Probabilistic framework for evaluating food security of households in the aftermath of a disaster

Saeed Nozhati[a*], Nathanael Rosenheim[b], Bruce R. Ellingwood[a], Hussam Mahmoud[a] and Maria Perez[b]

[a]Department of Civil and Environmental Engineering, Colorado State University, Fort Collins, CO 80523-1372, USA; [b]Department of Landscape Architecture and Urban Planning, Hazard Reduction and Recovery Center, College of Architecture, Texas A&M University, TAMU 3137, College Station, TX, USA

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ABSTRACT

For households of all income levels, and especially for those that are food insecure, food access can be threatened by natural hazards. Extreme natural hazards can disrupt critical infrastructure systems, such as the transportation or electrical power networks, damaging the roads and bridges critical for food supply chains or electrical transmission lines providing electricity for food preservation. Interdependencies among infrastructure systems within the food supply chain make it vulnerable to unanticipated and cascading consequences. Maintaining food security in the aftermath of a natural hazard challenges a community's resilience, recovery and social well-being. This study introduces a methodology to consider how the interconnectedness among civil infrastructure systems impacts food-security of urban inhabitants. To this end, different infrastructure systems along with their spatial distribution are modeled to evaluate the restoration of food security within a community. Food security metrics, including food availability, accessibility, and affordability, are defined and quantified to provide risk-informed decision support to policymakers in the aftermath of an extreme natural hazard. The methodology proposed herein that considers system interconnectedness and uncertainties in demand and supply can be

Corresponding author. Email: saeed.nozhati@colostate.edu

applied to identify practical policy interventions to hasten recovery of food systems and reduce the adverse impacts of food-insecurity on a community.

KEYWORDS

Community-level recovery; food availability; food security; functionality assessment; resilience

1. Introduction

Household well-being relies on interdependent critical infrastructure systems (ICISs) such as transportation, energy, water, and food distribution. While ICISs shape the ability of our communities to meet everyday household needs, the level to which these needs are met can be quite variable across households through time and space and there may well be acute periods of disruption due to events such as natural hazards. A focus on food security reveals the interplay between normal operations, chronic and disaster-induced acute issues. Household food security refers to the ability of households to procure food to meet member needs and is a prime example of where chronic issues can be compounded acutely by disaster-induced challenges among ICISs. Access and affordability of food are persistent problems for many Americans, even in 'normal' times where 11.8% are food insecure, including 4.5% who live with very low food security (Coleman-Jensen et al., 2015).

ICISs are a foundation of functioning modern societies and the social well-being of urban inhabitants (Corotis, 2009). These systems can be challenged severely by natural and anthropogenic hazards. Unexpected damages due to unpredictable cascading failures can become regional disasters when the interdependencies in infrastructure systems are not well-understood (Zimmerman, Zhu, & Dimitri, 2016). Hence, the performance of such systems has recently garnered attention in resilience research, with an emphasis on improving the resilience of communities in the aftermath of severe hazards (McAllister, 2013). Predictable functioning of these systems is a cornerstone of a resilient community, one that is able to resist, absorb, and adapt to variable circumstances and 'bounce back' to its initial state, or 'bounce forward' to a more robust state following a disturbance (Vale, 2014).

Resilience-related research during the past decade has led to recommendations of metrics to describe the proper performance of independent and, indeed, interdependent systems (Bruneau & Reinhorn, 2007). These metrics have been developed and investigated for different systems, such as Electrical Power Networks (EPN) (Ouyang, Dueñas-Osorio, & Min, 2012), Water Networks (WN) (Adachi & Ellingwood, 2009), residential buildings (Lin & Wang, 2017), health-care facilities (Cimellaro, Arcidiacono, Reinhorn, & Bruneau, 2013), and transportation systems (Pant, Barker, Ramirez-Marquez, & Rocco, 2014). However, there has been very little effort that connects disruption in civil infrastructure to failures in food distribution and food retail infrastructure, despite that fact that food security depends on these critical infrastructure systems that have been identified in the Presidential Policy Directive 21 (PPD, 2013).

