TIMING OF RECOVERY OF CRITICAL INFRASTRUCTURE IN LOWER PUNA FROM THE 2018 ERUPTION AT KĪLAUEA AND SOME IMPLICATIONS

A FINAL REPORT SUBMITTED TO THE DEPARTMENT OF EARTH SCIENCES, UNIVERSITY OF HAWAIʻI AT MĀNOA, IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN EARTH AND PLANETARY SCIENCES

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Table of Contents

ABSTRACT

The 2018 eruption in Lower Puna on the Big Island of Hawai'i showcased unprecedented levels of infrastructural damage during the 2018 LERZ eruption that altered communities and land for generations. A significant gap exists in the literature on the consolidation of key components of critical infrastructure damages and the recovery efforts concerning public road access, water, and electricity. This study gathered information from various sources to holistically understand the recovery efforts and expansion of that infrastructure that has been put into place or will be implemented in the coming years. When consolidating this information, it highlighted profound implications as a result of these efforts. Various factors have led to a continuous rise of new residents in Lower Puna since 2018. The increase in new residents is in direct contrast to the buy-out deal's efforts to discourage population growth in Lower Puna. Is the recovery and enhancement of critical infrastructure contributing to this population growth? Without having solitary, holistic information on the timeline of the damages and the recovery efforts that have taken place and will take place, it is difficult to measure the overall resiliency in Lower Puna. Seeing that the recovery of critical infrastructure in Lower Puna remains uncertain and ongoing, there are multiple potential trajectories that this inquiry may take. As such, the investigation may lead to various pathways of exploration, each of which may require in-depth analysis and consideration for the future of Lower Puna.

INTRODUCTION

Lava hazard zones 1 and 2 within the Lower East Rift Zone (LERZ) of the Big Island of Hawai'i define an area that is particularly vulnerable to volcanic activity. This area is home to numerous rural communities that have experienced multiple eruptions, and destructive lava flows in the last 200 years (Fig. 1). During volcanic activity in the LERZ, residents in the area can face a range of hazards, including lava flows, volcanic ash, scoria, and various toxic gasses. Lava flows destroy homes and infrastructure, while ash and acidic gasses are corrosive and can destroy metal and wooden features and cause respiratory problems and other health issues (Haney and Havice, 2019).

The unprecedented cost of the 2018 eruption in Hawai'i (Neal et al., 2019) reflects an intersection of physical and social events. The infrequent but highly destructive eruptions combined with exceptionally rapid population growth are the main factors influencing the risk level in Lower Puna. Kīlauea is one of the most active volcanoes on our planet (Cottrell, 2015). The vulnerability of residents in the LERZ is compounded by the fact that many people are attracted either to live on a dynamic landscape and/or by low land prices.

The heightened threat to Puna from lava flows from the LERZ (Wright et al., 1992; Kauahikaua and Tilling, 2014) ensured that land values were always depressed in Lower Puna, which sits within USGS's three highest lava hazard zones (1–3) (Fig. 1). The translation of high risk into low land prices attracted residents (Cooper and Daws, 1990) so that rapid population growth occurred during the absence of any locally sourced eruptions between 1961 and 2018.

Combined with the housing growth set the scene for the unprecedented levels of infrastructural damage during the 2018 eruption.

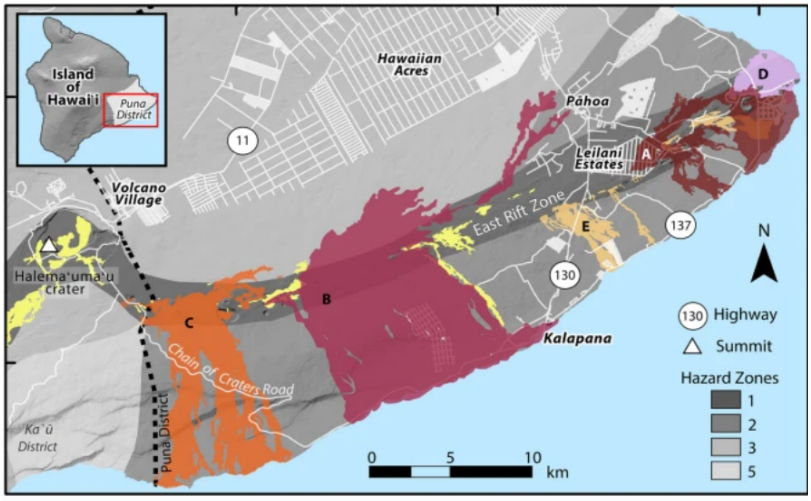

Fig. 1. *Map showing the catastrophic lava flows that have occurred along the East Rift Zone in the Puna District since 1950: A- 2018 LERZ lava flows (Dark brown), B- 1983–2018 Puʻuʻōʻō-Kūpaianaha lava flows (burgundy), C- 1969–1974 Mauna Ulu lava flows (orange), D-1960 Kapoho lava flows (light purple), E- 1955 lava flows (light brown). All additional flows have been colored yellow. The Halemaʻumaʻu vent within the Kīlauea caldera and hazard zones 1-3 are shown for context (Meredith et al., 2022).*

During the initial phase of the 2018 eruption, some residents chose to stay within hazard zones even though they had no power, cell phone reception, landlines, or county water; these areas were essentially “off the grid,” said Hawai'i Civil Defense Service officials (McLean, and Vera, 2018). At the end of the eruption, damage to public infrastructure reached an estimated $236.5 million (Kīlauea Recovery and Resilience Plan). This study analyzes the timelines in which damage to critical infrastructure occurred, as well as the recovery efforts and expansion that have been completed or are scheduled to be completed in the future.

Why is this project important?

Infrastructure takes time to rebuild completely, and any delays in the recovery may delay the healing process for the community. Meredith et al. (2022) concluded that when planning for and recovering from lava flow episodes, a holistic approach is required, taking into account a wider variety of hazards linked with fissure eruptions. “Their framework for damage state could be expanded to consider functionality as a function of time throughout the course of the eruptive crisis and the recovery phase” (Meredith et al., 2022). Presently, numerous studies discuss the damage to the properties of Lower Puna and the source parameters regarding the lava composition, eruption rate, and various other studies. However, the literature lacks consolidated information on the critical infrastructure's damage timelines and the efficacy of recovery efforts of public road access, water, and electricity. This paper gathers information from various news media, recovery websites, publications, and public videos to holistically understand recovery efforts. How did the loss of basic modern infrastructure impact the overall resiliency in this area? Does the lack of a comprehensive critical infrastructure plan affect the perception of resiliency in Lower Puna? And in what ways does this affect the emergency managers and policy planners moving forward?

Task: A detailed look into how the Lower Puna recovery plan (public road access, water supply, and electricity) impacted Lower Puna's revival. This study analyzes the timeline over which damage to critical infrastructure culminated and the recovery efforts and expansion of that infrastructure. First, this paper separately encapsulates each critical infrastructure's damage and timeline. Next, it will summarize the recovery efforts that have already occurred or are scheduled to be implemented within the next few years. In the third section, this paper will

discuss the implications and explore what these critical infrastructure recovery efforts may mean for residents wanting to return to Lower Puna. Finally, it will conclude with a summary of the main findings and implications for future research.

