allow the user to manually adjust those values. For example, the Structure Value Field in the attribute table of the Input Structures feature class (see Appendices A-2 and A-7) varies with the data assigned to the Input Structures variable. If the name of the Structure Value Field was left as a constant, the Structures submodel would malfunction when run with any Input Structures data lacking an attribute field with that exact name. Likewise, the widths of lava flows vary with lava characteristics and environmental factors, and thus the Buffer Distance input (Appendices A-1 and A-7) was set as a value parameter. After generalization, documentation was written for each submodel, detailing inputs and outputs, and summarizing the submodel's purpose, procedure and products. The four submodels were combined with the single eruption path tool to create the single continuous Lava Flow Vulnerability Model, and the aggregated model was documented in its own Item Description.

The third and final major task of this practicum was the further generalization of the Lava Flow Vulnerability Model to produce the Hazard Vulnerability Model. The Hazard Vulnerability Model can assess physical vulnerability of infrastructure anywhere in the world using the inundation footprint of any hazard. The transition to the Hazard Vulnerability Model was a simple matter of removing the single eruption path tool from the Lava Flow Vulnerability Model sequence and replacing it with the Input Hazard Footprint variable (Fig. 8, Appendix B). Model documentation was updated to reflect this change. The Lava Flow and Hazard models were each saved in an ArcToolbox and the option to store relative pathnames was activated for both. These steps preserve the pathname relationships that link each vulnerability model to its submodels, ensuring that the vulnerability models remain functional when transferred between computers in their Toolboxes. To test model functionality and efficiency, the completed Lava Flow Vulnerability Model was employed to assess infrastructure vulnerability in the potential scenario of a lava flow originating from a vent on Mauna Loa's northeast rift zone. Finally, when lava erupted from a fissure system on Kīlauea's lower east rift zone in the summer of 2018, an opportunity arose to utilize the Hazard Vulnerability Model as well. Both model applications are discussed in Chapter 4.

4. Model Applications and Discussion

4.1. Application: Vulnerability Assessment for a Lava Flow from Mauna Loa's NERZ

To test the functionality and efficiency of the Lava Flow Vulnerability Model, the model was applied to a scenario in which an eruptive vent opens at 9400 feet elevation along Mauna Loa's northeast rift zone (NERZ). The eruption produces a lava flow that exits the rift zone to the north, directly upslope from the city of Hilo. The model's spatial outputs, shown in Figure 10, illustrate the flow footprint predicted by the model for this event and the infrastructure that is vulnerable to the predicted lava flow. The infrastructure data used are the most current data available as of April 2018 (see Section 3.2). A Buffer Distance of 2 km was chosen for this scenario (see Appendices A-1 and A-7), giving the modeled lava flow a width of 4 km, which is the average width of past lava flows in the vicinity of the modeled flow (Trusdell and Lockwood 2017). As demonstrated in Figure 10, the path of steepest descent takes the lava flow through a broad swath of the city, resulting in the inundation of a great number of structures, hundreds of acres of agricultural land, and more than a hundred miles of roads before it reaches the ocean at Hilo Bay. The model's tabular outputs are shown in Tables 1 through 4, which detail the physical vulnerability of infrastructure in this scenario in terms of quantities potentially lost and the cost of those losses. The Hawaiian tax parcel data yields no means of classifying buildings; thus, the Output Structure Losses by Category table is not demonstrated in this paper. The flow would overwhelm Hilo's hospital, multiple fire and police stations, an electric substation, and over a dozen schools, among many other critical facilities. It would bury 109 miles of roads and over 700 acres of agricultural lands, and the total expected cost of physical infrastructure

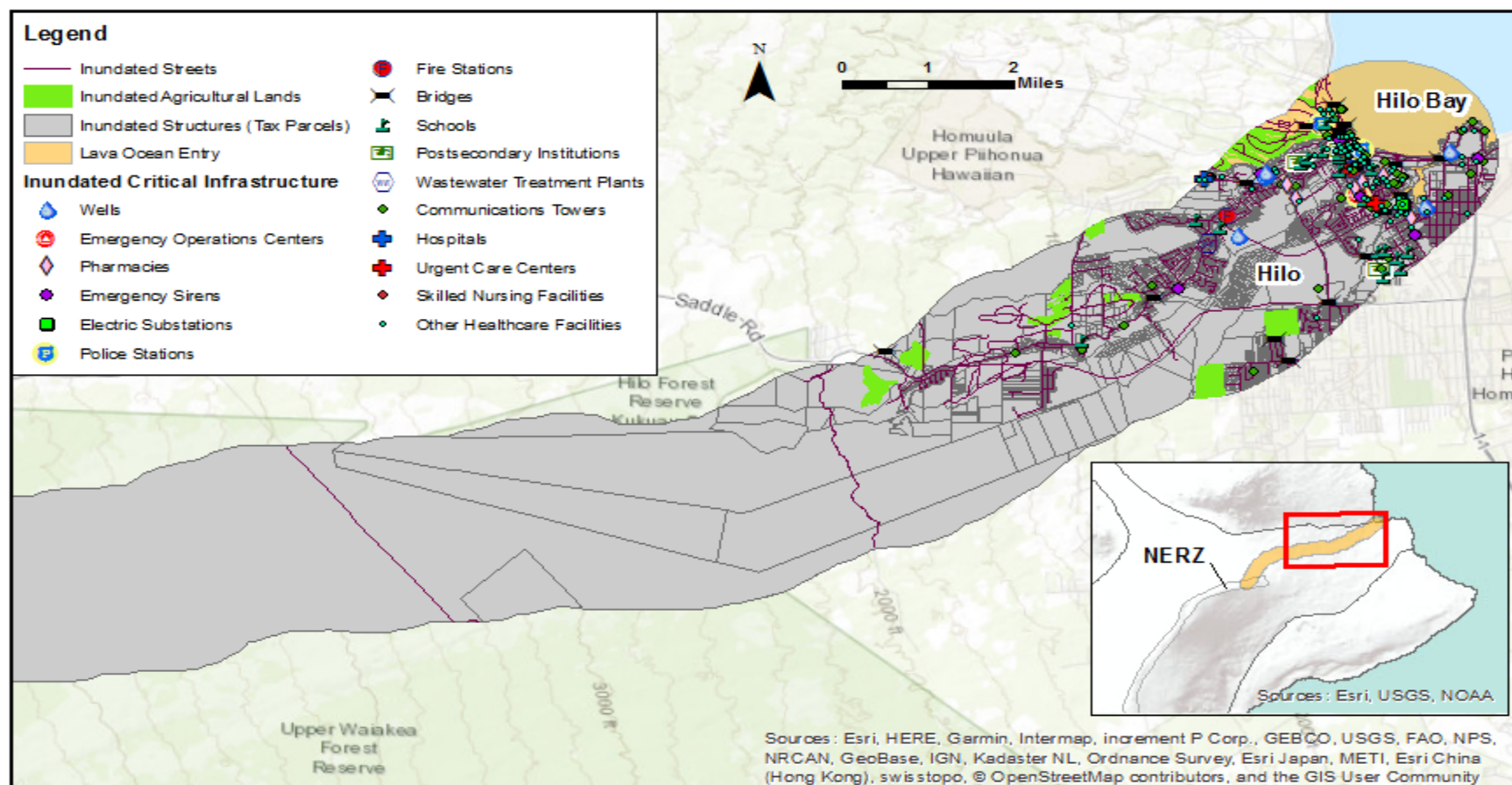


Figure 10: Spatial outputs of the Lava Flow Vulnerability Model for a lava flow initiating in Mauna Loa's northeast rift zone, as described in Section 4.1. The flow footprint mapped here is identical to the one shown in Figure 5. However, areas proximal to the eruption site are remote and vulnerable infrastructure in those areas is negligible. Therefore, this map is focused on the distal areas of the flow footprint where infrastructure vulnerability is high. All infrastructure feature classes are clipped by the model so that only infrastructure that falls within the predicted flow footprint is shown. The corresponding tabular model outputs, which explore counts and damage costs of elements-at-risk, are shown in Tables 1-4. Infrastructure data sources include the Pacific Disaster Center (Wells, Wastewater Treatment Plants, Hospitals, Other Healthcare Facilities, Emergency Sirens, Electrical Substations), Trusdell and Lockwood 2017 (Roads), State of Hawaii 2018 (Agricultural Lands, Tax Parcels, Skilled Nursing Facilities, Schools, Police Stations, Postsecondary Institutions, Hospitals, Other Healthcare Facilities, Fire Stations, Bridges), and U.S. DOHS 2017 (Urgent Care Centers, Pharmacies, Emergency Operations Centers, Communications Towers).

Table 1: Output Total Damage by Road Class for Mauna Loa NERZ Flow Scenario

| RD_CLASS | SUM_LENGTH | TOTRDCLSCOST |
|-------------|------------|--------------------|
| Major | 11.53658 | 34,609,740.419831 |
| Residential | 87.414578 | 174,829,155.145645 |
| Secondary | 10.293978 | 10,293,977.970839 |
| Tertiary | 0.06937 | 34,684.789446 |

For four road classes (RD_CLASS), the total length of roads buried by the lava flow (SUM_LENGTH) is shown in miles, and the total cost of those road losses (TOTRDCLSCOST) is recorded in U.S. dollars.

Table 2: Output Inundated Critical Infrastructure Count for Mauna Loa NERZ Flow Scenario.

| INFRACLASS | COUNT_INFRACLASS |
|------------------------------|------------------|
| Bridges | 18 |
| Communications_Towers | 64 |
| Electric_Substations | 1 |
| Emergency_Operations_Centers | 1 |
| Emergency_Sirens | 6 |
| Fire_Stations | 3 |
| Skilled_Nursing_Facilities | 1 |
| Urgent_Care_Facilities | 1 |
| Other_Healthcare_Facilities | 100 |
| Hospitals | 1 |
| Pharmacies | 7 |
| Police_Stations | 3 |
| Postsecondary_Institutions | 15 |
| Schools | 22 |
| Wastewater_Treatment_Plants | 1 |
| Wells | 8 |

This table records the number of entities (COUNT_INFRACLASS) overwhelmed by the lava flow for each category (INFRACLASS) of critical infrastructure. Note that is count is a number of structures. There are not 15 postsecondary institutions in the city of Hilo. Most of the structures in the postsecondary institutions count belong to the University of Hawaii at Hilo.

Table 3: Output Cost of Agricultural Losses by Category for Mauna Loa NERZ Flow Scenario.

| CROPCATEGO | FREQUENCY | SUM_POLY_AREA | SUM_CORRVALUE |
|------------------|-----------|---------------|------------------|
| Diversified Crop | 16 | 140.205938 | 451,329.476102 |
| Pasture | 118 | 363.897679 | 4,677,688.260815 |
| Tropical Fruits | 4 | 5.061728 | 51,832.837471 |

For each of a number of crop categories (CROPCATEGO), both the number of inundated parcels (FREQUENCY) and total inundated acres (SUM_POLY_AREA) are recorded. The cost of those agricultural losses (SUM_CORRVALUE) is also reported by the model.

Table 4: Output Total Lava Flow Damage for Mauna Loa NERZ Flow Scenario

| SUM_SUM_SUM_VA | SUM_SUM_SUM_LE | SUM_SUM_TOTRDC | SUM_SUM_SUM_PO | SUM_SUM_SUM_CO | SUM_TOTFLOWDMG |
|----------------|----------------|-----------------|----------------|-----------------|--------------------|
| 1,958,532,800 | 109.314505 | 219,767,558.326 | 730.478719 | 11,074,891.8121 | 2,189,375,250.1381 |

The information reported in this table is as follows: total cost of structure losses (SUM_SUM_SUM_VA), total length of inundated streets (SUM_SUM_SUM_LE) in miles, total cost of street losses (SUM_SUM_TOTRDC), total area of inundated agricultural lands (SUM_SUM_SUM_PO) in acres, total cost of immediate agricultural losses (SUM_SUM_SUM_CO), and the total expected cost of infrastructure losses in the modeled flow scenario (SUM_TOTFLOWDMG). All reported cost values are in U.S. dollars. NOTE: Since the Input Structures features for this scenario are tax parcels, the SUM_FREQUE field does not report an accurate structure count and was therefore omitted from this table.

losses is over \$2 billion. These results were produced by the Lava Flow Vulnerability Model in just over two minutes. As this is a hypothetical scenario, comparable quantity and cost estimates do not exist. However, such an event is not unprecedented. Mauna Loa lava flows paved similar swaths of what is now Hilo about 1300 years before present and again in 1880-81 (Trusdell and Lockwood 2017). Furthermore, the eruptive vent in the modeled scenario is in the vicinity of the vent that opened in the spring of 1984, producing a lava flow that generally followed the modeled trajectory and stopped less than 4.5 miles west of the city limits. While Hilo is vulnerable to potential lava flows from Mauna Loa's NERZ, the island's Puna district copes with its own great vulnerability to lava inundation from Kīlauea's very active east rift.