Problems in food access and affordability are greatly exacerbated following disasters when food distribution networks are compromised due to damage to facilities and damage and disruption to the critical infrastructure systems upon which they depend. For example, disaster-related food programs served 2.4 million households and distributed $928 million in benefits to households impacted by Hurricanes Katrina, Rita, and Wilma in 2005 (Food Research and Action Center, 2017). In 2008, similar programs issued $447 million in benefits to 1.2 million households impacted by wildfires in California and hurricanes making landfall on the Gulf Coast (United States Department of Agriculture, 2010). The human and economic losses and social disruption caused by failure of infrastructure systems are disproportionately high in relation to the actual physical damage to such systems, and the potential exists for even larger losses in the future, given that population and economic development in hazard-prone coastal areas of the United States has increased dramatically while investments in resilient infrastructure systems are lagging.

The food security of households within a community is in part a function of the pre-event spatial configuration and distribution of businesses and organizations comprising the food distribution network and the vulnerabilities and resilience of these business and organizations. The vulnerabilities of these entities are shaped, in part, by the vulnerabilities of the individual infrastructural systems (electricity, natural gas, water, waste water/sewer, etc.) upon which they depend and the characteristics of infrastructure system interdependencies. Unfortunately, there is little systematic data on the consequences of direct damage and disruption to infrastructure systems for the businesses and organizations within the food distribution network in local communities that can inform frameworks for understanding ICIS interdependencies in the context of natural hazards.

1.1. Literature review and definitions

1.1.1. Linking food security and critical infrastructure

The United Stated Department of Agriculture (USDA) identifies a household as *food secure* if it has 'access, at all times, to enough food for an active, healthy life for all household members'(Coleman-Jensen et al., 2015). The degrees of *food security* are characterized by four levels: (1) *high* food security, when there are no reported food access problems or limitations; (2) *marginal* food security, when there is concern about not having enough food; (3) *low* food security (food insecure without hunger), when the quality, variety or desirability is reduced, and (4) *very low* food security (food insecure with hunger), when eating patterns are disrupted and food intake is reduced (United States Department of Agriculture, 2017). According to Coleman-Jensen et al. (2015), the rates of low and very low food security are higher among households with children and minority households.

Food security is not just an issue of the ability of households to purchase or otherwise acquire food from a business or agency. It is also a function of a variety of dimensions of access to providers such as grocery stores, food banks, convenience stores, etc. In this regard, the five A's or dimensions of consumer's access to health care, first conceptualized by Penchansky & Thomas (1981), can be helpful to provide a taxonomic definition of access and improve the measurement science of fit between supply and demand (Biehl, Buzogany, Huang, Chodur, & Neff, 2017). These five (5) dimensions are: Accessibility, Availability, Affordability, Accommodation, and Acceptability.

For the purpose of this paper we focus only on three of the five dimensions that are particularly germane and relevant for the nexus between civil infrastructure and household food security in terms of accessibility, availability, and affordability. Our primary target is on supply side issues, with a focus on potential impacts of infrastructure damage and disruption for the retailers that are the direct providers or suppliers of food to households within local communities. The literature on business disruption after a natural hazard suggests that it is often not direct damage to an establishment's building or inventory that results in disruption and failure, but rather disruption of critical infrastructure (Graham, 2007; Tierney, 1997; Xiao & Van Zandt, 2012). The disruption of business activities and the failure of businesses and other food related organizations in turn has consequences for accessibility, affordability, and availability. The following offers a brief discussion of each of these dimensions food access and critical infrastructure.

Availability, the relationship between food supplied and the demand for food. For food to be available food retailers depend on infrastructure systems to operate such as water, electricity and buildings.

Accessibility, the relationship of physical access to food retailers, which is a function of the road network.

Affordability, the relationship between household income and food retailers. While this dimension of food access is not impacted by critical infrastructure, it is an important factor to capture pre-event levels of food security.

The availability, accessibility, and affordability dimensions of food access serve not only to assess households' vulnerabilities but also to link food security with critical infrastructure dependencies (Biehl et al., 2017). Critical infrastructure is crucial in guaranteeing a households' food security as it is among such highly complex technical systems, where 'unknown interdependencies between infrastructure services may lead to unpredictable and potentially cascading consequences' (Ayyub, 2014). The food system relies on a very complex supply chain. This supply chain heavily depends on transportation infrastructure, ports, interstate roads, rail networks, electricity and transportation fuel systems (Carolan, 2012; Freidberg, 2010). If a natural interrupts such complex systems, community resilience and the food security will be threatened (Paci-Green & Berardi, 2015).