BACKGROUND

Lower Puna population and demographics

Puna comprised 24% of Hawai'i's county population in 2010, only 10% of the total land area. Between 2000 and 2010, the most recent census counts, Puna's population increased by 66%, as opposed to 24% for the entire county. Many citizens commute from Puna to Hilo or to the island's west coast, where land is more expensive and scarce (Houghton et al., 2021). As previously mentioned, Puna's history with an absence of land use planning and its implications for random development in hazard-prone areas is lengthy and complex. A few of the significant resources in lower Puna include: The Puna Geothermal Venture's (PGV) energy plant (which provided 31% of the island with electricity in 2017), different quarries, and popular coastal beaches and tidal pools. As such, the Big Island saw a real estate boom in 1958, and land in Puna attracted developers because of its sizable and inexpensive lots. Almost 52,500 subdivision lots were constructed in Puna between 1958 and 1973, according to the Hawai'i County Planning Department. In comparison to the State and County of Hawai'i as a whole, the high-risk region surrounding the LERZ experienced a sharp surge in population between 1970 and 1980 (Fig. 2) (Haney and Havice, 2019). Large parcels of land formerly allocated for agricultural use were subdivided at this time. Housing growth within subdivisions in hazard zones 1 and 2 resulted in a continually expanding population at high risk from future volcanic

disasters. Some 80,000 new properties were created in the county between 1968 and 1975, at a time when the population of the entire island was less than 80,000 (Houghton et al., 2021). With an estimated population of 35,248 in 2017, according to Landscan statistics (Rose et al. 2018), the Puna District had the greatest population growth rate on Hawai'i Island until 2018 (County of Hawai'i 2008).

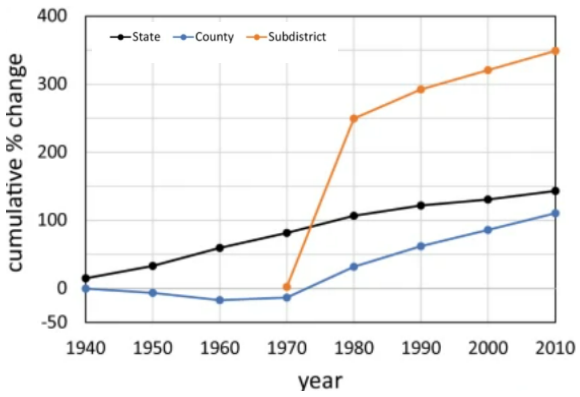

Fig. 2. *Census data from the State and County of Hawaii, and the Pāhoa-Kalapana Division are represented in the graph. Between 1970 and 1980, a sharp increase in population was unequaled by growth rates in the rest of the county or the state (Houghton et al., 2021).*

According to Cooper and Daws (1985), the low cost of land due to the danger of natural hazards in the development attracted developers even if the lots were economically worthless. Many of the Big Island's prominent citizens during the 1960s and 1970s had connections to developers, which created pervasive and complicated issues (Cooper and Daws 1985).

Effects of eruptions in the Lower East Rift Zone and Puʻu ʻōʻō

A long-lasting eruption from the middle of the ERZ began in January 1983. After the 1983 eruption's initiation, the volcanic cone known as Puʻuʻōʻō grew till 1986. Puʻuʻōʻō is

situated nineteen kilometers east of Kīlauea's summit caldera. After becoming centralized at a single vent, Pu‘u‘ō‘ō lavas continued their path toward the ocean and impacted the coastal community of Kapa‘ahu. Then, in its most destructive act, lava buried the town of Kalapana in 1990-1992. During 1992-2007 the activity returned to Pu‘u‘ō‘ō and experienced many collapses that extended the crater. After a 12-day pause, lava returned during 2007-2011. Pu‘u‘ō‘ō's last eruptive phase (2011- 2018) before the 2018 collapse kept the residents of Pāhoa on edge as lava threatened to cut off Highway 130 in 2014. This flow did inundate some residential properties but ultimately stopped before a major disaster and destruction of the highway. Pu‘u‘ō‘ō's last collapse was due to the summit magma reservoir being drained during the LERZ eruption.

History of previous land-exchange deals after eruptions

Due to the number of volcanic eruptions in the LERZ over the years, there have been several instances of land buy-out deals and exchanges. One significant event was the eruption of the Kīlauea volcano in 1955, which destroyed several homes. The State of Hawaii subsequently bought out the land from affected homeowners and established the Kalapana State Recreation Area. In 1983, a new eruption in the LERZ caused significant damage to homes and infrastructure. The State of Hawaii again implemented a land buy-out program, which acquired more than 100 properties from affected residents. In 1990, the State of Hawaii established the LERZ Geothermal Resource Area, which allowed for the development of geothermal power plants (Cooper and Daws, 1990). They then acquired additional land through voluntary land exchanges with landowners as part of this program. Overall, the history of land

buy-out deals and exchanges in the LERZ of Hawaii reflects the unique geological challenges and risks associated with living in an area prone to volcanic activity. The risks associated with disasters can manifest as sociopolitical inequities and challenges, particularly in areas that are particularly susceptible to such events.

2018 ERUPTION

Summary and consequences of the 2018 LERZ eruption

This event is noteworthy because it was the biggest eruption and summit collapse in the LERZ in 200 years (Neal et al., 2018). It was also the most destructive eruption in Hawaiʻi during that time. The crisis began in May 2018, when the East Rift Zone of Kīlauea saw hundreds of small earthquakes, prompting authorities to issue evacuation orders for certain parts of the Puna District. On May 2, 2018, the US Geological Survey (USGS) published a report stating that ground deformation caused by magma entering beneath the Leilani Estates development had led to fractures on the roads inside and outside the neighborhood. The first phase of the 2018 eruption from weeks 1–2 saw small-volume lava flows from relatively short-lived fissures. From weeks 2–3, the fissure farthest down the rift produced fountains, explosive bursts, and relatively viscous flows. The second eruption phase from weeks 3–4 saw higher temperatures, more fluid lava, and a higher effusion rate (Gansecki et al. 2019). The increased effusion rate resulted in a channelized lava flow system that advanced southeastward, cut across Highway 137, and reached the ocean on May 19th. The third and most voluminous phase lasted until approximately August 4, the last time magma was seen in one of the 2018 vents. The 2018 eruption lasted for over three months. During that time, the flow covered 35.5 square

kilometers of land, producing an estimated volume of 1.4 cubic kilometers. Almost 700 structures were completely consumed or inundated (612 being homes), and 48 kilometers of the road were covered in lava, forcing residents to flee. Lava flows also made other unburied properties inaccessible in the LERZ (Fig. 3). A total of 24 fissures opened up; Fissure 8, which formed a cone called Ahu‘ailā‘au, produced the most lava, with 92–96% of the total volume (Gansecki et al. 2019).