4.2. Application: Vulnerability Assessment for the 2018 Eruption of Kīlauea's LERZ

As discussed in Section 2.2, Kīlauea lava flows have claimed swaths of Puna communities multiple times in the last half-century, notably in 1955, 1960 and 1990. On May 3, 2018, lava surfaced on Kīlauea's lower east rift zone (LERZ) once again, discharged from a series of fissures that opened within the Leilani Estates subdivision. This breach marked the commencement of an eruptive episode that persisted for over 12 weeks and paved 35.5 km² of land, including the addition of more than 3.5 km² of new land to the island (Hawaiian Volcano Observatory Staff 2018). The lava flow devastated 25 percent of Leilani Estates (HVO pers. comm.) and parts of the communities of Pohoiki and Kapoho. The footprint of the 2018 flow was mapped by HVO geologists as the flow developed (Hawaiian Volcano Observatory Staff 2018), and it was the Input Hazard Footprint for the Hazard Vulnerability Model (Fig. 8, Appendix B) in this analysis.

The model completed the analysis within 5 minutes. Map outputs are displayed in Figure 11. Tables 5 through 8, the model's tabular outputs, detail physical vulnerability of infrastructure to the 2018 flow in terms of quantities lost and cost of those damages. Once again, Hawaiian tax parcels were used in the analysis and the Output Structure Losses by Category table is not demonstrated. According to the model, the Puna district suffered the losses of 16 critical structures, including three communications towers, two emergency sirens, and several wells. Thirty miles of roads and more than 1100 acres of agricultural land were buried, and structural losses total nearly \$114 million. The model's predicted total cost of damages is greater than \$168 million. The eruption ended in early September of 2018. It occurred in an area defined as Hazard Zone 1 (Wright et. al. 1992) and thus reinforces the notion that there are real costs for development in hazardous areas. Furthermore, this eruption demonstrates the necessity for the implementation of volcanic hazard and vulnerability assessments on Hawai'i Island.

4.3. Discussion of Model Limitations

Kīlauea's summer 2018 lava flow provided a unique opportunity to explore the Hazard Vulnerability Model's ability to produce realistic damage estimates. The island's current infrastructure data do not reflect the nature of the built environment during the volcano's previous eruptions. Thus, testing the legitimacy of model results requires a contemporary event. The numbers obtained in Section 4.2 are comparable to real estimates of Puna's infrastructure losses to the 2018 eruption. The University of Hawaii College of Tropical Agriculture and Human Resources conducted a post-disaster survey

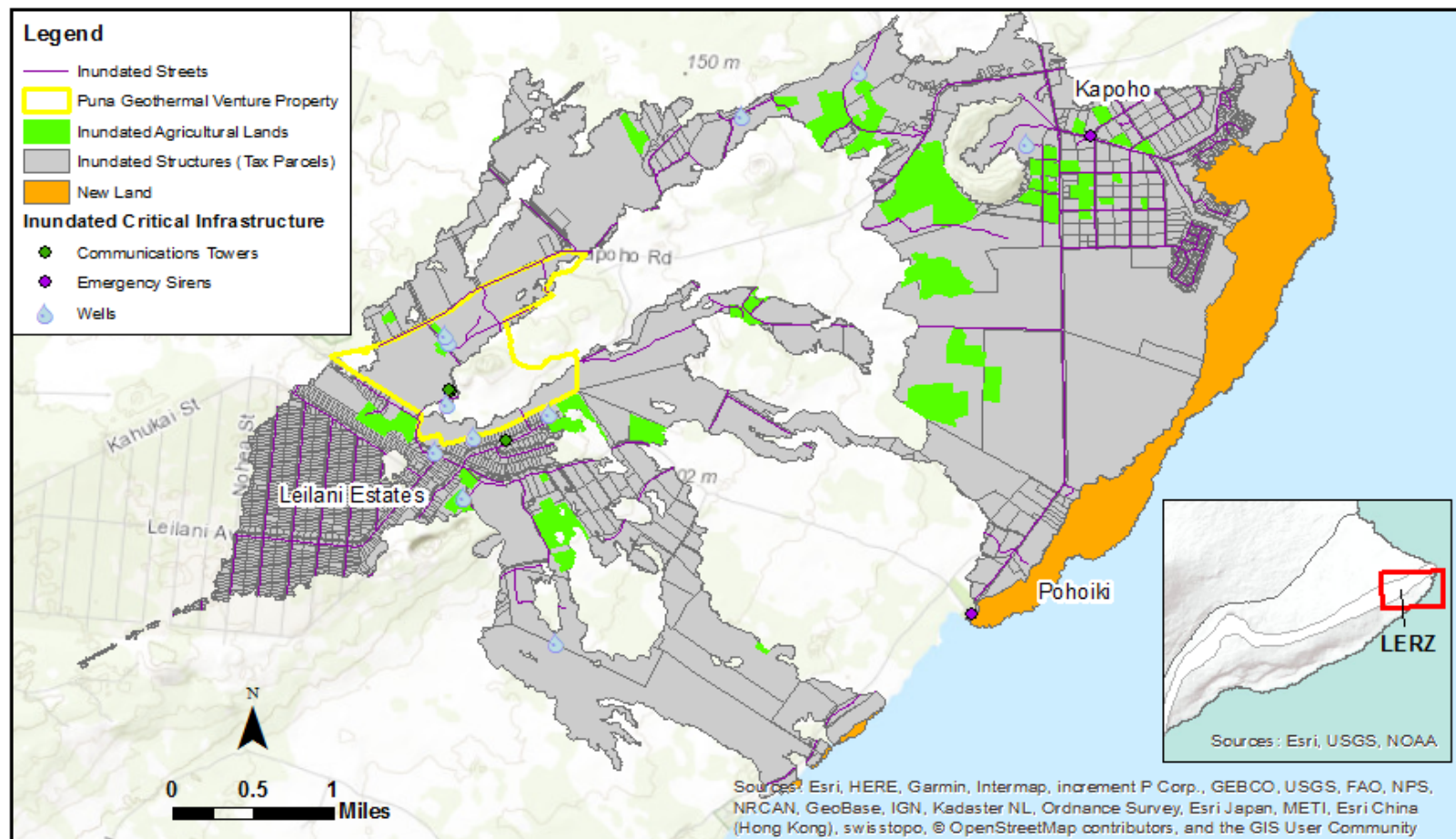


Figure 11: Spatial outputs of the Hazard Vulnerability Model for the 2018 lava flows from Kilauea's lower east rift zone, as described in Section 4.2. This flow footprint reflects the extent of the flows as of September 2018, at which time eruptive activity ceased. The portion of the flow footprint shown in orange is new land added to the island by this eruption. All infrastructure feature classes are clipped by the model so that only infrastructure that falls within the flow footprint is shown. The corresponding tabular model outputs, which explore counts and damage costs of elements-at-risk, are shown in Tables 5-8. Infrastructure data sources include the Pacific Disaster Center (Wells, Emergency Sirens), Trusdell and Lockwood 2017 (Roads), State of Hawaii 2018 (Agricultural Lands, Tax Parcels), and U.S. DOHS 2017 (Communications Towers). The flow footprint and Puna Geothermal Venture shapefiles are from HVO (Hawaiian Volcano Observatory Staff, 2018).

Table 5: Output Total Damage by Road Class for the 2018 Kīlauea LERZ Eruption.

| RD_CLASS | SUM_LENGTH | TOTRDCLSCOST |
|-------------|------------|------------------|
| Residential | 21.448009 | 42,896,017.6509 |
| Secondary | 7.370823 | 7,370,823.04502 |
| Tertiary | 2.046894 | 1,023,447.117566 |

For three road classes (RD_CLASS), the total length of roads buried by lava (SUM_LENGTH) is shown in miles, and the total cost of those road losses (TOTRDCLSCOST) is recorded in U.S. dollars.

Table 6: Output Inundated Critical Infrastructure Count for 2018 Kīlauea LERZ Eruption.

| INFRACLASS | COUNT_INFRACLASS |
|-----------------------|------------------|
| Emergency_Sirens | 2 |
| Communications_Towers | 3 |
| Wells | 11 |

This table records the number of structural entities (COUNT_INFRACLASS) overwhelmed by the lava flow for each category (INFRACLASS) of critical infrastructure. Note that this count is a number of structures.

Table 7: Output Cost of Agricultural Losses by Category for 2018 Kīlauea LERZ Eruption.

| CROPCATEGO | FREQUENCY | SUM_POLY_AREA | SUM_CORRVALUE |
|-------------------------------|-----------|---------------|------------------|
| Aquaculture | 3 | 6.608453 | 14,526.509766 |
| Diversified Crop | 3 | 31.374574 | 201,125.321777 |
| Flowers / Foliage / Landscape | 40 | 96.490983 | 820,115.360791 |
| Macadamia Nuts | 20 | 40.714425 | 188,225.878067 |
| Papaya | 35 | 818.563318 | 1,782,849.494509 |
| Pasture | 28 | 24.894669 | 246,306.036156 |
| Tropical Fruits | 27 | 118.306236 | 427,872.2955 |

For each of a number of crop categories (CROPCATEGO), both the number of inundated parcels (FREQUENCY) and total inundated acres (SUM_POLY_AREA) are recorded. The cost of these agricultural losses (SUM_CORRVALUE), based on land values, is also reported by the model.

Table 8: Output Total Damage for 2018 Kīlauea LERZ Eruption.

| SUM_SUM_SUM_VA | SUM_SUM_SUM_LE | SUM_SUM_TOTRDC | SUM_SUM_SUM_PO | SUM_SUM_SUM_CO | SUM_TOTHAZDMG |
|----------------|----------------|-----------------|----------------|-----------------|-------------------|
| 113,645,000 | 30.865726 | 51,290,287.8135 | 1,136.952659 | 3,681,020.89657 | 168,616,308.71007 |

The information reported in this table is as follows: total cost of structure losses (SUM_SUM_SUM_VA), total length of inundated streets (SUM_SUM_SUM_LE) in miles, total cost of street losses (SUM_SUM_TOTRDC), total area of inundated agricultural lands (SUM_SUM_SUM_PO) in acres, total cost of immediate agricultural losses (SUM_SUM_SUM_CO), and the total expected cost of infrastructure losses to the eruption (SUM_TOTHAZDMG). All reported cost values are in U.S. dollars. NOTE: Since the Input Structures features for this scenario are tax parcels, the SUM_FREQUE field does not report an accurate structure count and was therefore omitted from this table.

of agricultural damages, the results of which were published in the Honolulu Star Advertiser on October 12, 2018. The article reports that lava buried about 1,337 acres of farmland valued at \$4.2 million (Wu 2018). The model determined that 1,137 acres of farmland valued at \$3.6 million were lost. The model underestimated both the quantity (acres) lost and cost of those losses by about 15 percent. This error is most likely

attributed to the fact that the most current available data on the island's agricultural parcels were collected in 2015 (State of Hawaii 2018). Between 2015 and the 2018 LERZ eruption, the agricultural presence in lower Puna likely grew by the 200 acres unaccounted for by the model. As of January 2019, no other comparable loss estimates for this eruption have been published. However, the presence of error in the model's estimates of agricultural damage highlights the importance of using up-to-date spatial data in GIS-based vulnerability assessments.

The availability and quality of hazard and elements-at-risk data stand as major limitations to realistic vulnerability modeling. The models presented in this paper - the Lava Flow Vulnerability Model and its generalized Hazard Vulnerability counterpart - are as accurate as the data put into them. The quality of model results depends on the completeness, currentness, positional accuracy, and precision of the input data. Currentness is the most challenging of these data qualities to maintain. The built environment is constantly developing and changing, making it difficult to keep even the newest infrastructure datasets up to date. This is especially true in a rapidly growing place like Hawai'i Island. Some data used in the above lava flow vulnerability assessments, despite being the most current data publicly available, are over a decade old. The accuracy of the above model results may also be limited by the completeness of the input data. Even the most current datasets could be missing one or more relevant elements-at-risk that exist on the island. In addition, duplication of records may have skewed these results. All input data for this project were checked for repeated records, as described in Section 3.2, before they were imported to the geodatabase. However, human error allows for the possibility that the models processed some duplicates. A

data precision issue presents itself in the use of Hawai'i tax parcel data in the Structures submodel to calculate the total count and cost of structural losses to the lava flows. In both analyses, some parcels were only partially inundated by lava. When only part of a parcel is inundated, some buildings on that parcel may not be impacted, and thus the actual losses would be lower than the total value of buildings given in the tax parcel data. If a feature class of actual Hawai'i building footprints was available, it would make a better candidate for the Input Structures variable (see Appendix A-2). Such a feature class would offer a more precise picture of structure locations and values than does the tax parcel data. The currentness, completeness, positional accuracy, and precision of geospatial infrastructure data can be verified through field studies, imagery analysis, and by comparison to the infrastructure records of local governments, developers, and contractors. In addition to the models' data quality limitations, there are restrictions on the scope of their applicability.