The direct effect on consumers and suppliers after a natural hazard, demonstrates the importance of research related to a community's food security (Hori & Iwamoto, 2014; Mundorf, Willits, & Rose, 2015; Rose, Bodor, Rice, Swalm, & Hutchinson, 2011; Thomas & Mora, 2014). Regardless of their income level, households may be unable to preserve or access food before, during or after the damages occur. Additionally, ensuring 'food access during emergencies serves two functions: it prevents individuals from declining into an emergency health situation and reduces the likelihood of mass migration out of the region' (Paci-Green & Berardi, 2015).

1.2. Objectives and scopes

This paper studies the impact of interconnectedness among critical physical infrastructure, specifically EPN, WN, and transportation systems, on the functionality and accessibility food retailers in a moderate-size community exposed to severe earthquake hazards. Food availability, accessibility, and affordability are the basis for the food insecurity metrics, defined subsequently, that quantify the impacts of the disrupted critical systems on the food security of urban inhabitants in the aftermath of a severe earthquake. The probability distributions of these metrics are developed by simulating spatial and temporal recovery processes that capture various uncertainties following the earthquake. The methodology and the associated metrics are illustrated using a testbed community modeled after Gilroy, California.The rest of this paper is structured as follows: Section 2 introduces the applied methodology to model the network dependencies and interdependencies. To use the methodology of Section 2, the Gilroy community and its recovery-related characteristic's along with the hazard simulation are introduced in Sections 3,4, and 5. Section 6 introduces the food security formulation based of *availability*, *accessibility*, and *affordability.* Finally, Section 7 provides conclusions and includes directions for future research.

2. The role of interdependency in community functionality

Understanding dependencies and interdependencies among critical civil infrastructure systems (networks[1]) and different critical sectors within a system is essential for quantifying reliability, vulnerability, survivability (robustness), and recoverability (rapidity) of such systems (Bruneau & Reinhorn, 2007). Further, metrics for measuring the resilience of communities and performance of systems and components to support risk management and decision-making requires the consideration of the consequences of system interdependencies. Several sources of uncertainty propagate through the phases of transition of a system, from its initial condition prior to a disruptive event to a stable condition of normalcy following a period of recovery. The study of these uncertainties provide metrics that permit the effect of external disruptive events on systems and their corresponding recovery activities to be quantified from a stochastic viewpoint.

Interdependencies can be categorized by four basic types: physical, cyber, geographic, and logical (Rinaldi, Peerenboom, & Kelly, 2001). In this study, physical interdependency of networks are modeled by graph theory with an augmented adjacency matrix, denoted as $\mathbf{A}$.

Consider a directed network *G(N, E)*, where N denotes the set of nodes, and E represents the set of edges in G. The adjacency matrix of $\mathbf{A}$ is a square matrix of dimension N in which element $\mathbf{A}_{ij}$ represents the dependency of two nodes of i and j. The square matrix $\mathbf{A}$ is symmetric for undirected graphs, but not necessarily symmetric for directed graphs (networks). In order to consider epistemic uncertainty in the strength of coupling between nodes over time, one can model dependency by different time-dependent distributions, such as uniform, triangular, and pert-beta. Defining $x_i(t)$ as the state of the node i, the network state vector at time t, $\mathbf{x}(t) = (x_1(t), x_2(t), \ldots, x_N(t))$, denotes the state of all nodes at time t. The system function $\varphi(\mathbf{x}(t))$, which can be assessed for any likely realization of $\mathbf{x}(t)$, maps the network state vector into a network performance at time t.

[1]The term network is regularly used to model a system in which the links between components, as opposed to the components themselves, are unreliable (Aslett, 2012). In this study, however, the terms network and system as well as the terms of nodes and components are used interchangeably.

The system performance function $\varphi(t)$ represents the system behavior at time t and quantifies the system resilience. Figure 1 shows stages that characterize the system transition over time.

[Figure 1 about here.]

The system resilience given the disruptive event e at time t is (Barker, Ramirez-Marquez, & Rocco, 2013):

$$R_{\varphi}(t_r|e) = \frac{\varphi(t_r|e) - \varphi(t_d|e)}{\varphi(t_0) - \varphi(t_d|e)} \qquad t_r \in (t_s, t_f) \tag{1}$$

Pant et al. (2014) defined other temporal resilience metrics along with the stochastic ratio of the resilience defined by Equation (1). The metric 'time to full network service resilience, $T_{\varphi(\mathbf{x}(t))(e)}$' and the metric 'time to $\alpha{\times}100\%$ resilience, $T_{\alpha(e)}$,' shows the entire time taken from the time when recovery activities commence, at time t_s, up to the time, t_α, when the system service is restored to $\alpha \times \varphi(\mathbf{x}(t_0)$ (i.e., $R_{\varphi(t_r|e)} = \alpha$; $\alpha \in (0, 1]$). Different recovery strategies can be commensurable in favor of temporal metrics.