Despite the destruction the lava flows caused, they created about 30 square kilometers of new land on the South East Coast of the Big Island. Volcanic air pollution (vog) produced around 200,000 metric tons of SO2 daily, during the peak of the eruption; This vog was experienced throughout the Hawaiian Islands and as far away as Guam. These emission rates constituted 10 megatonnes of SO2 between May and early August 2018 and are the highest ever recorded on Kīlauea (Kīlauea, 2021).

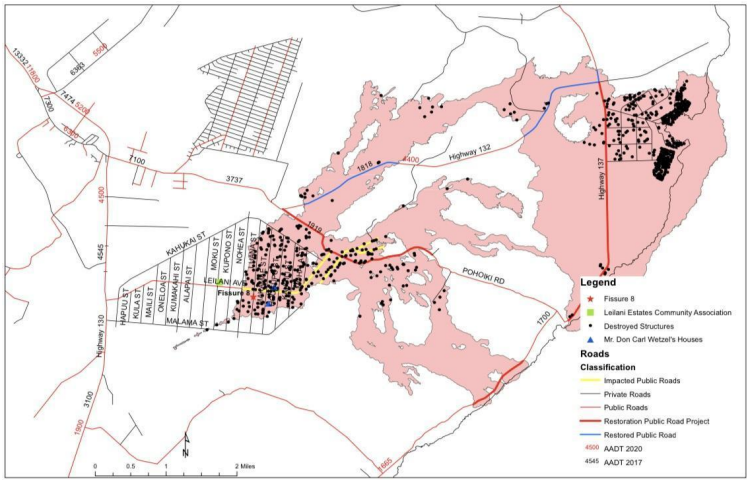

Fig. 3. *Map created to display the level of destruction of houses and public roads impacted (National Disaster Preparedness and Training Center, 2022).*

The land Buy-Out Deal

In response to the 2018 eruption, the County of Hawaiʻi launched a Housing Recovery Survey in February 2021. This survey was to help guide recovery projects that preceded the Voluntary Housing Buy-out Program. 1,275 residents were mailed the survey; 815 responded. 55% of displaced residents still lived on the island, 238 of those in Puna. 706 houses were inundated; 29 were isolated, and 30 suffered thermal damage. 593 homes were owner-occupied at the time of the eruption, while 85 were rentals. 625 respondents indicated that they were considering pursuing a grant from the buy-out deal; however, 192 wanted only to regain access, 47 wanted to retain their land, and 213 were still uncertain. Within the County of Hawaiʻi survey, the participants were asked what the homeowner's primary motivations were in their decision to accept or reject the buy-out deal when offered. As indicated in Fig. 4, these were, in order of importance, road access, electricity, feasible agriculture, residential water, financial reasons, agricultural water, and safety. If accepted landowners will not be allowed to use these grants for infrastructure construction in hazard zones 1 and 2. According to the County of Hawai'i Kīlauea Disaster Recovery Team, The Community Development Block Grant Disaster Recovery (CDBG-DR) Voluntary Housing buy-out Program was designed to assist those impacted by the 2018 Kīlauea eruption using approximately $107 million in federal Department of Housing and Urban Development funds. The purpose of this program is for the County to acquire affected properties to keep them from being impacted again by future eruptions and maintain the sites as open spaces. The program's purpose is to “help as many eligible property owners as possible, with a particular focus on those in the low- to moderate-Income range, as

mandated by the HUD, who were impacted by the 2018 eruption" (Hawai'i County, HI Recovery Site, 2021).

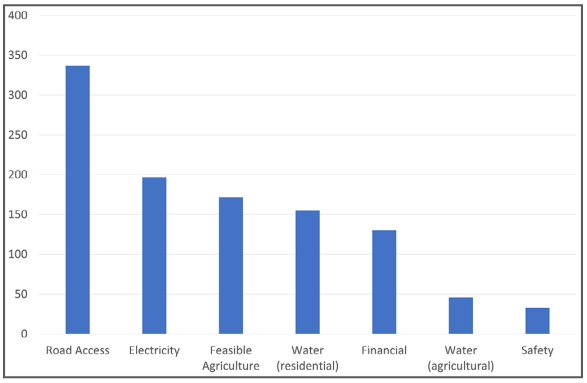

Fig. 4. *Graph indicating homeowner's main motivations for their decision to accept or reject the buy-out deal (CDBG-DR Voluntary Housing buy-out Program, 2021).*

In April 2021, the buy-out offer was officially launched using $107 million in federal funding to acquire affected properties. This buy-out deal acquires residential properties up to a price of $230,000 (County of Hawai'i 2020 a, b). The buy-out deal had three phases of applications; Phase 1 (April 30 -July 30, 2021) for homes that were primary residences. Phase 2 (November 1, 2021-January 31, 2022) for secondary residences and long-term rentals, and Phase 3 (July 18-October 31, 2022) extended to undeveloped properties (predominantly agricultural land). As of March 10, 2023, the program is still focused on closing applications for low- to moderate-income people who lost their primary home in the eruption. After that, the recovery team stated that they aim to close the remaining primary home applications by the middle of 2024. They will then move on to secondary homes/long-term rentals, and finally undeveloped properties with any remaining funds'' (Fig. 5) (Hawai'i County, HI Recovery Site).

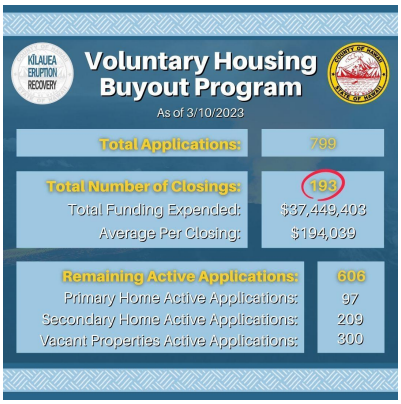

Fig. 5. *Image summarizing application progress as of March 10th, 2023 (Hawai'i County, HI Recovery Site 2023).*

Communities and land are altered for generations in large lava-producing eruptions. Will this encourage people to move to land outside of these zones? Today, landowners have made the difficult choice between the buy-out program and re-developing their existing properties with the certain but low risk of exposure in future LERZ eruptions.

DAMAGE TO KEY UTILITIES AND INFRASTRUCTURE DURING THE ERUPTION

Once evacuation orders were lifted, people immediately wanted to check how their property fared. However, access and a resumption of normal life was difficult, even if residents' property survived. During the 2018 Kīlauea eruption, lava buried and/or cut off roads and essential utilities. Meaning those that still had a home were left without critical infrastructure.