These models are scope-limited both in the types of hazards for which they can assess vulnerability and in the categories of vulnerability they can evaluate. A key assumption of the Lava Flow Vulnerability and Hazard Vulnerability models is that all elements-at-risk located within the hazard footprint are completely destroyed. This is a valid supposition in the case of a lava flow, which buries whatever infrastructure it does not burn. However, this assumption limits the models' applicability to hazards like ash fall and floods, which cause partial damage far more often than they cause complete destruction. Model evaluations of these hazards would produce significant overestimates of infrastructure losses. Also, the generalized Hazard Vulnerability Model is most applicable to hazards such as lava flows and lahars that have a distinct footprint

with relatively uniform intensity. The model assumes that the infrastructure within that distinct zone is destroyed while infrastructure outside of it is not affected. This vulnerability analysis is less effective for hazards like earthquakes and ash fall, in which intensity follows a diminishing gradient away from the hazard's source. In these cases it is not possible to draw precise boundaries of the affected area, which in turn diminishes the accuracy of the Input Hazard Footprint (see Appendix B). Furthermore, these models do not account for potential damages caused by secondary hazards. A secondary hazard is a destructive phenomenon distinct from but initiated by the studied (primary) hazard. Fire is the major secondary hazard associated with lava flows, which ignite trees, brush, and any other fuel they contact. The resulting fires have their own footprints, separate from that of the lava flow, and can cause a great deal of damage outside of the area in direct contact with lava. The Lava Flow Vulnerability Model assumes that no secondary hazards occur, which is only sometimes the case. The Hazard Vulnerability Model can assess damages within the footprint of a secondary hazard if it is used in conjunction with a model that predicts the secondary hazard's propagation or with a footprint mapped in its aftermath.

In addition to their restricted suitability to particular hazard types, the models are limited to the assessment of a single category of vulnerability. They assess only physical vulnerability in the form of quantities and costs of immediate structural losses. They do not perform a systemic vulnerability assessment. There is no exploration of the susceptibility of different demographic populations to the hazard (social vulnerability), the potential damage to the economy of the affected community (economic vulnerability), the capacity of ecosystems to tolerate the hazard (environmental

vulnerability), or of the relative influences of physical, social, economic, and environmental susceptibilities on the study area's overarching (territorial) vulnerability to the hazard (see Section 2.1). Furthermore, these models do not evaluate risk. That is, they do not explore the probability that the modeled hazard will occur in a given time period or determine a range of probabilities that each element-at-risk will be damaged or destroyed. These models are limited to assessments of physical vulnerability and operate under the assumptions that a) the hazard in question has a distinct footprint, and b) the infrastructure within the hazard footprint is completely destroyed. Despite these limitations, they produce valid estimates of infrastructure vulnerability to lava flows, as demonstrated in the quantities and costs of agricultural damage they obtained for the summer 2018 eruption of Kīlauea. This validity is among the models' strongest traits.

4.4. Discussion of Model Strengths

The strengths of the Lava Flow and Hazard Vulnerability Models lie in their efficiency, their flexibility, and the fact that they meet the objectives of this practicum. These models fulfill the practicum's overarching purpose of providing HVO with an efficient means to assess the impacts of a volcanic hazard event on Hawaii's infrastructure. The first of the project's three objectives was to create a model that identifies elements-at-risk in a hazard scenario and estimates the quantity and cost of infrastructural losses to that hazard. These models identify at-risk infrastructure via a map overlay of the hazard footprint upon infrastructure layers. Quantities lost are recorded in the output tables and include lengths of inundated streets, structure count, counts of critical infrastructure by class, and counts and total areas of agricultural lands.

Associated costs per category and total costs are reported for roads, agricultural lands, and structures. A grand total expected cost for the hazard scenario is reported by both the Lava Flow and Hazard Vulnerability models.

This practicum's second objective was to provide outputs in both tabular and spatial form. Figures 10 and 11 illustrate the spatial outputs of the models, which are shapefiles depicting the hazard footprint and inundated streets, structures, critical infrastructure, and agricultural lands. The tabular outputs, most of which are demonstrated in Sections 4.1 and 4.2, include three combined count and cost tables that detail losses of streets, structures, and agricultural lands, the categorized critical infrastructure count table, and the summary table. The summary table records total length of inundated roads, total area of inundated agricultural lands, total number of inundated structures, total costs of damage to streets, structures, and agriculture, and the grand total cost of infrastructure losses in the lava flow scenario. The third and final objective was to produce a model that runs consecutively and seamlessly with the Observatory's existing lava flow models and is adaptable to other volcanic and related hazards. HVO's single eruption path lava flow hazard assessment tool is imbedded within the Lava Flow Vulnerability Model, and thus the goal of creating a seamless, consecutive hazard-to-vulnerability model sequence is met. The goal of producing a tool that is adaptable to other hazards is met by the Hazard Vulnerability Model, which assesses infrastructure vulnerability for any input hazard footprint.

This adaptability is another strong attribute of these vulnerability models. The Hazard Vulnerability Model produces its most accurate cost results when the assumptions that the hazard has a distinct footprint and destroys all infrastructure within

its footprint are valid, such as for lava flows. However, for less destructive hazards with distinct footprints, such as floods, the model still highlights the infrastructure that is directly impacted and produces accurate reports of the types and lengths of affected roads, the classes and areas of affected agricultural lands, and the counts and categories of affected critical infrastructure. Furthermore, the applicability of both the Lava Flow and Hazard Vulnerability Models is not restricted to Hawai'i Island. By simply updating the input data, these models can be applied to lava flow and other hazard scenarios in any location on Earth. An additional strength is inherent in the efficiency of the models' analyses. Recall that HVO's previous vulnerability assessment methodology involved manually running the clip and statistical analyses for each infrastructure element, one by one. Both models described herein analyze any number of infrastructure shapefiles within one model cycle that runs in a matter of minutes. The analyses in Sections 4.1 and 4.2 were completed within three and five minutes, respectively. These models can produce quick results at the onset of a hazardous event or immediately after one occurs. They also provide a more efficient means to perform routine vulnerability studies at HVO.

5. Conclusions

Two ArcGIS models - the Lava Flow Vulnerability Model and its generalized counterpart, the Hazard Vulnerability Model – are the products of this practicum. They fulfill its purpose of constructing a vulnerability model that explores the impacts of a hazardous event on Hawaii's property and infrastructure. These models assess exposure and physical vulnerability in terms of potential quantities lost and associated damage costs. They produce both tabular and spatial outputs detailing the impacted infrastructure in the hazard event. The Lava Flow Vulnerability Model operates as a seamless extension to the Hawaiian Volcano Observatory's single eruption path model, which predict lava flow footprints. The Hazard Vulnerability Model is applicable to any hazard that has a distinct footprint and adaptable to any locality in the world. Both models serve to automate vulnerability analysis and yield results within minutes; thus, they increase the accuracy and efficiency of HVO's vulnerability assessment process. These models assume complete loss of infrastructure within the hazard footprint. They do not evaluate risk and are limited to the quantitative assessment of physical vulnerability. These limitations of the models do not outweigh their strengths; however, further research and model development could reduce them. Opportunities to build upon the existing models include the construction of an additional submodel to account for utility network vulnerabilities and the inclusion of a damage weighing scheme to the Hazard Vulnerability Model.

The models do not assess impacts to utility infrastructure such as electrical networks and above-ground water networks, even though destruction of these elements would significantly contribute to damage costs in a hazard event. Thus, both models

would benefit from an additional submodel focused on the vulnerability of utility networks. Like the Streets submodel (Appendix A-3), this utilities submodel would need to calculate the lengths and replacement costs of inundated utility lines. However, the utilities submodel would be set apart from the Streets submodel by the incorporation of an iterator. Iteration is necessary because, while all types of input streets are typically encompassed by a single feature class, different utilities tend to be recorded in separate feature classes. The iterator would apply the utilities submodel sequence to each of any number of input utility network feature classes. In addition to a utilities submodel, the Hazard Vulnerability Model would be enhanced by an alteration that enables it to assess different degrees of damage. This upgrade would make the model more applicable to hazards that cause partial damage, such as floods. It would require the addition of a process to each submodel that assigns a percent indicator for predicted damage severity to each element-at-risk. The indicator would be based on a structural attribute (e.g. building material) or tolerance trait (e.g. hardiness of a crop against flood waters). Each infrastructure element's associated monetary value would be scaled by this indicator. Implementation of such an enhancement would require extensive research on structural attributes, tolerance traits, and how these characteristics affect the resistance of infrastructure to a variety of hazards.

Submodel alterations that enable assessment of damage severity and the introduction of a utilities submodel are two ways to build upon the models created during this practicum and further improve their accuracy and applicability. Development and improvement upon the Hazard and Lava Flow Vulnerability Models will provide continued support to HVO's mission of enabling timely and accurate warning of

hazardous events and increasing awareness among Hawaii's residents. Valid and efficient vulnerability assessment is set to become an increasingly vital service of the Hawaiian Volcano Observatory as the island's population grows and developmental pressure prompts communities to expand further on to the hazard-prone flanks of Hawaii's most active volcanoes.

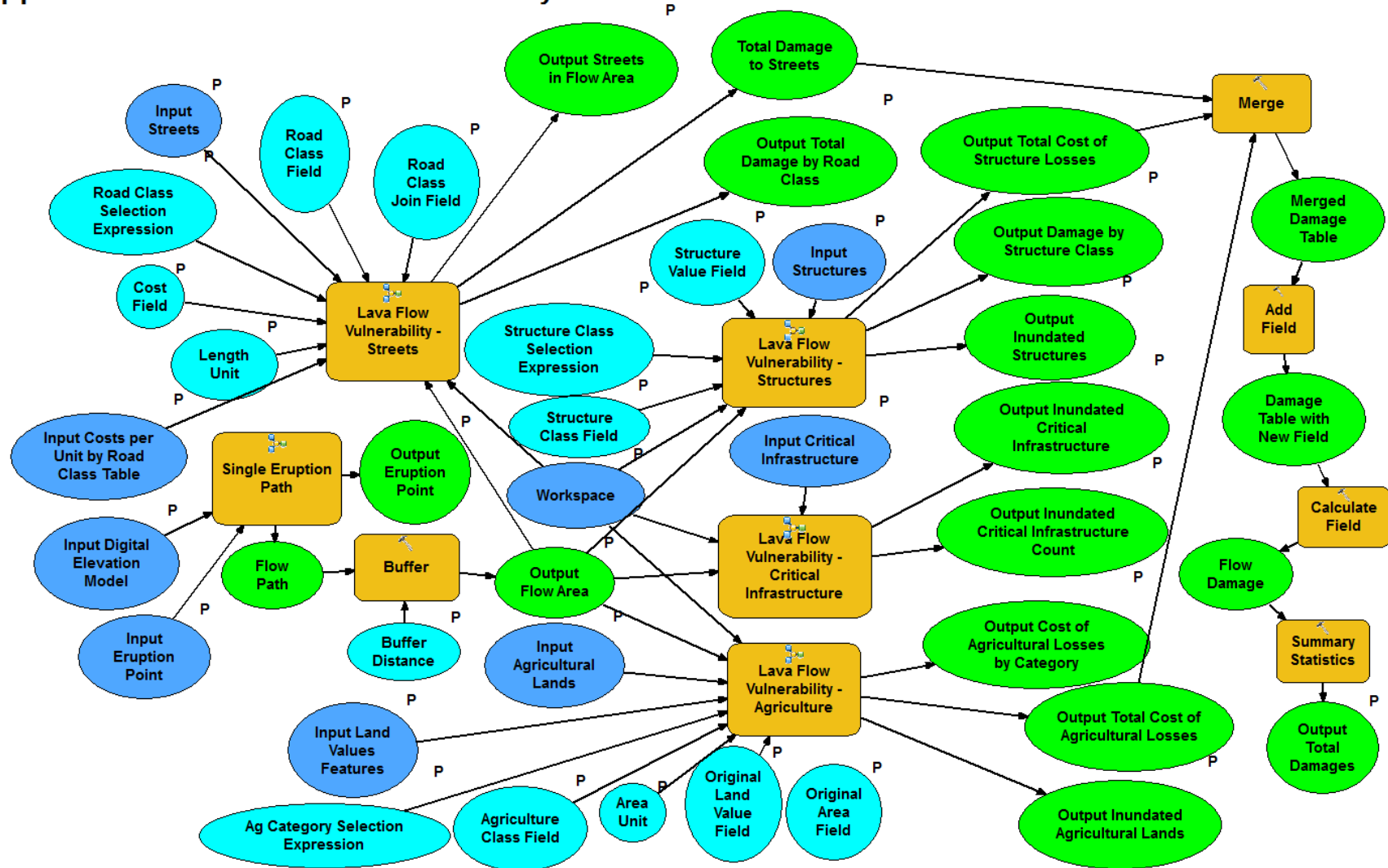
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Appendix A-1: Lava Flow Vulnerability Model



Appendix A-1: Lava Flow Vulnerability Model (Continued)

Chart explanation: Dark blue ovals denote data inputs (feature classes, workspaces, and tables). Light blue ovals are value parameters, as defined in Section 3.1. Orange boxes denote model processes, including the vulnerability model's four submodels: Streets, Structures, Critical Infrastructure, and Agriculture. Green ovals are data outputs (also tables and feature classes). Note that the data inputs, value parameters, and some data outputs are marked with a "P". These are model parameters. For detailed descriptions of the model parameters, refer to Appendix A-7. Arrows reveal the progression of the model.