3. Testbed community- Gilroy, CA

The community investigated in this study is Gilroy, CA, located in Santa Clara County, CA, approximately 50 kilometers (km) south of the city of San Jose (see Figure 2). Gilroy is at the intersection of two main highways, U.S. 101, which extends through the City in the north-south route and SR 152, which extends in an east and west direction (Gilroy Annex, 2011). As a result, damage to the highway bridges disrupts the accessibility to the critical facilities, like main food retailers in the aftermath of an extreme disruptive event. The area of Gilroy is approximately 41.91 km^2 with a population of 48,821 in 14,175 household units at the time of the 2010 Census. While not all characteristics of Gilroy are covered in this study, our model of the community maintains adequate detail to study the dependency of food retailers on the availability and functioning of water, power, structure and transportation networks following a hazard.

3.1. *Urban grids*

The study area is divided into 36 grids (about 1.0-1.14 km^2) to define the properties of infrastructure systems, residential buildings, and the population in sufficient detail. Figure 2 shows the density of the population through a heat map distributed over the defined grids. Other population qualities, such as racial and ethnic composition and age distribution are tabulated in Tables 1 and 2, respectively.

[Figure 2 about here.]

[Table 1 about here.]

[Table 2 about here.]

Household units are increasing at a faster pace in Gilroy than in Santa Clara County or the State of California (Harnish, 2014). In 2010, the average number of persons per household in Gilroy was 3.4, higher than the state and county average. 95.4% of Gilroy's housing units are occupied. The heat map of household units over the defined grids is shown in Figure 3.

[Figure 3 about here.]

For each urban grid the total population and population in three age categories (child ages 0-17, adult ages 18-64, and senior ages 65+) were estimated using 2010 Census block data (United States Census Bureau, 2010a). The 2010 Block data provides the smallest level of geography for population counts with detailed characteristics such as age groups. Limitations in the way household data is reported and the lack of age characteristics for people living in group quarters leads to a slight reduction in the estimated population and the 2010 estimates discussed in Tables 1 and 2. For the data used in the models the total population was 47,905, the population for children ages 0-17 was 14,674, the population for adults ages 18-64 was 29,163, and the population for seniors ages 65+ was 4,068. Grids 11 and 21 both had the smallest population with 21 persons, and grid 23 had the largest population with 4,390 persons.

To estimate chronic, or pre-event food insecurity, by urban grid we assumed that an area-weighted poverty rate would provide a reasonable measure. For example, 11% of the population in Gilroy was predicted to have some degree of food insecurity and 11% of the population lived at or below the poverty level (Feeding America, 2016; United States Census Bureau, 2016). For each urban grid the percentage of the population living below poverty was calculated with an area-weighted method from the census tract level percentage of persons below poverty estimate from the 2014 5-year American Community Survey. The poverty rates ranged from 4.0% (Grids 27 and 32) to 34.5% (Grid 25). The average poverty rate was 14.0% and the median grid (Grid 23) had a poverty rate of 12.1%. Overall the median value is within the margin of error for the poverty rate reported by Census for the entire city of 11.3 ± 2.1% and the mean value is just above the 90% confidence interval (United States Census Bureau, 2014).

3.2. Description of infrastructure systems in Gilroy City

The Electrical Power Network (EPN) components that are located within the study area are shown in Figure 4. An 115 kV transmission line supplies the Llagas power substation, the major source of power in the study area. Distribution line components are spaced at 100 m and modeled from the substation to the urban grids centers, food retailers, water pumps, and water tanks.

[Figure 4 about here.]

The Water Network (WN) includes the Llgas sub-basin, recharged by Llagas and Uvas Creeks, is the sole source of domestic water of Gilroy (Semseler & Akel, 2010). The potable water wells, situated in wood-frame structures, pump water into the distribution system. The Gilroy municipal water pipelines range from 102 mm to 610 mm in diameter (Semseler & Akel, 2010). This study considers the main potable water pipelines, wells, water tanks, and booster pump stations (BPS), shown in Figure 5, along with the dependency of water pumps on the availability of electricity.