Prior to the eruption, critical infrastructure was already constrained in terms of quality and capacity. The main transportation for people living in Puna is via a combination of state highways and county roadways (Kīlauea Eruption Recovery Team, 2020a). Most of the local roads within the subdivisions in Puna District are privately owned and not intended for through

traffic. There are few water and wastewater facilities in the area and residents must use hospitals outside of Puna. The Puna Geothermal Venture (PGV), which produces electricity from geothermal steam on the LERZ, is a major source of employment and electrical power. County water had provided service to the Lanipuna Gardens development, and public wells supplied water to farms and homes in the Vacationland and Kapoho Beach lots subdivisions through private distribution. In the short term, the lava flow's persistently high temperatures made rebuilding water lines impossible. The eruption altered the terrain in the region in a way that made it difficult to restore these water supplies and also compromised water quality at private wells near the ocean. Lava damaged the water lines and road infrastructure leading to several key recreational resources, including Isaac Hale Beach Park, leaving the community without access and public amenities. As lava covered Ahalanui Park, all of the infrastructure that provided services to the park were destroyed. Once Pohoiki Bay had filled in with debris eroded by wave action from the front of the lava flow, the Pohoiki boat ramp became landlocked and rendered useless (Sea Engineering Services, 2019). PGV's connection to Hawai'i Electric Power Company was lost because of the eruption.

According to the Kīlauea Disaster Recovery Team at the Puna infrastructure development meeting, some of the recovery priorities voiced by members of the community in Lower Puna included: “Can’t live here if you can’t get here.” – “Establish emergency access” – “Public transportation is an absolute must, especially of a kind that is affordable and reliable.” - “Connectivity is our #1 issue.” – “Better cell phone service and internet hotspots are needed for safety, business, and convenience” (County of Hawai‘i Recovery Team, 2019). Developing safe, accessible, and affordable systems are paramount. In spite of the fact that parts of the critical

infrastructure in Lower Puna have been restored, some work may not reach completion until at least 2026. To what extent did this timing of repairs to critical infrastructure affect the daily lives and long-term planning of the residents in Lower Puna?

The impact of the 2018 Kīlauea eruption on Lower Puna's critical infrastructure highlights the challenges emergency managers and policy planners face. The eruption destroyed or damaged key infrastructure, leaving the community without access and amenities. At the same time, the recovery priorities voiced by the community in Lower Puna underscore not only the urgent emergency needs but longer term enchantment of their communities. Addressing these challenges is essential for emergency managers and policy planners to rebuild Lower Puna's critical infrastructure and restore the community's access to essential services. The timing of repairs to critical infrastructure will also have a significant impact on the daily lives and long-term planning of the residents in Lower Puna. Therefore, policymakers and emergency managers must prioritize and consider all angles of the short-term and long-term restoration and enhancement of critical infrastructure to minimize the negative impact on the affected community.

Nature and Timing of Road Damage

**Most roads in Lower Puna are private roads and are therefore not considered in detail in this paper, only publicly-owned roads.*

Road access was the principal consideration for homeowners considering returning to their property, according to the County of Hawai'i Kīlauea Disaster Recovery Team’s Housing Recovery Survey administered in February 2021. Most of Lower Puna is linked to the rest of the

island by Highway 130. However, use was restricted due to the damage to the road surface during the eruption. After the eruption ended, a total of 52 kilometers (km) of roads were damaged - 20 km of County and 32 km of private roads (County of Hawai'i. 2020b). In other places, roads were rendered unusable due to cracking and fracturing accompanying the eruption (Fig. 6).

Fig. 6. *HVO geologists examined widening cracks on Nohea Street in Leilani Estates at Kīlauea's LERZ on May 17th, 2018 (Global Volcanism Program, 2018).*

Date (2018)	**Location**	**Description**
May 3rd	Roads adjacent to Leilani Estates	Small cracks start to appear.
May 7th	Highway 130	Damage to the highways started to appear when ground cracking was observed across Highway 130 due to a dike movement beneath the highway.

May 8th	Highway 130 --- Pohoiki Road	Highway 130 is closed between Malama Street and Kamaili Road. --- Pohoiki Road is closed.
May 16th	Highway 130 --- Highway 137	Highway 130 was bridged over and reopened. --- Plans to pave over cracks in Highway 137 or Beach Road were scheduled to commence.
May 17th	Nohea Street (Fig. 6)	Widening cracks on Nohea Street in Leilani Estates.
May 18th	Pohoiki Road	A lava flow from fissure 20 blocked Pohoiki Road.
May 19th	Highway 137	Paving over cracks on Highway 137 was completed.

It was not until the second phase (May 17th-27th) of the eruption that the first major highway was cut. A system of channelized flows crossed Highway 137 and reached the coast on May 19th.

Date (2018)	**Location**	**Description**
May 27th	Leilani Avenue and Luana Street	A sizable perched lava pond breached, creating a lava flow.

May 28th	Pohoiki Road --- Highway 132	A lava flow crossed and blocked Pohoiki Road. --- Authorities shut down Highway 132. (Beach Road is the only access to Lower Puna).
May 29th	Section of Hawai'i Route 132, linking Pāhoa and Kapoho	Lava blocked the access road to the PGV and forced the closure of Route 132 from the west and the east.
May 30th	Highway 132	Lava flows from Leilani Estates along Highway 132.
June 2nd	Intersection of Highway 132 and 137	Lava flow blocks both highways

Between May 28th - August 4th, the channelized lava flow from Fissure 8 crossed Highway 132 and flooded the Kapoho Farm Lots. The Wai'ōpae Tidepools were submerged on June 3rd when the flow reached the ocean at Kapoho Bay (Meredith et al., 2022).

**Data on road timeline was collected from Meredith et al., 2022, County of Hawaiʻi News, Global Volcanism Program, 2018, Hawaiian Volcano Observatory, Gomes, 2018, and Hawaii.gov, 2021.*

Road repairs

Roadways can only be rebuilt once the lava interior has sufficiently cooled. For instance, Highway 132 was reopened by re-surfacing 7 meters of lava about 15 months after the eruption

ceased (County of Hawai`i 2019; US Geological Survey 2020b). Road cracks are also an issue; cracks can still be observed across property parcels and roads in Leilani Estates and across Highway 130 (Meredith et al., 2022). In Leilani Estates, Leilani Avenue is the only county roadway; all side roads are private. The damage to private roads meant the subdivision had to outsource contracts for most of the repairs (Harlow and Hiraishi, 2018).

In a public notice, FEMA's Infrastructure Restoration Project offered funding for two projects to repair roads (and install water lines) along Pohoiki Road, Leilani Road, Highway 137, and Kumukahi Lighthouse Road. "The proposed action would repair damage from the 2018 Kīlauea volcano eruption in the Puna district's southeastern portion of the island to bring the roads back to their pre-disaster function" (FEMA, 2021). According to a cost agreement between the County and FEMA that was made public in March 2020, the damage to public roadways brought on by the eruption (excluding Highway 132) was assessed to be worth $82 million. 75%, or about $61.5 million, will be covered by the federal government. The County's 25% local match, which comes to about $20.5 million, will be paid for by funds awarded by the State's Legislature. FEMA issues funding on a repayment basis (FEMA, 2021). It is spearheaded by the Department of Public Works; among the institutions involved are the Recovery Team, Puna Community Development Plan Action Committee, Puna Connectivity Working Group, and community partners.