Descriptions of Model Processes:

The **Single Eruption Path** tool creates a vector Flow Path from a DEM and a user-specified eruption point, as described in Section 2.3.

The **Buffer** tool draws a polygon of either uniform or variable width (see Buffer Distance in Appendix A-7) around the Flow Path to create the Output Flow Area, or the "footprint" of the lava flow.

The **Structures** submodel is detailed in Appendix A-2.

The **Streets** submodel is detailed in Appendix A-3.

The **Critical Infrastructure** submodel is detailed in Appendices A-4 and A-5.

The **Agriculture** submodel is detailed in Appendix A-6.

The **Merge** tool combines the output quantity and cost tables from the Structures, Streets, and Agriculture submodels into one table, preserving the fields from the submodels' tables and placing the quantity and cost numbers from each submodel into their own row.

The **Add Field** tool adds a new field named TotFlowDmg to the merged table and the **Calculate Field** tool populates the TotFlowDmg field with the sum of costs across each row of the merged table (the total cost of damages for each submodel).

The **Summary Statistics** tool calculates the sum of values in the TotFlowDmg field and writes it to a new Output Total Lava Flow Damages Table (see Appendix A-7) along with the total quantity values from the submodels' output tables and the cost totals from the previous step.

Appendix A-2: Structures Submodel

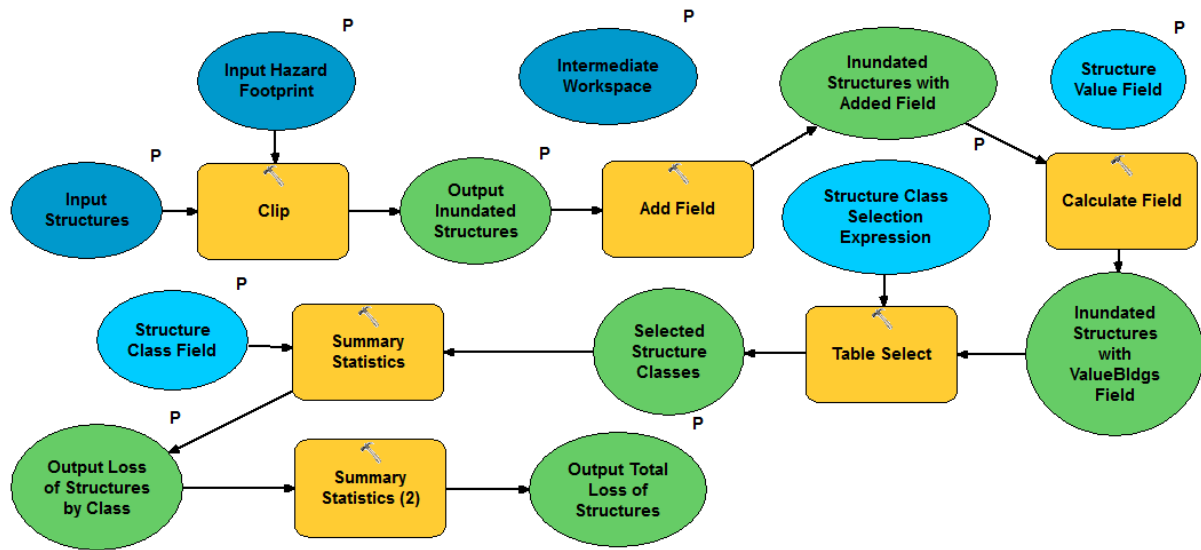


Chart explanation: Dark blue ovals denote data inputs (feature classes, workspaces, and tables). The light blue oval is a value parameter, as defined in Section 3.1. Orange boxes denote model processes. Green ovals are data outputs (also tables and feature classes). Note that the data inputs, value parameters, and some data outputs are marked with a “P”. These are submodel parameters. Arrows reveal the progression of the model.

Descriptions of Model Processes:

The **Clip** tool overlays the Input Structures with the hazard footprint (e.g. Flow Area) and produces a new feature class containing only the buildings or parcels that fall within the hazard footprint.

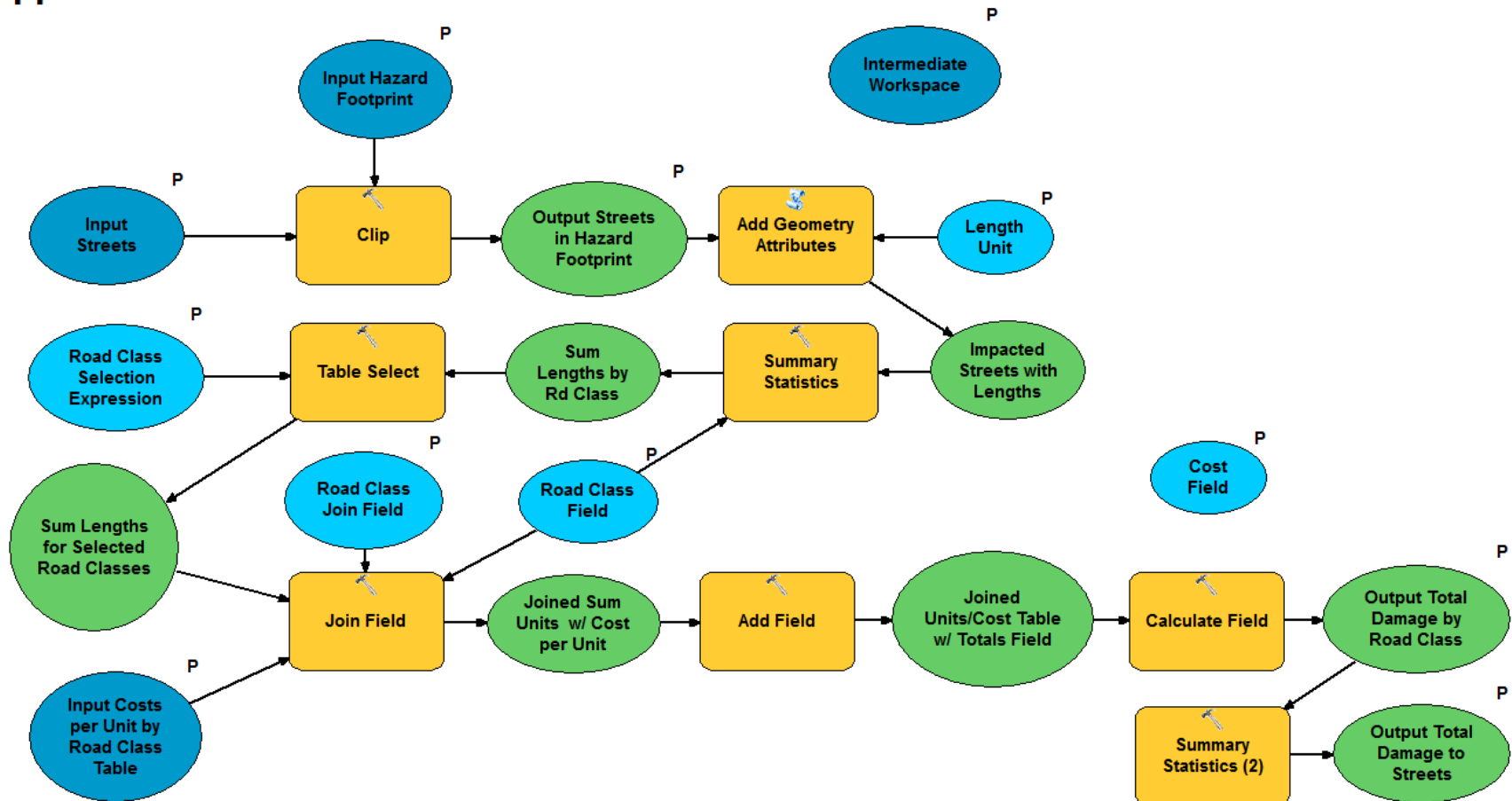
The **Add Field** tool adds a field named ValueBldgs to the attribute table of the Output Inundated Structures feature class and the **Calculate Field** tool populates that field with a copy of the data from the Structure Value Field (see Appendix A-7). This step simplifies the input to the Summary Statistics tool (and overall model) by enabling the tool’s Statistics Field to be set as a constant (ValueBldgs) instead of as the Structure Value Field variable.

The **Table Select** tool optionally allows for the selection of only certain structure classes for analysis via an SQL expression. See Structure Class Selection Expression in Appendix A-7.

The **Summary Statistics** tool calculates the number and cost of inundated structures in each structure class and records these sums in the Output Loss of Structures by Class table.

The **Summary Statistics (2)** tool calculates the total number and total cost of inundated structures and reports these sums in a new Output Total Loss of Structures table.

Appendix A-3: Streets Submodel



Appendix A-3: Streets Submodel (Continued)

Chart explanation: Dark blue ovals denote data inputs (feature classes, workspaces, and tables). Light blue ovals are value parameters, as defined in Section 3.1. Orange boxes denote model processes. Green ovals are data outputs (also tables and feature classes). Note that the data inputs, value parameters, and some data outputs are marked with a “P”. These are submodel parameters. Arrows reveal the progression of the model.

Descriptions of Model Processes:

The **Clip** tool overlays the Input Streets with the hazard footprint (e.g. Flow Area) and produces a new feature class containing only the roads that fall within the hazard footprint.

The **Add Geometry Attributes** tool calculates the length, in user-selected units, of each street segment that falls within the hazard footprint. This is a crucial step because the Clip tool splits some of the lines in the input feature class but fails to recalculate the lengths of the inundated segments, and instead simply copies the lengths of the original segments into the attribute table of the clipped feature class. The Add Geometry Attributes tool corrects this issue.

The **Table Select** tool optionally allows for the selection of only certain road classes for analysis via an SQL expression. See Road Class Selection Expression in Appendix A-7.

The **Summary Statistics** tool calculates the total length and total value of inundated streets for each road class and records these sums in a new table.

The **Join Field** tool appends the data from the Input Costs per Unit by Road Class table to the output of the Summary Statistics tool to produce a table containing length of inundated streets and cost per length unit for each road class.

The **Add Field** tool adds a field named TotRdClsCost to the Join Field tool’s output table and the **Calculate Field** tool populates that field with the total cost of damages for each road class (the product of the total inundated length and cost per length unit) to produce the Output Total Damage by Road Class table.

The **Summary Statistics (2)** tool calculates the total inundated length and total damage cost for all roads and records these values in the Output Total Damage to Streets table.