The functionality of WN components, such as wells and water tanks depends not only on the physical structure but also on the electric power distribution lines which provide electricity of them. Thus, the interdependency of the EPN and WN is considered in this study. The reader interested in more details of EPN and WN is referred to references (Nozhati, Ellingwood, Mahmoud, & van de Lindt, 2018a; Nozhati, Sarkale, Ellingwood, Chong, & Mahmoud, 2019; Sarkale, Nozhati, Chong, Ellingwood, & Mahmoud, 2018; Semseler & Akel, 2010). The major highways through Gilroy are U.S. Route 101 and State Route 15. This study considers seven bridges, mainly constructed over U.S. Route 101. Unlike the metropolitan areas, the transportation network of Gilroy only contains routes and highway bridges and does not depend on the electrical power network.

[Figure 5 about here.]

3.3. Food retailers

The vast majority of the food requirements of the city inhabitants are supplied by six main food retailers, summarized in Table 3, each of which has more than 100 employees. In this study, the availability of each food retailer depends on the physical structure that houses the food retailer as well as the availability of electricity and potable water. Figure 6 shows the locations of all main food retailers within the study area.

[Table 3 about here.]

[Figure 6 about here.]

We compute the probabilities of shopping activities for each urban grid with the gravity model proposed by Adigaa et al. (2015), as follows:

$$P(r|c) \propto w_r e^{bT_{cr}} \tag{2}$$

where w_r is the capacity of food retailer r, determined by Harnish (2014), b is a negative constant, and T_{cr} is the travel time from urban grid c to food retailer r.

In addition to availability, a food retailer should be accessible in the aftermath of an extreme disruptive event. The concrete bridges across the South Valley Freeway limit the accessibility of Gilroy inhabitants to the food retailers, especially Costco, Walmart, and Target.

4. Damage and restoration assessment of facilities

Seismic fragilities can be utilized to model the physical damage to infrastructure facilities within a community, such as buildings, water tanks, wells and bridges. The fragility of a component is defined as the probability of exceeding a given damage state, conditioned on a level of a ground motion Intensity Measure (IM). HAZUS-MH (FEMA, 2003) is one nonproprietary source of the seismic fragilities used herein. The fragility curves are defined by log-normal distribution functions; for example, as functions of Peak Ground Acceleration (PGA) would be:

$$Pf_{PGA}(pga) = \int_0^{pga} \frac{1}{\sqrt{2\pi}\zeta s} exp[-\frac{1}{2}\{\frac{ln(s)-\lambda}{\zeta}\}] \tag{3}$$

where $Pf_{PGA}(pga)$ denotes the damage state probability, given PGA = pga, λ is the mean of ln(PGA), and ζ is the standard deviation of ln(PGA).

This study follows the assumptions in the study by Adachi & Ellingwood (2009), in which the components are assumed to be either fully functional or nonfunctional. The failure probability of a pipe is bounded as (Adachi & Ellingwood, 2009):

$$1 - G_{\varepsilon PGV}(-CL\mu_{PGV}) \leq E[P_f] \leq 1 - E[exp(-CL\mu_{PGV})] \tag{4}$$

in which $G_{\varepsilon PGV}(.)$ is the moment-generating function of (the residual of the PGV), P_f is the failure probability of a pipe, L is the length of pipe, and μ_{PGV} is the average PGV for the entire length of the water main. The term C for water pipe segment i is $C = K \times 0.00187 \times PGV_i$, where K is a coefficient determined by the pipe material, diameter, joint type, and soil condition based on the guidelines prepared by the American Lifeline Alliance (ALA) guidelines (Eidinger, 2001). The Upper Bound (UB) and exact solutions in Equation (4) are close enough that in practical applications, the UB assessment (conservative evaluation) can be used (Adachi & Ellingwood, 2009).