Further analysis of the repairs includes the County's plans to take action to restore public road access via the following projects:

-Restore Pohoiki Road with improvements for safe two-way traffic through a new alignment intersecting Highway 137.

-Restore Highway 137 to Vacationland and near ʻOpihikao, where temporary measures were completed.

-Restore Lighthouse Road along with an integrated management plan for Kumukahi.

-Restore a section of Leilani Avenue to allow access to isolated properties in the kīpuka near Pohoiki Road.

The progress so far is that Highways 132 and 137 (to Beach Road) have been repaired and re-opened.

During a press release in March 2022, The County of Hawai'i Planning Department provided updates on Infrastructure Restoration along Pohoiki Road; this project is to be followed by the completion of an environmental assessment. However, several delays have occurred. As of March 19th, 2023, the environmental assessment document is undergoing final changes after being reviewed by FEMA's legal team. FEMA is working on finishing the procedure and providing the final environmental assessment for the public's appraisal and input. Over the next six weeks, the County will work closely with FEMA to finalize the document. Once the draft is completed and released by FEMA, a 30-day comment period will likely occur in May 2023. These road and water line developments are aimed to be completed by four synchronized projects, with construction set to start in the fourth quarter of 2023. Public Works Director Ikaika Rodenhurst stated that the Department of Public Works and Water Supply would finish the engineering documents; the completion time is based on estimates. The estimates revolve

around available equipment, staffing, and materials (Fig. 7) (Kīlauea Eruption Recovery Team, 2022).

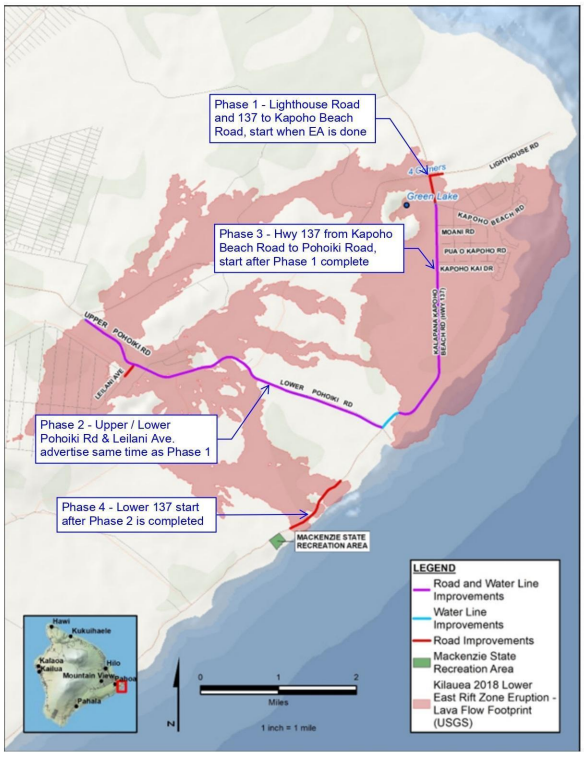

Fig. 7. *Map indicating the phases of repair to the roads and water lines (Kīlauea Eruption Recovery Team, 2022).*

<u>The projected future timelines for the projects in Fig. 7 are as follows:</u>

1) Combined Road and Water Line Projects along Pohoiki Road and Highway 137:

a. Lava-Inundated Upper Pohoiki Road

• Construction start: Quarter 4, 2023

• Construction completion: Quarter 3, 2024

b. Lower Pohoiki Road to Highway 137

• Construction start: Quarter 3, 2024

• Construction completion: Quarter 2, 2025

c. Highway 137 from Pohoiki Road to Kapoho Beach Road

• Construction start: Quarter 2, 2025

• Construction completion: Quarter 4, 2025

2) Highway 137 from Four Corners to Kapoho Beach Road

• Construction start: Quarter 4, 2023

• Construction completion: Quarter 2, 2024

3) Highway 137 from Mackenzie to Pohoiki Road

• Construction start: Quarter 4, 2023

• Construction completion: Quarter 2, 2024

4) Lighthouse Road

• Construction start: Quarter 4, 2023

• Construction completion: Quarter 2, 2024

Nature and Timing of Damage to Water Supplies

Water supply was the fourth-ranked concern for homeowners considering returning to their property, according to the recovery survey in February 2021. After the eruption ended, “23 km of water lines were destroyed, one water well inundated, two reservoirs isolated, and private catchment systems destroyed or damaged” (County of Hawai‘i, 2019).

According to the County Department of Water Supply (DWS), Fissure 6 damaged a major water main beneath Pohoiki Road. This cut off the water supply to numerous homeowners east of the subdivision. The water main's exact fate is unknown; under other circumstances, the department would dig to identify the issue, but for obvious reasons, it was not feasible to do so. Even though many locals in the area use water catchment systems rather than municipal water, the service interruption impacted 250 consumers (Brestovansy, 2018).

Date (2018)	**Location**	**Description**
May 5th	All residences in the Kapoho area and all areas east of Leilani Estates.	DWS declared emergency water status for Leilani Estates due to lava damage on water lines. Kapoho area faces water shortage, but spigots and tankers deployed.
May 12th	Leilani Estates and its surrounding northeastern areas	Due to emergency water restriction. Residents were advised to limit their water use to preserve the water still in the main pipeline.
May 14th	Vacationland neighborhood and Nanawale Estates	Temporary pipe bypasses to provide water flow to impacted areas.
May 22nd	Pohoiki road	Bypass covered by lava. Plans to retrofit unused tank near Green Lake that has been inactive for 20+ yrs.

May 27th	Customers along Highway 132	Notice that customers along Highway 132 may have their water service interrupted.

**Data on the water timeline was collected from the County of Hawai'i, 2020b. Department of Water Supply, County of Hawai‘i News, Global Volcanism Program, 2018, and Hawaii.gov, 2021.*

Water repairs

In addition to the County of Hawai’i Planning Department updates on infrastructure restoration along Pohoiki Road, mentioned in the FEMA’s Infrastructure Restoration Project (Fig. 7), the repairs DWS wants to implement are to provide access to safe drinking water throughout the county’s 23 separate water systems and invest in infrastructure that creates long-term resilience. The Puna District's reservoirs and water delivery systems that were disrupted by the lava flows from the 2018 eruption are scheduled to be repaired starting in the fourth quarter of 2023. The DWS acquired a $30 million obligation for payment from FEMA based on agreed-upon cost predictions for the rehabilitation of damaged infrastructure. The County will match the federal funds with a local contribution of $10 million. Funding will be used to restore two reservoirs and 23 km of damaged water lines (Kīlauea Eruption Recovery Team, 2022).

Nature and Timing of Damage to Electricity Supply

During the 2018 eruption, it was common for some parts of neighborhoods to lose power while others did not. Unlike the Pāhoa lava flow in 2014, where there were attempts to safeguard utility poles, no measures were taken during the LERZ lava flows (Fig. 8). A major reason was the rapid advance of the 2018 flows, quite unlike the slow-moving 2014 lava. Some

structures that were not directly consumed by lava still lost their functionality or became unusable (Meredith et al., 2022). At the end of the eruption, 900 utility poles were destroyed, two geothermal wells were inundated, one was isolated, and one electrical substation was isolated (The Associated Press, 2021).