Appendix A-4: Critical Infrastructure Submodel

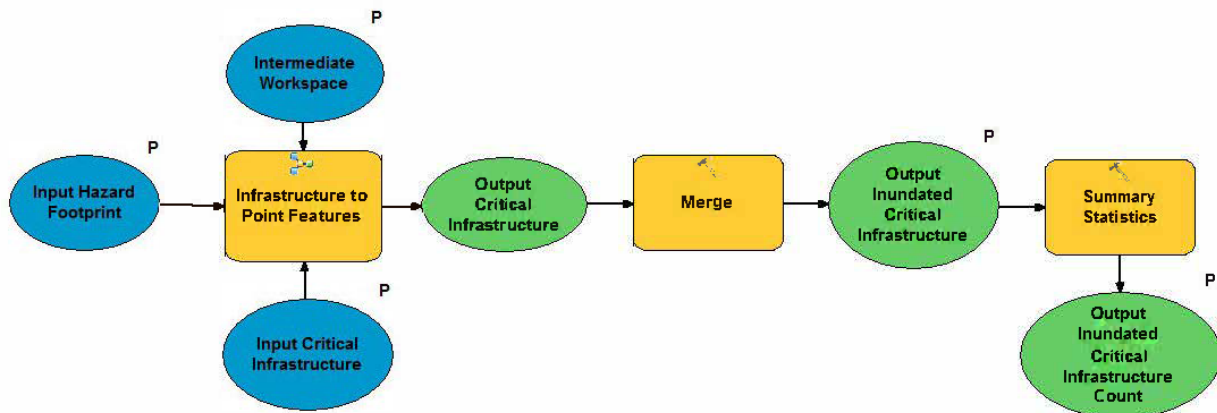


Chart explanation: Dark blue ovals denote data inputs (feature classes, workspaces, and tables). Orange boxes denote model processes. Green ovals are data outputs (also tables and feature classes). Note that the data inputs and some data outputs are marked with a “P”. These are submodel parameters. Arrows reveal the progression of the model.

Descriptions of Model Processes:

The **Infrastructure to Point Features** sequence is detailed in Appendix A-5. This sequence is iterated over all feature classes in the Input Critical Infrastructure dataset and produces a group of point shapefiles that contains all inundated critical infrastructure features.

The **Merge** tool combines the output shapefiles of the Infrastructure to Point Features sequence into a single point shapefile.

The **Summary Statistics** tool counts the number of inundated features in each critical infrastructure class and records these counts in the Output Inundated Critical Infrastructure Count table.

Appendix A-5: Infrastructure to Point Features Sequence

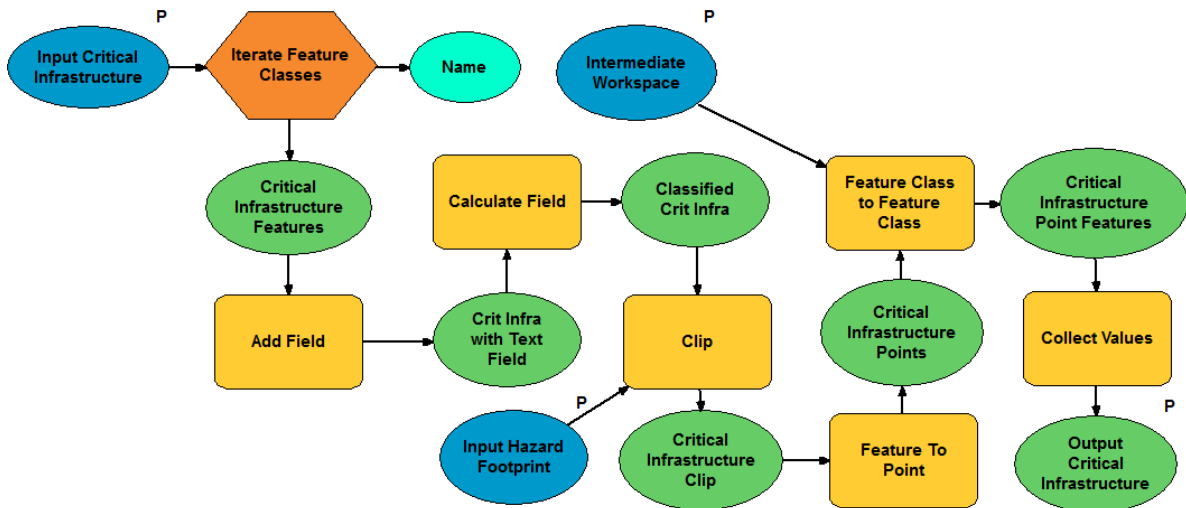


Chart explanation: Dark blue ovals denote data inputs (feature classes, workspaces, and tables). The red hexagon is an iterator. Orange boxes denote model processes. Green ovals are data outputs (also tables and feature classes). Note that the data inputs and one data output are marked with a “P”. These are submodel parameters. Arrows reveal the progression of the model.

Descriptions of Model Processes:

The **Iterate Feature Classes** applies the six processes in the sequence to every feature class in the Input Critical Infrastructure feature dataset and collects and stores the name of that dataset.

The **Add Field** tool adds a field named InfraClass to the attribute table of each input critical infrastructure feature class and the **Calculate Field** tool populates that field with the name of the feature class as collected by the iterator.

The **Clip** tool overlays each input critical infrastructure feature class with the hazard footprint (e.g. Flow Area) and produces a new feature class containing only the critical features that fall within the hazard footprint.

The **Feature to Point** tool converts all clipped feature classes to point features so that they are able to be merged into one point shapefile by the Critical Infrastructure submodel.

The **Feature Class to Feature Class** tool eliminates all fields in the attribute tables of the new point feature classes except for the InfraClass and Identity fields. This further simplifies the merging process in the Critical Infrastructure submodel.

The **Collect Values** tool gathers all outputs of the iterated Feature Class to Feature Class tool into a single input for the Critical Infrastructure submodel's Merge tool.

Appendix A-6: Agriculture Submodel

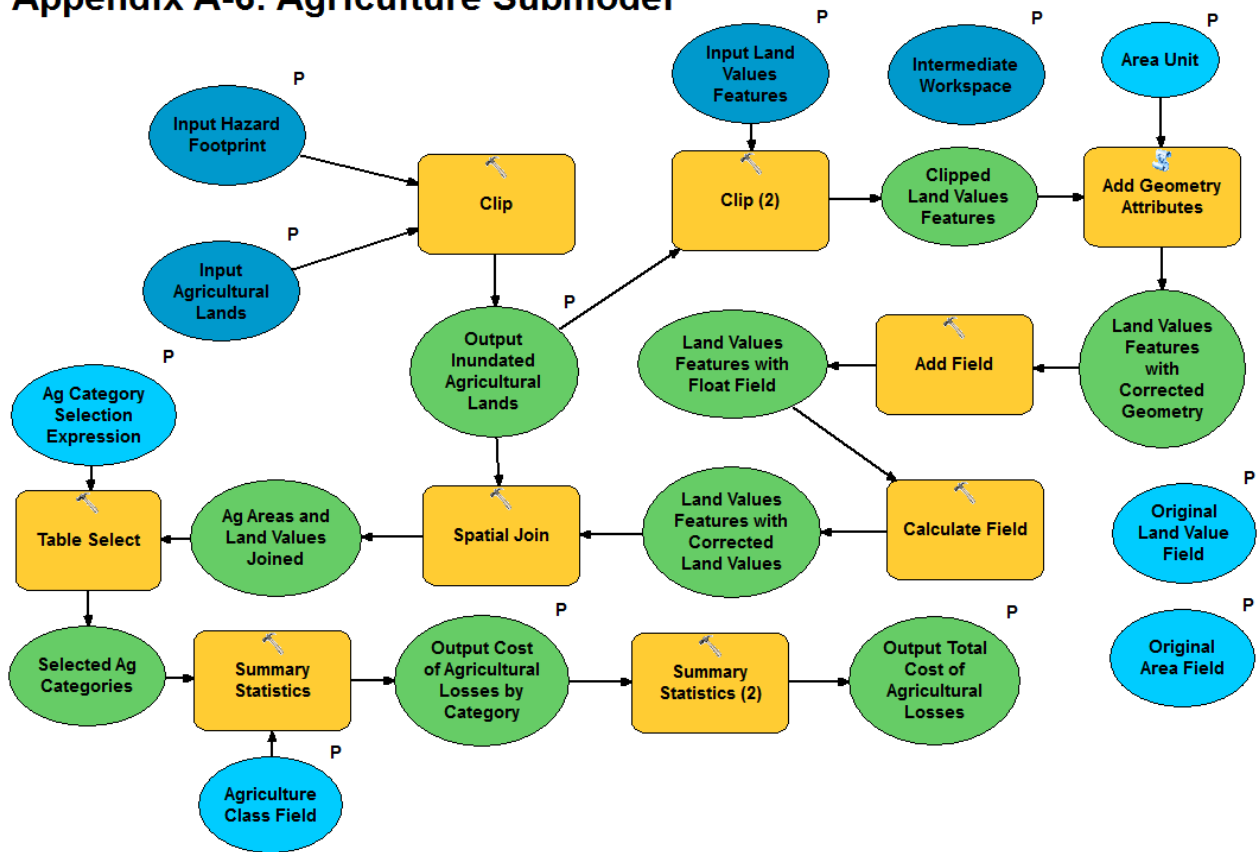


Chart explanation: Dark blue ovals denote data inputs (feature classes, workspaces, and tables). Light blue ovals are value parameters. Orange boxes denote model processes. Green ovals are data outputs (also tables and feature classes). Note that the data inputs, value parameters, and some data outputs are marked with a “P”. These are submodel parameters. Arrows reveal the progression of the model.

Descriptions of Model Processes:

The **Clip** tool overlays the Input Agricultural Lands feature class with the hazard footprint (e.g. Flow Area) and produces a new feature class containing only the agricultural lands that fall within the hazard footprint.

The **Clip (2)** tool overlays the Input Land Values features with the clipped agriculture features and creates a new feature class with only the portions of the land values features that overlap the clipped agriculture features. In most cases, a single clipped land values feature corresponds to a single clipped agricultural feature and the geometries of the corresponding features are identical. In some cases, however, multiple land values features overlap a single agriculture feature. In these cases, the sum of the geometries of the clipped land values features is identical to the geometry of the clipped agriculture feature.

The **Add Geometry Attributes** tool calculates the area, in user-selected units, of each agricultural polygon (and thus each land values feature) that falls within the hazard footprint. This is a crucial step because the Clip tool splits some of the agricultural polygons in the input feature class but fails to recalculate the areas of the inundated portions, and instead simply copies the areas of the original polygons into the attribute table of the clipped feature class. The Add Geometry Attributes tool corrects this issue.

The **Add Field** tool adds a field named CorrValue to the attribute table of the clipped land values features and the **Calculate Field** tool populates that field with the estimated monetary value of each inundated agricultural land area using the following expression: $[(\text{Area of Inundated Portion of Agricultural Land Polygon} / \text{Area of Entire Agricultural Land Polygon}) * \text{Original Land Value Field}]$. This step calculates the ratio of the inundated area of each agricultural parcel to the area of the whole parcel and scales down the original land value (as reported in the attribute table of the Input Land Values Features) by that ratio to estimate the value of the inundated portion.

The **Spatial Join** tool uses a one-to-many join operation to combine the attribute tables of the clipped land values and clipped agricultural lands feature classes. As a result, each clipped land values polygon is joined with its corresponding agriculture polygon, and each agricultural polygon is associated and with the corrected land area(s) and corrected monetary value(s) of the corresponding land values polygon(s).

The **Table Select** tool optionally allows for the selection of only certain agriculture categories for analysis via an SQL expression. See Ag Category Selection Expression in Appendix A-7.

The **Summary Statistics** tool calculates the total inundated area and total cost of damages for each crop category denoted by the Agriculture Class Field and records these sums in a new table. The Agriculture Class Field is an optional parameter, and if the user chooses not to specify this field the Summary Statistics tool will simply report the total inundated area and total cost of damages across all crop categories.

The **Summary Statistics (2)** tool calculates the total inundated area and total cost of damages across all crop categories reported in the output table of the Summary Statistics tool and records these values in the Output Total Damage to Streets table. If crop categories are not specified, this tool's output is identical to that of the previous Summary Statistics tool.

Appendix A-7: In-Program Documentation of the Lava Flow Vulnerability Model and Its Parameters

The following documentation appears in the model's item description and dialog box when opened in ArcMap.

Summary

The Lava Flow Vulnerability Model generates the most likely footprint of a lava flow originating at a user selected point and predicts the damages, in both quantities and cost, to infrastructure within the flow footprint. This tool operates under the assumption that a lava flow destroys all infrastructure it inundates. It is an aggregation of the Single Eruption Path tool, the Lava Flow Vulnerability - Streets Tool, the Lava Flow Vulnerability - Structures Tool, the Lava Flow Vulnerability - Critical Infrastructure Tool, and the Lava Flow Vulnerability - Agriculture Tool. The Single Eruption path tool utilizes inputs of an elevation raster and a user-selected eruption point to predict the path of steepest descent from the eruption point, thus identifying the path a lava flow is most likely to take. Utilizing inputs of a lava flow footprint, street features, and a table of values per length unit by road class, the Streets tool estimates the damages to streets inundated by the lava flow, in terms of length units of streets lost and total cost of the damage. Utilizing the lava flow footprint and structure data, the Structures tool estimates the losses of structures inundated by a lava flow, in terms of the quantity and cost of structural losses. Utilizing the flow footprint and a dataset of critical infrastructure features, the Critical Infrastructure tool determines which critical infrastructure features are inundated in the flow scenario and counts of number of inundated features per critical infrastructure class. Finally, using the flow footprint, agricultural parcels and land value data, the Agriculture tool determines what agricultural lands are inundated in the flow scenario and estimates the cost of those immediate losses.

IMPORTANT: The Lava Flow Vulnerability Model permanently changes some input data, so make copies of data to use as model inputs if preserving the original state of the data is desired.

Model Inputs

Input Eruption Point (Data Input)

Specify the Input Eruption Point. This input is a point feature class or layer file that contains or allows the user to choose a point of origin for the modeled lava flow.

Input Digital Elevation Model (Data Input)

Specify the Input Digital Elevation Model. This input is a raster containing elevation values.

Buffer Distance (Value Parameter)

Enter the desired distance to extend the flow boundary from the Input Lava Flow Path polyline. The buffer will extend the specified distance on each side of the polyline. There are two ways to specify Buffer Distance. The desired distance can be entered as a numerical value with a unit selected from the dropdown menu. Alternatively, a buffer field from the Input Lava Flow Path feature class that contains the distance to buffer each flow segment may be selected, provided the input polyline feature class is composed of line segments and a valid buffer field exists in its attribute table. The width of a lava flow depends on slope, topography, volume of lava erupted, and viscosity of the lava, among other factors. If specifying the buffer distance with a numerical value, one might determine an appropriate Buffer Distance by averaging the widths of previous flows in the vicinity of the potential flow modeled by this tool, and then dividing the average width by 2 (because the Buffer Distance is applied to each side of the Input Lava Flow Path polyline, and thus is half the total flow width).

Input Streets (Data Input)

Specify the input feature class that represents a street network. This feature class must include both an attribute field that contains the lengths of street features and an attribute field that classifies the street features. A street classification is required because the model assesses road value, and thus damage cost, on the basis that road value is dependent upon road class. In other words, a mile of one road class (say, a major highway) costs more to repave than a mile of another road class (a residential street). A Streets polyline shapefile with a Shape_Length field and a Road_Type field that categorizes the street features as "Highway", "Arterial Road", "Secondary Road", "Residential Road", "Driveway/Parking Lot", "Dirt Road" and "Trail" is one example of a valid input for this parameter.

Road Class Field (Value Parameter)

Enter the field in the attribute table of the Input Streets feature class that classifies the street features. Enter this field name manually if it is not available in the drop-down menu. A street classification is required because the model assesses road value, and thus damage cost, on the basis that road value is dependent upon road class. In other words, a mile of one road class (say, a major highway) costs more to repave than a mile of another road class (a residential street). A Road_Type field that categorizes the street features as "Highway", "Arterial Road", "Secondary Road", "Residential Road", "Driveway/Parking Lot", "Dirt Road" and "Trail" is one example of a valid input for this parameter.

Road Class Selection Expression (Value Parameter) (Optional)

In some cases, the user may desire to include only certain road classes in the lava flow vulnerability assessment. To do so, a Road Class Selection Expression must be entered. The expression must be written in Structured Query Language (SQL), and must take on the following form:

"Field" = 'Desired Value 1' OR "Field" = 'Desired Value 2' OR ...

In the above example (see help text for Input Streets), the Road_Type field includes "Dirt Roads" and "Trails". Damage costs for these road types are negligible when compared to damage costs for the other five road classes, and so they can be omitted. This omission is accomplished by entering the following for the Road Class Selection Expression:
"Road_Type" = 'Highway' OR "Road_Type" = 'Arterial Road' OR "Road_Type" = 'Secondary Road' OR "Road_Type" = 'Residential Road' OR "Road_Type" = 'Driveway/Parking Lot'

This expression selects only the road classes desired for use in the vulnerability assessment. Note that field names must be enclosed in double quotations and values must be enclosed in single quotations.

In some cases, the Input Costs per Unit by Road Class Table may only have cost per unit data for selected road classes. The Road Class Selection Expression should be used in such cases to select and proceed with only the road classes that have corresponding data in the Input Costs per Unit by Road Class Table. If the Road Class Selection Expression parameter is left blank, all classes in the Road Class Field will be included in the vulnerability assessment.

Length Unit (Value Parameter)

Choose the desired unit in which to report street lengths. This unit should match the unit in the field in the Input Costs per Unit by Road Class Table that contains the cost per unit values for each road class.

Input Costs per Unit by Road Class Table (Data Input)

Specify the Input Costs per Unit by Road Class Table. This input table must have a road classification field that corresponds to the Road Class Field above and contains all values specified by the Road Class Selection Expression. An additional field containing a cost per unit value for each road class, where the unit (e.g. miles) is the same as the Length Unit, is also required.

Road Class Join Field (Value Parameter)

Select the field in the Input Costs per Unit by Road Class Table that corresponds to the Road Class Field specified above. These two fields provide the basis on which their tables are joined.

Cost Field (Value Parameter)

Enter the name of the field from the Input Costs per Unit by Road Class Table that contains the cost to replace one length unit of each road class. The length unit in this field must be identical to the Length Unit specified above. If this field name does not appear in the tool's drop-down menu, type it in manually.

IMPORTANT NOTE: For the SUM_TOTHAZDMG value in the Output Total Lava Flow Damage table to be accurate, the Structure Value Field, the Cost Field, and the Original Land Value Field must have the same units of currency.

Input Structures (Data Input)

Specify the input feature class that contains structure data. This feature class must include an attribute field that contains structure values and an additional field that classifies the structures.

Structure Value Field (Value Parameter)

Enter the name of the field in the attribute table of the Input Structures feature class that contains the structure values. If no drop-down menu appears for this parameter, manually enter the exact field name.

IMPORTANT NOTE: For the SUM_TOTHAZDMG value in the Output Total Lava Flow Damage table to be accurate, the Structure Value Field, the Cost Field, and the Original Land Value Field must have the same units of currency.

Structure Class Field (Value Parameter)

Choose a field in the attribute table of the Input Structures feature class that classifies the structure features by type.

Structure Class Selection Expression (Value Parameter) (Optional)

In some cases, the user may desire to include only certain structure categories in the lava flow vulnerability assessment. To do so, the Structure Class Selection Expression must be entered. The expression must be written in Structured Query Language (SQL), and must take on the following form:

"Field" = 'Desired Value 1' OR "Field" = 'Desired Value 2' OR ...

For example:

"Bldg_Type" = 'Industrial' OR "Bldg_Type" = 'Commercial' OR "Bldg_Type" = 'Mixed Use' OR "Bldg_Type" = 'Residential'

This expression selects only the specified structure classes desired for use in the vulnerability assessment. Note that field names must be enclosed in double quotations and values must be enclosed in single quotations.

If the Structure Class Selection Expression parameter is left blank, all categories in the Structure Class Field will be included in the vulnerability assessment.

Input Critical Infrastructure (Data Input)

This input must be a Workspace or Feature Dataset that contains all the critical infrastructure feature classes to be processed by the model. Critical infrastructure is defined as any vital element(s) of the built environment that would have a debilitating effect on public security, health, safety, or wellbeing if incapacitated or destroyed. Examples of critical infrastructure include fire stations, hospitals, and schools.

The critical infrastructure feature classes within the Workspace or Feature Dataset can be point, line, or polygon features, or any combination thereof. However, all feature classes should meet the following conditions:

1. All feature classes must have a field titled Identity. This field should contain an identifying record for each individual feature in a feature class. If the Identity field does not already exist for all feature classes, the user must manually create it using the Add Field function within each feature class attribute table. Identifying records can be copied over to the Identity field from another identifying field such as Name, Address, Facility, etc., or entered manually by the user.
2. It is recommended that the name of each feature class is simple yet descriptive of the type of critical infrastructure data it contains. E.g., a feature class containing hospital point features should have "Hospitals" somewhere in the feature class name.

Input Agricultural Lands (Data Input)

Specify the input polygon feature class that represents agricultural lands. This feature class must include a field that classifies the agricultural lands by type.

Agriculture Class Field (Value Parameter)

Choose a field in the attribute table of the Input Agricultural Lands feature class to classify the agriculture polygons by type.

Ag Category Selection Expression (Value Parameter) (Optional)

In some cases, the user may desire to include only certain agriculture categories in the hazard vulnerability assessment. To do so, the Ag Category Selection Expression must be entered. The expression must be written in Structured Query Language (SQL), and must take on the following form:

"Field" = 'Desired Value 1' OR "Field" = 'Desired Value 2' OR ...

For example:

"Crop_Class" = 'Pasture' OR "Crop_Class" = 'Corn' OR "Crop_Class" = 'Avocado' OR
"Crop_Class" = 'Macadamia' OR "Crop_Class" = 'Coffee'

This expression selects only the specified agriculture classes desired for use in the vulnerability assessment. Note that field names must be enclosed in double quotations and values must be enclosed in single quotations.

If the Ag Category Selection Expression parameter is left blank, all categories in the Agriculture Class Field will be included in the vulnerability assessment.

Input Land Values Features (Data Input)

Specify the input polygon feature class that represents land parcels and their values. This feature class must include an attribute field that contains polygon areas, and a field that contains land values in any currency. A State or County Tax Map Key shapefile typically has the required attribute fields and is one example of a valid input for this parameter.

Original Area Field (Value Parameter)

Specify the attribute field in the Input Land Values Features table that contains land areas. If no drop-down menu appears for this parameter, manually type in the exact field name.

Area Unit (Value Parameter)

Choose the desired units in which the areas of inundated agriculture polygons will be reported. The Area Unit must be identical to the units of the Original Area Field in the attribute table of the Input Land Values Features.

Original Land Value Field (Value Parameter)

Specify the attribute field in the Input Land Values Features table that contains the land value for each agriculture polygon. If no drop-down menu appears for this parameter, manually type in the exact field name.

IMPORTANT NOTE: For the SUM_TOTHAZDMG value in the Output Total Lava Flow Damage table to be accurate, the Structure Value Field, the Cost Field, and the Original Land Value Field must have the same units of currency.

Workspace (Data Input)

Specify the workspace in which to save all intermediate data generated during model processing.

Data Outputs

Shapefile: *Output Eruption Point*

Choose a name and folder for the Output Eruption Point. This output is a point feature that indicates the location of the selected Input Eruption Point.

Shapefile: *Output Flow Area*

Choose a name and folder for the Output Flow Area. This output is a polygon feature class displaying the predicted inundation footprint of the lava flow.

Shapefile: *Output Streets in Hazard Footprint*

Choose a name and folder for the Output Streets in Hazard Footprint. This output is a polyline feature class that displays the streets that fall within the Output Flow Area.

Table: *Output Total Damage by Road Class*

Choose a name and folder for the Output Total Damage by Road Class. This output is a table that contains the total quantity of streets by road class damaged by the predicted lava flow, in the units specified by the Length Unit parameter, and the total cost of damage to each street type by the flow, in the currency used in the Input Costs per Unit by Road Class Table. The SUM_LENGTH field contains the total length of streets damaged in each class, and the total cost of damages to each road class is listed under TOTRDCLSCOST.

Shapefile: *Output Inundated Structures*

Choose a name and folder for the Output Inundated Structures. This output is a polygon feature class that displays the parcels or structures that fall within the Output Flow Area.

Table: *Output Loss of Structures by Category*

Choose a name and folder for the Output Loss of Structures by Category. This output is a table with the fields FREQUENCY, which lists the number of inundated structure features for each structure class, and SUM_ValueBldgs, which lists the total cost of damage to each structure class in the currency of the Structure Value Field.

Shapefile: *Output Inundated Critical Infrastructure*

Choose a name and folder for the Output Inundated Critical Infrastructure. This output is a point feature class that identifies and displays all elements of critical infrastructure that fall within the Output Flow Area. This output's attribute table displays the Identity field with its input values, as well as an InfraClass field that classifies the critical infrastructure features by type based on the names of the input critical infrastructure feature classes.

Table: Output Inundated Critical Infrastructure Count

Choose a name and folder for the Output Critical Infrastructure Count. This output is a table with the fields INFRACCLASS, which lists each type of inundated critical infrastructure, and COUNT_INFRACCLASS, which provides the total number of inundated critical infrastructure elements in each INFRACCLASS type.

Shapefile: Output Inundated Agricultural Lands

Choose a name and folder for the Output Inundated Agricultural Lands. This output is a polygon feature class that displays the agricultural areas that fall within the Output Flow Area.