Fig. 8. *Lava destroying telephone pole during the 2018 eruption (Gebers, 2018).*

Date (2018)	**Location**	**Description**
May 5th	Leilani Estates	“Utility equipment has been damaged by lava in the Leilani Estates subdivision” (Corrigan, 2018).
May 9th	Whole area	Despite the Puna Geothermal Venture plant shutdown, HELCO claimed it still had the adequate capacity to meet the island's needs. Spectrum installed free Wi-Fi access at various locations.
May 16th	Whole area	HELCO announced that power disturbances might start to happen.

May 19th	Whole area, especially Leilani Estates	HELCO creates backup plans and options in case Lower Puna might be cut off by lava flows. Vital infrastructure, such as mobile phone towers, will be powered using both conventional power systems, including diesel and portable solar-battery generators.
May 27th	Lower Puna	HELCO told its customers, especially in Kapoho, they may experience extended power interruptions.
May 27th	Whole area	HECO said power interruptions likely in the lower East Rift Zone. Power will be rerouted to Leilani Estates and Lower Puna.

**Data on the electricity timeline was collected from the Corrigan, 2018, County of Hawai‘i News, Hawaii.gov, 2021, Big Island Video, HELCO, and HECO website.*

HELCO eventually disconnected power from the areas at risk of lava flow impact (Meredith et al., 2022) and continued monitoring the encroachment of the lava. According to the Hawai'i County Civil Defense, cell phone and landline coverage was reportedly extremely poor in the Kapoho region (Peterkin, 2018). HELCO reported that the lava had damaged and destroyed electric poles and impacted utility equipment, completely turning off electricity in numerous places.

Electricity repairs

Even though two of the PGV wells were blocked by lava, the island's power supply continued to operate normally since alternate energy sources were employed until the power plant reopened (Meredith et al., 2022). After a damage assessment was completed and the region had been declared safe to access. Power was restored to the remote households that had been cut off by the loss of utility poles. Around September 14, 2018, HELCO employees began working in Leilani Estates to remove damaged electrical poles and equipment as well as to repair and replace any equipment that the eruption and seismic activity had harmed (Hawai'i 24/7, 2018). Beyond replacing damaged poles, the electric recovery project seeks to improve the electricity supply in Puna, including broadband capability. The priority was internet connectivity, supporting economic redevelopment, and improving access to quality health services.

Internet connection is essential for education and will open up new commercial options, especially for home-based firms. However, numerous service gaps still exist on the island. In some places, it is not economically feasible for providers to build broadband facilities due to the lack of population. The desired outcomes for this project are increased access to information, education, and training possibilities. Economic revival in Puna for new industries and local entrepreneurship requires reliable internet and phone service for communities. A close working relationship with private communications providers will be necessary for implementation.

Nature and timing of damage to Geothermal Power Plant

Puna Geothermal Venture (PGV) is owned and operated by a subsidiary of Ormat Technologies, Inc. The PGV plant generates electricity by harnessing the earth's natural heat through geothermal wells, which tap into underground steam and hot water. The steam is used to power turbines, which generate electricity that is then sent to the grid to power homes and businesses. The PGV plant has a capacity of 38 megawatts and provides clean, renewable energy to HELCO, which serves customers on the Big Island. The plant also provides a source of baseload power, meaning it can generate electricity consistently around the clock, unlike other renewable energy sources like solar and wind. In addition to generating electricity, the PGV plant also produces byproducts, such as hot water and steam, which can be used for industrial and agricultural purposes (Hawai'ian Electric, 2023). The complex as a whole was not destroyed but located within a Kīpuka or isolated patch (Fig. 9). However, the substation and a nearby warehouse that housed a drilling rig were set on fire by the lava flow. At the start of the eruption, PGV had serious considerations before the lava flow arrived at their doorsteps. For instance, the plant needed to move 60,000 gallons of volatile pentane gas but could not do so until the required containers were delivered from California.

Fig. 9. *View of the PGV within a Kīpuka, with Leilani Estates in the background. The main lava river channel and Fissure 8 are both to the right of the PGV. The channel was crusted over, and lava was still flowing beneath it at the time of this photograph since it had stopped flowing on August 9th (Roc Doc Travel, 2018).*

Date (2018)	**Location**	**Description**
May 5th	PGV	PGV was closed until further notice amid the ongoing unrest.
May 8th	PGV	Puna Geothermal plans to move 60,000 gallons of pentane off its property.
May 9th	PGV	Officials started to examine and evaluate the current PGV Emergency Response Plan and create a unique mission to reduce probable lava consequences. Plans for securing and evacuating local populations will be prepared in case lava intrusions result in the discharge of high concentrations of sulfur dioxide or hydrogen sulfide. No activity was reported by PGV, and the site was secured. Nevertheless, flammable materials were starting to be removed offsite.
May 10th	PGV	Governor Ige declared emergency powers over PGV to form a team to address the removal of flammable pentane from the property.
May 11th	PGV	PGV finished removing its 60,000 gallons of pentane, reducing concerns. The PGV deep wells were packed with hydrogen sulfide

		and other gasses were a concern. Plans call for equipment that would have to be sent from California to fill the wells with water to prevent a blowout.
May 15th	PGV	Plans to quench the geothermal wells with cold water and install iron caps to confine fluid in the wells.
May 18th	PGV	Governor Ige stated that work has begun to pump water into wells and prepare iron well caps. PGV received $7.2 million from insurance for a drilling rig destroyed by the lava. Lava covered three of six PGV energy production wells. The lava also burned a substation and adjacent warehouse that housed the drilling rig.
May 21st	PGV	Lava destroyed a warehouse near the geothermal site; the company said, “worries over lava encroachment are overblown". PGV indicates that lava flow on the Lower East Rift Zone dwarfs any emissions that could result from a breach of the geothermal wells. USGS had stationed crews at PGV to monitor the flow of lava near the property.
May 27th	PGV	Hawai'i County reported at 1:00 p.m. that Lava flows that overran part of the PGV ceased overnight after covering two wells earlier in the evening.

**Data on the electricity timeline was collected from the County of Hawai‘i News, Hawaii.gov, 2021, and Big Island Video News. a2018, c2019.*

Geothermal power plant repairs

Without PGV in service, the island's renewable percentage had fallen to 35% in 2019, a 25% decrease from before the shutdown. After the eruption ended, PGV opened a gravel access route that also allowed access to their site on April 1, 2019. Before the road was rebuilt, PGV and landowner properties in the Highway 132 kīpuka were accessed by hiking over the lava flow or helicopter (Big Island Video News 2019c). In September 2019, during a public hearing, PGV stated that after cleaning one of its production wells, it was debated whether to drill a new well or possibly work on cleaning a second well. The plan of operation approved in 2006 permits PGV to construct as many as 28 wells. There are currently 11 wells on site. The State Department of Land and Natural Resources authorized applications for two new geothermal wells in August 2019. However, PGV officials stated at the time that they were still being considered and had no concrete plans. As announced during the meeting, PGV and HELCO have been re-connected. "We have integrated HELCO electricity into our main switch gear, which is good to get off generators. We do have one of our main water pumps working off HELCO power" (Salmons, 2019).