Table: Output Cost of Agricultural Losses by Category

Choose a name and folder for the Output Cost of Agricultural Losses by Category. This output is a table with the fields SUM_POLY_AREA, which lists the inundated land area for each agriculture category, and SUM_CORRVALUE which lists the total costs of damages to each agriculture category in the currency of the Original Land Value Field.

Table: Output Total Lava Flow Damage

Choose a name and folder for the Output Total Damages. This output is a table detailing the financial losses expected in the modeled flow scenario. The table's fields are defined as follows.

SUM_SUM_FREQUE: This field contains the total number of inundated structure features.

SUM_SUM_SUM_VA: This field contains the total cost of structure losses, in the currency of the Structure Value Field.

SUM_SUM_SUM_LE: This field contains the total length of inundated streets, in the Length Unit.

SUM_SUM_TOTRDC: This field contains the total cost of street losses, in the currency of the Cost Field.

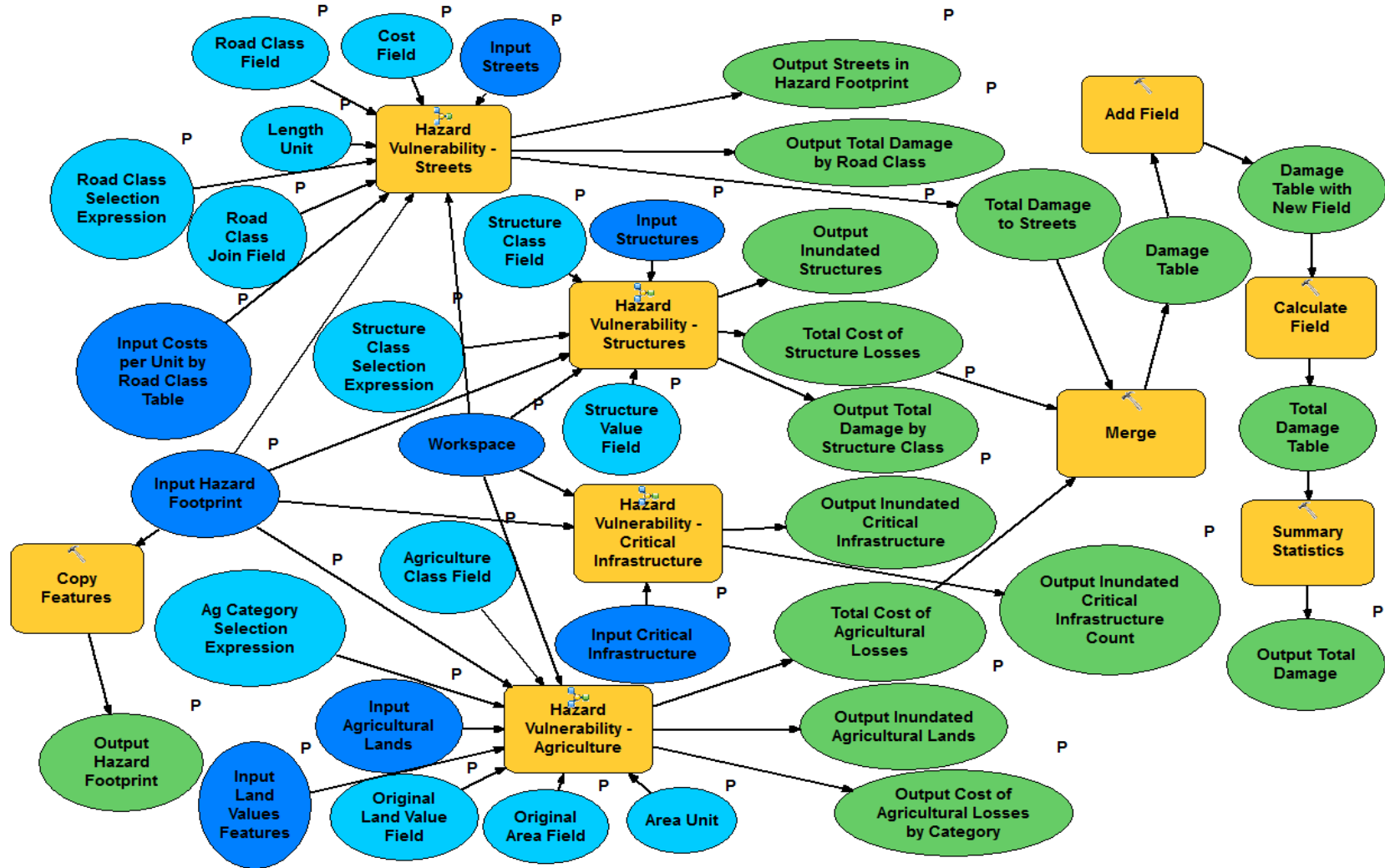
SUM_SUM_SUM_PO: This field contains the total area of inundated agricultural lands, in the Area Unit.

SUM_SUM_SUM_CO: This field contains the total cost of immediate agricultural losses, in the currency of the Original Land Value Field.

SUM_TOTFLOWDMG: This field contains the total expected cost of infrastructure losses in the modeled flow scenario. The SUM_TOTFLOWDMG value is the sum of the SUM_SUM_SUM_VA value, the SUM_SUM_TOTRDC value, and the SUM_SUM_SUM_CO value.

IMPORTANT NOTE: For the SUM_TOTFLOWDMG value in the Output Total Lava Flow Damage table to be accurate, the Structure Value Field, the Cost Field, and the Original Land Value Field must have the same units of currency.

Appendix B: Hazard Vulnerability Model



Appendix B: Hazard Vulnerability Model (Continued)

Chart explanation: Dark blue ovals denote data inputs (feature classes, workspaces, and tables). Light blue ovals are value parameters. Orange boxes denote model processes. Green ovals are data outputs (also tables and feature classes). Note that the data inputs, value parameters, and some data outputs are marked with a “P”. These are model parameters. Arrows reveal the progression of the model. The Hazard Vulnerability Model is nearly identical to the Lava Flow Vulnerability Model, with three small exceptions. First, the Single Eruption Path and Buffer tools have been removed and the Input Hazard Footprint is now a model parameter in their place. The hazard footprint is now an input to the Copy Features tool. The remaining processes and parameters of the Hazard Vulnerability Model are essentially identical to the processes and parameters of the Lava Flow Vulnerability Model described in Appendix A. The only difference is that the words “Lava Flow” are altered to “Hazard” in the documentation of the Hazard Vulnerability Model.

Descriptions of Model Processes:

The **Copy Features** tool translates the Input Hazard Footprint into an output feature class and displays it in the map document.

The **Streets** submodel is detailed in Appendix A-3.

The **Structures** submodel is detailed in Appendix A-2.

The **Critical Infrastructure** submodel is detailed in Appendices A-4 and A-5.

The **Agriculture** submodel is detailed in Appendix A-6.

The **Merge** tool combines the output quantity and cost tables from the Structures, Streets, and Agriculture submodels into one table, preserving the fields from the submodels' tables and placing the quantity and cost numbers from each submodel into their own row.

The **Add Field** tool adds a new field named TotHazDmg to the merged table and the **Calculate Field** tool populates the TotHazDmg field with the sum of costs across each row of the merged table (the total cost of damages for each submodel).

The **Summary Statistics** tool calculates the sum of values in the TotHazDmg field and writes it to a new Output Total Damage Table (see Appendix A-7) along with the total quantity values from the submodels' output tables and the cost totals from the previous step.

Appendix C: Detailed Practicum Timeline, January to May 2018

Note: This internship included two major projects: (1) the vulnerability models presented in this paper and (2) writing metadata and the organization of an SDE geodatabase for all of HVO's spatial data. Also included were a handful of minor projects and events. The number of hours spent on the modeling (practicum) project are given adjacent to each date.

16 Jan - First day of internship, 0 Practicum Hours

Attended weekly touch-base meeting, got a tour of the building and a list of computer training courses. Scheduled appointments for computer access card and respirator. Prepared for kids' corner at tomorrow night's Mauna Loa public awareness event.

17 Jan - 0 practicum hours

Access card appointment in Hilo. Also ran kid's corner for the Mauna Loa public awareness event.

18 Jan - 0 practicum hours

Respiratory appointment in Hilo. Afternoon spent working on training courses.

19 Jan - 0 practicum hours

Learned how to use a respirator and about safety when working in vog-heavy environments. Helped collect soil samples along the Ka'ū Desert trail. Beginning of govt shutdown.

22 Jan - 0 practicum hours

Government is shut down. No work today.

23 Jan - 0 practicum hours

Waiting for activation of computer access. I worked on an inventory of legacy maps in HVO's library.

24 Jan - 0 practicum hours

Finished written inventory of legacy maps. Computer access activation was completed at the end of the day.

25 Jan - 6 practicum hours

Completed practice CSAV GIS lava flow modeling and vulnerability analysis exercise. This is the skeleton of the modeling methodology. Jotted down questions, potential improvements, and research points. Started spreadsheet for legacy maps.

26 Jan - 6 practicum hours

Completed spreadsheet for legacy maps. Started working on a set of ModelBuilder refresher tutorials. Helped with prep and loading vehicles for tomorrow's Mauna Loa awareness event.

29 Jan - 4 practicum hours

Finished ModelBuilder exercise. Then spent time getting to know HVO's SDE database and making plans for re-organizing and renaming files. Learned how to use Representations in ArcGIS.

30 Jan - 4 practicum hours

Learned how to write metadata, have it checked for compliance to USGS standards, and fix non-compliant data in Notepad++. Then spent the remainder of the day downloading infrastructure data from the State of Hawaii's data portal for vulnerability project.

31 Jan - 7 practicum hours

Worked on the vulnerability project. Spent a lot of time reading up on Tax Map Key (TMK) parcel data. This will be extremely useful because land and building values are included. Also brainstormed what utility networks might be affected by lava flows. Power lines certainly. Other networks are largely underground - need to do more research to figure out which, if any, to include.

1 Feb - 1 practicum hour

Continued learning how to write metadata that meets Federal Geographic Data Committee (FGDC) standards for geospatial metadata. Was introduced to an online metadata parser tool that detects errors in my written metadata. Ran one metadata file through again and again, correcting errors, for 6 hours. Spent the last hour researching the web for data useful to the vulnerability project, but found nothing new.

2 Feb - 1 practicum hour

Continued steep learning curve learning how to write metadata that meets FGDC standards. Finally polished metadata for the Airports shapefile! As with yesterday, I spent my last hour researching the web for useful data, with nothing new found.

5 Feb - 0 practicum hours

Continued working on writing metadata.

6 Feb - 0 practicum hours

Made steady progress on metadata today. Second shapefile, Hospitals, is complete and third one started.

7 Feb - 0 practicum hours

More progress on metadata. Third shapefile, Small Boat Harbors, is complete, fourth one started.

8 Feb - 7 practicum hours

Spent the day building a fully-automated model that calculates total damage, in U.S. dollars, to roads inundated in a lava flow scenario, with inputs of an eruption point, a DEM, a Streets feature class, and a table of road values. The outputs are a lava flow area (map) and total cost of inundated roads (tabular).

9 Feb - 0 practicum hours

Finished metadata for the Dams layer. Then worked on merging overlapping health facility data into one layer. Finished the day by attending a guest talk on volcanic projectiles at the office.

12 Feb - 4.5 practicum hours

There were a couple of meetings today. Finished creating the Health Facilities feature class and wrote most of its metadata.

13 Feb - 6 practicum hours

Finished metadata for the Health Facilities feature class. Spent the remainder of the day attempting to generalize the streets vulnerability model so that it can use any streets data. Finished the day with lots of things not working and much troubleshooting to do.

14 Feb - 6 practicum hours

Tried to write metadata for Hawai'i County streets shapefile using Metadata Wizard tool. Saved in the wrong (temp) folder and lost it all. Got the generalized streets vulnerability model working. Not so much troubleshooting after all.

15 Feb - 8 practicum hours

Found a streets shapefile from the U.S. Census Bureau's TIGER Database that came with up-to-standard metadata. Streets submodel is complete! Also created a single Schools shapefile today by merging a handful of State data files.

16 Feb - 7 practicum hours

Wrote metadata for the Schools shapefile I created yesterday using the Metadata Wizard tool. It was a success! Also generalized the Streets Vulnerability model to work for any length units, not just miles, and started writing descriptions for the Lava Flow Vulnerability - Streets tool and all of its parameters.

20 Feb - 1 practicum hour

Made a little progress on descriptions for the Lava Flow Vulnerability - Streets tool and its parameters. After that it was a field day at the active flow.

21 Feb - 6 practicum hours

Completed descriptions for the Lava Flow Vulnerability - Streets tool. Then I wrote metadata for the commercial harbors shapefile and almost finished metadata for the fire stations shapefile.

22 Feb - 6 practicum hours

Finished metadata for the fire stations shapefile. Added one new parameter to the Lava Flow Vulnerability - Streets tool. Finally, I created the generalized Hazard Vulnerability - Streets tool.

23 Feb - 6 practicum hours

Finished touching up the Hazard Vulnerability - Streets tool. Then I created metadata for the TMK shapefile and started metadata for the Police Stations shapefile. Afternoon meeting about mosaics and efficient raster storage in and outside of SDE databases.

26 Feb - 0 practicum hours

Finished metadata for the Police Stations shapefile and wrote metadata for the Postsecondary Institutions shapefile.

27 Feb - 7 practicum hours

Constructed and started the Item Description for the Lava Flow Vulnerability - Structures model that calculates cost of structure losses based on Tax Map Key data. Explored the idea of using building footprints in this model instead of TMK, but such data is not available and I lack the resources to create my own.

28 Feb - 0 practicum hours

Wrote metadata for Hotels and Banks/Credit Unions layers. I also got about halfway through metadata for Bridges.

1 Mar - 7 practicum hours

Finished Bridges metadata. Then I worked out a possible methodology for assessing damage to agricultural land. Not committed to this yet, and it's not a priority. Finally, I switched a Calculate Field tool to a Geometry Calculation tool in the Lava Flow Vulnerability - Streets tool to correct the fact that the Clip tool doesn't split values when it splits polygons.

2 Mar - 7 practicum hours

Downloaded Landmarks and Military Installations and their metadata from the U.S. Census Bureau website. Then I corrected the Hazard Vulnerability - Streets tool in the same manner the Lava Flow Vulnerability - Streets tool was corrected. Finally downloaded and started sorting through infrastructure shapefiles from the DOHS's HIFLD database.

5 Mar - 5 practicum hours

Created Communication Towers layer from several HIFLD data layers and added Urgent Care data to Health Facilities shapefile. Wrote metadata for Ag Baseline shapefile.

6 Mar - 7 practicum hours

Added Pacific Disaster health data to Health_Facilities layer and updated it's metadata. Then built the Hazard Vulnerability - Structures tool. Started the process of moving the Lava Flow Vulnerability Streets and Structures tools into the master Lava Flow Vulnerability model.

7 Mar - 7 practicum hours

I got the master Lava Flow Vulnerability model up to date. Then I scoured the Communications Towers shapefile for duplicates and wrote it's metadata.

8 Mar - 0 practicum hours

Another steep learning curve today with matching and imbedding metadata with the right shapefiles. Worked on building the SDE geodatabase, adding a handful of feature datasets with feature classes and their imbedded metadata.

9 Mar - 7 practicum hours

Started building the Lava Flow Vulnerability - Critical Infrastructure model, which will count the number of inundated structures of each infrastructure type. Struggling with getting this one to work. Processing multiple shapefiles at one time is difficult. Need to get some help on this next week.

12 Mar - 4 practicum hours

Polished metadata and uploaded roads shapefiles to the practicum's infrastructure geodatabase. Also, polished metadata and added thumbnails for all files already in the database.

13 Mar - Field Day (0 practicum hours)

Accompanied an HVO scientist and college geology field camp to Lua Manu, Mauna Ulu and fissure, Hilina Pali Road and Kīlauea Caldera and learned a ton about the lava lake, tree molds, spatter ramparts, Hawaiian language, and explosive eruption debris.

14 Mar - 4 practicum hours

I spent the day imbedding metadata into Hawai'i State infrastructure shapefiles and importing them to the infrastructure geodatabase. I also fixed type attributes for misidentified lines in the boundaries feature class and coastline feature class (SDE geodatabase).

15 Mar - 7 practicum hours

Finished moving State and Census critical infrastructure data into infrastructure geodatabase, and added an Infrastructure Category field to each of them for use in the Merge tool (Critical Infrastructure submodel). Also worked on simplifying and rebuilding this submodel.

16 Mar - Field day

Participated in an igneous geology field trip across the Saddle Road from Hilo to Kona with visiting college students.

19 Mar - 4 practicum hours

Wrote metadata for and imported the Wastewater Treatment Plants feature class to the infrastructure geodatabase. Started working on cracks_and_fissures shapefile for SDE. Also started a spreadsheet of feature classes that have complete metadata.

20 Mar - 4 practicum hours

Finished the HI_cracks_and_fissures feature class for the SDE geodatabase. Wrote metadata for the EOC feature class and imported it to the infrastructure (practicum) geodatabase.

21 Mar - 4 practicum hours

Wrote metadata for and imported the Petroleum_Terminals feature class to the Critical Infrastructure dataset. Made some more progress on the Critical Infrastructure submodel. Now it just needs to be tested.

22 Mar - 6 practicum hours

Successfully tested the Critical Infrastructure submodel and created a map of the results. Also wrote metadata for the haw_milemarkers feature class for the SDE database.

23 Mar - 4 practicum hours

Created and embedded metadata for the Pharmacies shapefile and uploaded it to the infrastructure geodatabase. Also got the DRG hydrology and annotation shapefiles for the SDE linked to their metadata. Started metadata for the Airstrips/Airfields shapefile.

26 Mar - 7 practicum hours

Finished metadata for Airstrips and Airfields shapefile and wrote metadata for Chemical Facilities and Electric Substations shapefiles, all from PDC. Imported all three shapefiles to the infrastructure geodatabase.

27 Mar - 3 practicum hours

Wrote and imbedded metadata for and uploaded Emergency Sirens and Wells shapefiles from PDC to the infrastructure geodatabase. Wrote metadata for the HI_Quads shapefile as well. Updated list of completed files and ones still missing metadata.

28 Mar - 5 practicum hours

Uploaded infrastructure GDB to the SDE. Then worked on the Critical Infrastructure submodel. Trying out an Iterator in place of a Batch analysis. Rough going so far, but good ideas keep coming.

29 Mar - 0 practicum hours

Started going through existing feature classes on the SDE, sorting them into Datasets, updating metadata to the federal standard, and eliminating duplicates. Got through 1000ft and 40ft contours today.

30 Mar - 4 practicum hours

Fixed several feature class names in the SDE database to include file type (point, line, poly). Updated metadata for remaining contour and geographic place names shapefiles. Then made progress on the Iterator version of the Critical Infrastructure model. The Calculate Field tool works now, but the Merge tool does not.

2 Apr - 6 practicum hours

Used a feature class to feature class conversion and organized workspace folders to (hopefully) solve the Merge issue from 3/30. Needs testing and tweaking. Latest is that the Feature to Point tool failed...

3 Apr - 6 practicum hours

Got the Critical Infrastructure submodel fully functional! Now working on updating the tool so that it will include an Identity field in the output Critical Infrastructure feature class.

4 Apr - 2 practicum hours

Imbedded metadata and migrated all the national park boundary shapefiles to the SDE database. Then made some headway on adding an Identity field to the Critical Infrastructure submodel's output.

5 Apr - 0 practicum hours

Found a coordinate system error in several of the SDE feature classes that had to be corrected, a project which took the entire day.

6 Apr - 6 practicum hours

Attempted to include an Identity field in the Critical Infrastructure model output table, but had zero luck. Without any coding knowledge, it appears the only option here will be to include the Identity field in all of the inputs.

9 Apr - 6 practicum hours

Finished the Critical Infrastructure model. The issue was resolved by including the Identity field in each feature class prior to processing. Put together an informal presentation to touch base with the team on model work.

10 Apr - 5 practicum hours

Polished the informal presentation started yesterday and touched base with the team. Performed a couple of minor tweaks to the Streets model (added an output table detailing cost per street class) and Structures model (added a map output of inundated structures). Started metadata for the Land_Use_Poly feature class for the SDE database.

11 Apr - 5 practicum hours

Imbedded metadata in the Land_Use_Pt and Land_Use_Poly shapefiles and uploaded them into the SDE database. Separated the Skilled Nursing Facilities, Urgent Care, and Hospitals feature classes from the Health_Facilities feature class and uploaded them to both geodatabases individually. Wrote an Item Description for the Lava Flow Vulnerability - Critical Infrastructure submodel and generalized it to the Hazard Vulnerability - Critical Infrastructure submodel

12 Apr - 4 practicum hours

Imbedded metadata in the HI_Volcanoes and HI_Populated_Places shapefiles and uploaded them to the SDE database. Polished the item description for the Critical Infrastructure submodel

and added the Critical Infrastructure submodel to the master Lava Flow Vulnerability model. Started work on modeling inundated agricultural parcels.

13 Apr - 6 practicum hours

Imbedded metadata and uploaded the two annotation feature classes into the SDE database. Then worked on constructing The Agriculture Vulnerability submodel.

16 Apr - 6 practicum hours

Finished constructing the Agriculture submodel. Then got started on metadata for the Ag Baseline shapefile and uploaded the shapefile to the infrastructure and SDE geodatabases.

17 Apr - 1 practicum hour

Finished metadata for the Ag shapefile. Also wrote metadata for and uploaded the following to the SDE: Tsunami Zones, Large Ocean Poly, corrected Administrative Boundaries, and Vegetation. Vegetation is nearly complete.

18 Apr - 1 practicum hour

Spent a good chunk of the day on a helicopter flight to Pu'u 'Ō'ō. Finished the Vegetation feature class metadata and got it uploaded to the SDE. Did the same for the Coastal Place Names features. Reopened brainstorming some ways to add a name field to the Critical Infrastructure submodel without having it as part of each attribute table beforehand. Possible progress.

19 Apr - 7 practicum hours

Tried to get an iterated join operation to work for adding a Name field to the output of the Critical Infrastructure submodel. No luck though. Looks like there's a limit to the number/size of tables that ArcGIS/ the available computer system can handle. So this method not a good idea for a generalized, adaptable tool.

20 Apr - 4 practicum hours

Wrote metadata for the All Historical Flows shapefile. Still need to import it to the SDE. Meeting on the Next Generation of Hazard Assessment. Then made plans to present my project to the staff and finished polishing and documenting the Agriculture submodel.

23 Apr - 6 practicum hours

Aggregated submodels into master Lava Flow Vulnerability Model. Lots of troubleshooting.

24 Apr - 10 practicum hours

Finished polishing, documenting and testing the generalized Hazard Vulnerability Model. Modeling is officially complete!

25 Apr - 8.5 practicum hours

Put together PowerPoint for model presentation.

26 Apr - 9 practicum hours

Tweaked and practiced model presentation.

27 Apr - 2 practicum hours

Final practice and then gave the model presentation.

30 Apr - 0 practicum hours

Finished metadata and uploaded to the SDE for the All Volcanoes, Mauna Loa, and Hualālai historic flows shapefiles.

1 May - 4 practicum hours

Finished Kīlauea historic flows shapefile. It is uploaded and has metadata. Started reading through HAZUS report, and started on a vulnerability assessment for hazard zones on Kīlauea in response to the recent peak in activity.

2 May - 5.5 practicum hours

Finished Kīlauea vulnerability assessment.

3 May - 0 practicum hours

Manned a GPS monitoring station in Kapoho for the day. Beginning of LERZ eruption.

4 May - 0 practicum hours

Worked on modeling potential flow paths for lava erupting from the fissures in Leilani Estates. Read over HAZUS assessment. Helped create some informational posters for recent events. Spent a lot of time under desks and door frames... crazy earthquake activity.

6 May - 0 practicum hours

Ran lava flow hazard models for sections of the ERZ. This is the start of a new hazard zones map for Kīlauea.

7 May - 0 practicum hours

Refined lava flow models for new ERZ hazard zones map. Also updated the map of eruptive fissures in Leilani Estates.

8 May - 4 practicum hours

Finished flow models for ERZ hazard zones map. Polished documentation for overall vulnerability models.

9 May - 7 practicum hours

Finished final documentation for both Lava Flow and Hazard Vulnerability models. Some more Leilani eruption vulnerability assessments aside, the practicum project is complete!

10 May - 7 practicum hours

Ran the Hazard Vulnerability Model for Kīlauea LERZ Lava Hazard polygons, as well as for Leilani Estates.

11 May - 0 practicum hours

Last day of internship spent in the field documenting state of eruption in Leilani Estates and then doing a helicopter overflight.

Monthly Totals:

January: 27 practicum hours

February: 66.5 practicum hours

March: 96 practicum hours

April: 100.5 practicum hours

May: 27.5 practicum hours

Total practicum hours: 317.5