In December 2019, the rebuilding of the substation capacity to produce power and deliver it to the grid run by HELCO was still necessary before the company could resume operations, according to the senior director of the company. A power purchase deal between the companies was negotiated for most of 2019. The company sought permission for the

foundation work for a new electrical substation (Hawai'i Public Radio, 2019). In early 2020 testing of the electricity grid began to take place over several weeks while production progressively continued to rise. In November 2020, PGV was back online (Simek, Kelly, 2022). New transmission lines now link the PGV facility to the grid. The cost of the repairs were covered by Ormat Technologies, Inc., the owner of PGV, and its insurers (Fig. 10).

Fig. 10. *Aerial view showing PGV reestablished with the 2018 lava flow pictured in the background (Big Island Video News, 2020b).*

DISCUSSION

Will the rate and timing of infrastructure recovery influence buyout decisions?

The 2018 eruption as a whole was an unprecedented event that severely affected critical infrastructure. Whether it was road access, public water supply, electricity failure, or the loss of power from the Puna Geothermal Venture, Puna suffered from a combined loss of utilities. The extensive network of roadways linking bridges, utilities, and buildings required to maintain everyday life are considered key components of critical infrastructure. These essential systems are necessary for energy, clean water, transportation, and business. As such, they influence the economic lifeblood and the activities or sectors that can grow inside a community and are

essential for ensuring the economy operates well (U.S. Department of Homeland Security, 2023). In short, for the effective functioning of Lower Puna, there needs to be road access, water supply, and electrical continuity. This means establishing safe, accessible, and affordable systems is paramount (Kīlauea Eruption Recovery Team, 2022). Parts of the critical infrastructure in Lower Puna have been restored; however, some work may not reach completion until at least 2026. To what extent did the timing of repairs to the critical infrastructure influence the homeowner's acceptance or rejection of the buy-out deal?

Following the eruption, construction was completely suspended in hazard zones 1 and 2; although people continued to buy existing homes regardless of the relative unavailability of insurance. In Leilani Estates, there have been five home sales in the last three months. Due to the COVID-19 pandemic, there was also an increase in mainland employees from outside of Hawai'i falling in love with the relatively isolated lifestyle and buying property (Nakaso, 2022). The rise of new residents is in direct contrast to the buy-out deal's efforts to discourage population growth in Lower Puna. Is the recovery and enhancement of critical infrastructure contributing to population growth? The Recovery Teams' plan is both complex and promising, but its ultimate success remains uncertain. Without having solitary, holistic information on the timeline of the damages and the recovery efforts that have taken place and will take place, it is difficult to measure the overall resiliency in Lower Puna.

Examples from Hawai'i and worldwide

A useful comparison to the destruction and partial recovery is the town of Kalapana after the 1990-1992 lava flows. These lava flows mostly buried Kalapana; however, in spite of

the desolation, the draw of a barren landscape continues to entice eager individuals to consider building simple structures on the fresh flow (Fig. 11). Some people were drawn to such a landscape either for the cheap land price, a spiritual attachment to the land, a desire to live in a dynamic and evolving landscape, or a wish to be off the grid physically and emotionally. In total, 75 simple structure homes were erected in Kalapana while the Lower Puna eruption raged in 2018 (Gomes, 2018b). This proves that despite the harsh elements, people will continue to live and rebuild in areas prone to situations ripe for disaster. The new lots for sale in the new Kalapana Gardens community ranged between $1,000 to $20,000, some of the cheapest real estate in Hawai'i. Despite the draw for new residents in Kalapana, their houses have no running water or electricity. The largest outside resource available in this area is the 3.5 km Kalapana side portion of a dirt road used as an emergency escape route constructed by the County of Hawai'i, overseen by the National Park Service and Federal Highways Administration (Ferracane, 2014). On account of the extensive destruction in this vicinity, it stands to reason why few recovery efforts were made in the area.

Fig. 11. *The old Kalapana Gardens, which was buried under 40 to 60 feet of lava in 1990, is being replaced directly above by the rebuilt Kalapana Gardens. (Koning, 2018).*

Volcanic eruptions have a long history of devastating local communities, and Hawai'i is not the only place that has experienced the catastrophic impact of these events. Other

examples can be seen around the world, including the 2021 La Palma eruption in the Canary Islands, the frequent eruptions of Mt. Etna in Italy, the 2010 eruption of Merapi in Indonesia, and the infamous eruption of Mt. Vesuvius in Italy that destroyed the ancient city of Pompeii in AD 79. These are many eruptions that have not only caused widespread destruction and loss of life but have also highlighted the importance of disaster preparedness and response. Emergency managers and policy planners in these areas must constantly reassess their strategies and plans to ensure that they are able to respond effectively to these events. It is critical that they take into account the unique challenges presented by volcanic eruptions, such as the unpredictability of the eruptions and the potential for secondary hazards.

Other factors influencing recovery and decisions concerning the property buyout

It is important to examine qualitative social, cultural, and economic factors as decisions that reflect a complex physical, social, and behavioral balance. These include:

- *The condition of the land and infrastructure after the eruption.* Properties suffered varying levels of impact in the eruption, so will this influence decisions to take or reject the buy-out deal?
- *Financial resources (options/choices limited by available funds).* During the eruption, people with heavy financial commitments may have no alternatives to accepting a buy-out.
- *Length of ownership of land.* Will the individuals/families with the land passed down to them be reluctant to lose control of their property, knowing they may never get it back? Will people who have recently (0-5 years) bought the land be more willing to relocate?

- *Spiritual attachment to the land.* People who are deeply connected to the land may not see the buy-out offer as worth the loss of a place central to their identity and culture.
- *Sense of community.* A solid community connection affects the perception of resiliency. Loss of community could thus be a significant factor. The eruption could have heightened or weakened bonds.
- *Desire to live in a dynamic, evolving landscape.* Life in a changing environment of a lava flow field compensates for the risk of future eruptions for some residents. Thus, they have a desire to rebuild.
- *Wish to be off-the-grid physically and emotionally*. Whether it is for sustainability, a sense of freedom, or a general dislike of society, individuals may choose to live independently.

The decision to accept or reject a buy-out offer in the aftermath of a volcanic eruption is not a simple matter such as financial gain or loss. Instead, it is influenced by a range of social, cultural, economic, and other personal factors. Examining and understanding these factors is crucial in making decisions that balance physical, social, and behavioral considerations, ultimately leading to the best outcomes for affected individuals and communities.

Long term planning beyond recovery

Despite the lack of resolution, the recovery team has a long-term plan for the future. One project that encompasses all such resiliency efforts in Lower Puna, and extends beyond re-building, is Project 360, which targets the area's resiliency. Project 360 is another recovery-triggered initiative to encourage resiliency by strengthening the County Citizen Corps

Council and Civil Defense Agency. The recovery priorities include increasing the community and the county's capacity to prepare and its ability to respond and recover from hazard events. An in-depth description of this project states, “resiliency starts in our homes and communities. Project 360 starts at the family (or ohana) level and moves out through the community, volunteer organizations, and Civil Defense to enhance our family, community, and communications networks to create a prepared, self-reliant, and connected island population” (Kīlauea Eruption Recovery Team, 2020a). The desired outcomes of this project include increasing the number of communities on the Island of Hawai‘i that have emergency response teams, Community Emergency Plans, participants in the ‘Ohana Emergency Plan and the Civil Defense alert system, and broadening Community-based Emergency Communications Capacity and Capability. Possible funding sources include FEMA/Homeland Security, Hawai’i Island Emergency Management, and the County of Hawai’i. This will be an ongoing project with Civil Defenses as the lead, with Hawai‘i County Citizen Corps Council (Community Emergency Response Teams, Neighborhood Watch, Voluntary Organizations Active in Disasters, Medical Reserve Corps) as partners (Kīlauea Eruption Recovery Team, a2020).

This Recovery and Resilience Plan serves as a strategic plan to address recovery from the 2018 Kīlauea eruption from a comprehensive perspective and provides direction on fostering resilience in the Puna communities that were impacted by the eruption. Many of the projects and community-based recovery actions can proceed with available funding and full participation among partners. Recovery efforts specific to the economy and infrastructure often require specific studies or feasibility assessments to build consensus on goals and objectives, identify or

define actions, design a project, and secure funding for implementation. The implementation of long-term recovery and building resilience also require mechanisms such as the development of codes, regulations, design standards, programs, and policies or procedures to move from planning to action. These mechanisms can also help to institutionalize the lessons learned and successes of long term recovery, which in turn build resilience within the County and community to be better prepared for natural disasters in the future. This Recovery and Resilience Plan does not describe the entire universe of recovery and resilience projects and actions; but rather invites all sectors of the community to act collaboratively to advance recovery, readiness, and resilience strategies included here. The Recovery Team will be responsible for coordinating the implementation of the Recovery and Resilience Plan. The Recovery Team will work closely with county, state, and federal partners, and the community to implement recovery projects that are feasible and consistent with the Recovery Plan, General Plan, and other local and County efforts. The Recovery Team will also work with the sector-based Recovery Working Groups to foster collaboration and build partnerships in support of project implementation.

Recovery and resilience relate to emergency managers, policy planners, and residents as a whole. Emergency managers and their influence extend beyond the immediate aftermath of an event, and as such, must consider recovery efforts in their broader emergency management strategies to ensure the safety and well-being of affected communities. While the response phase is focused on immediate safety concerns, such as evacuation and search and rescue operations, the recovery phase prioritizes long-term needs, such as addressing physical damages, economic losses, and emotional trauma. The insights gained from recovery efforts can

help inform future strategies, particularly with regard to safety and evacuation. For example, recovery efforts may reveal areas of vulnerability that require mitigation measures, such as barriers that hinder evacuation routes in Lower Puna. Furthermore, recovery efforts can highlight inequity gaps and inform improvements for future events. Therefore, recovery efforts play a crucial role in shaping emergency management strategies and ensuring the safety and well-being of affected communities.

The recovery phase involves rebuilding and restoring the affected community to its pre-disaster state or better. This requires a coordinated effort by all stakeholders, including federal, state, and local governments, private insurance companies, and individual property owners. Recovery efforts can inform the location, priorities, and investment of public and private assets, as well as highlight the role of private funds, savings, and insurance in the recovery process. The allocation of resources in the recovery phase can depend on various factors, including the extent of the damage, the availability of funds, and the needs of the affected community. Recovery efforts can also influence the development of policies and plans to improve the resilience of affected communities to future disasters. For instance, enforcing building codes and zoning regulations could play a vital role in mitigating potential future losses to properties and establishments, as demonstrated by the restrictions on construction in high-risk areas in Lower Puna. The success of recovery efforts depends on the effectiveness of coordination among stakeholders and the ability to balance the needs of the affected community with available resources.

Lastly, these recovery efforts significantly impact residents impacted by a disaster, as well as those who stand to gain or lose from the recovery process. An equity lens is necessary to

ensure that the social welfare of poor or low- and moderate-income residents is prioritized in the recovery efforts, as they are often disproportionately impacted by disasters. Equity, fairness, and social justice are critical considerations in the recovery process. The county must address concerns about equity and fairness by ensuring that the allocation of resources is done equitably. Furthermore, The county must address concerns regarding equity, fairness, and social justice by ensuring that the allocation of resources is done equitably and that private interests do not come at the expense of public welfare so as to not repeat the same cycle of disaster in Lower Puna.

CONCLUSIONS

Future considerations

Seeing that the recovery of critical infrastructure in Lower Puna remains uncertain and ongoing, there are various future studies one could consider examining.

1. Future work may include measuring the current and future risk perception in residents in the study area. This could stand independently or be combined with any trends in population growth. By understanding how residents perceive the resiliency of their community, policymakers and stakeholders can make more informed decisions about how to allocate resources and plan for the long-term sustainability of the area. Additionally, this research could be combined with an analysis of population trends to better understand the impact of recovery efforts on the community's growth. By examining whether or not population growth is occurring in areas where critical infrastructure has been restored or expanded upon,

researchers can determine whether or not there is a correlation between recovery efforts and population growth and, thus, if those efforts are repeating the cycle.

2. Another worthwhile study would include an in-depth study of the expansion of recovery efforts of critical infrastructure to understand better if these efforts were leading Lower Puna into a false sense of resiliency. This research could focus on understanding the potential unintended consequences of recovery efforts on critical infrastructure in Lower Puna. Specifically, the study would investigate whether or not the restoration of critical infrastructure has attracted a larger population to the area, despite the risks associated with living in an area prone to natural disasters.

3. A potential duality of perspectives can be adopted within a singular framework of the buy-out deal. The specific focus lies on the lens that encompasses the buy-out endeavors aimed at curtailing the movement and construction of dwellings in high-risk zones. One plausible avenue for exploration would be a comprehensive evaluation of the impact of the buy-out deal on fostering a better, more resilient community in Lower Puna. In this regard, it is crucial to undertake an in-depth analysis of the social, cultural, and behavioral dimensions that shape the decision-making processes. The other trajectory pertains to investigating the extent to which the timing of repairs to the critical infrastructure had influenced the acceptance or rejection of the buy-out deal.

Overall, this research would be valuable in helping policymakers, and stakeholders make better-informed, equitable decisions about allocating resources for recovery efforts and promoting sustainable growth and development in Lower Puna. By interpreting the potential unintended consequences of recovery efforts, they can make adjustments as necessary to

ensure that the community remains resilient in the face of future disasters. As new information and advancements emerge, it is crucial to carefully approach future studies and actions, considering all potential outcomes and their long-term implications.

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