Restoration quantification suffers from the lack of documented data on delay and repair time for different components of a community. The analysis of uncertainties in component restoration is an interdisciplinary endeavor. HAZUS-MH (FEMA, 2003) has restoration curves primarily based on expert judgment and available empirical data. The HAZUS-MH restoration curves are based on the assumption that restoration can be modeled by a normal distribution, which admits the possibility that restoration times can be negative. There are several studies of the appropriate repair restoration time distributions, like exponential (Carter & Malerich, 2007), lognormal (Lin & Wang, 2017), and Weibull distribution (Limnios , 2013). Accordingly, this study utilizes exponential distributions to model the repair times. The exponential distributions used herein are synthesized from FEMA (2003) and Nozhati et al. (2018a), as summarized in Table 4.

[Table 4 about here.]

5. Seismic hazard models

Gilroy, CA is susceptible to severe earthquakes. The epicenter of the 1989 Loma Prieta Earthquake was nearly 25 km northwest of Gilroy on a section of the San Andreas Fault System. The Loma Prieta Earthquake caused an estimated $6 billion in property damages, 63 fatalities, and 3,757 injuries (National Research Council, 1994). In this study, a scenario earthquake similar to Loma Prieta with moment magnitude, $M_w =$ 6.9 is simulated at one of the closest points on the San Andreas Fault to downtown Gilroy, an epicentral distance of approximately 12 km.

The conditional probability of exceeding a ground motion intensity measure at a particular geographic site for a specific source is specified by ground motion prediction equations (GMPE). To estimate spatially varying intensities measures as a function of the earthquake and site features different GMPEs are available. In this study, the IMs and associated uncertainties are modeled by (Abrahamson, Silva, & Kamai, 2013) GMPE. The United States Geological Survey (USGS) provides the average shear-wave velocity in the top 30 m of soil (V_{S30}) for different locations of Gilroy. Figure 7 demonstrates two simulated ground motion fields (PGA and PGV) generated within the defined boundary.

[Figure 7 about here.]

Permanent ground displacements (PGD) due to liquefaction occur only in zones where the PGV exceeds 75 cm/s (30 in/s) (O'rourke & Jeon, 2000). As Figure 7b shows the PGV of Gilroy area does not exceed roughly 35 cm/s, the likelihood of pipe breakage by PGD due to liquefaction is negligible.

6. Results of Probability of Food security Model

In this study, three conditions of *availability*, *accessibility*, and *affordability* must be satisfied to consider a household or an urban grid as a food secure area in a community; see Figure 8 and Equation (5). The first condition is availability (C_1), i.e., the household unit and a food retailer both must be functional (F), see Equation (6). In this study, a building is considered as functional when it has a safe structure and the potable water and electricity (U) are available, see Equation (7).

$$P_{FoodSecurity} := P\left(\bigcap_{i=1}^{3} C_i \middle| i \in \{availability, accessibility, affordability\}\right) \quad (5)$$

$$C_1 := \left(\bigcap_{j=1}^{2} F_j \middle| j \in \{home\ functionality, retailer\ functionality\}\right) \quad (6)$$

$$F := \left(\bigcap_{k=1}^{3} U_k \middle| k \in \{structure, electricity, water\}\right) \quad (7)$$

The second condition is accessibility (C_2). There are several modes of transportation, such as driving, bicycling and walking. This study considered driving as the mode of transportation, which includes cars and local buses. ggmap by using Google's routing API was called from within R to compute all alternative driving routes between each food retailer and each urban grid center by using the *ggmap* package (Kahle & Wickham, 2018). *ggmap* computes all the alternative routes between a household unit and retailers. Once a route is found, the accessibility from the origin to the destination is satisfied.

The third condition is affordability (C_3), which means that household residents should be able to purchase all essential food items. Food security within a community depends on many factors and the likelihood that a household unit is in a state of food insecurity immediately following a severe hazard event can be substantial. Availability and accessibility are prevalence factors in food insecurity following a hazard, while affordability is the most significant factor prior to a hazard. The role of availability along with accessibility is assessed in the next section and the role of affordability is discussed in Section 6.2. It should be noted that there are several potential improvements related to the mentioned definitions. For example, one can consider the wastewater system and telecommunication networks in the definition of functionality and different transportation mode in the definition of accessibility.

[Figure 8 about here.]

6.1. The role of availability and accessibility

There are several factors that affect the recovery trajectory of a network, among which the number of recovery crews that can be allocated, network age, event area, and event type are most important (Barabadi & Ayele, 2018). Uncertainties in the earthquake IM, components' responses, and interdependencies among components yield uncertainty in the recovery process. These uncertainties in the examined metrics and recovery paths are considered below.

In order to restore the networks, a number of available resource units (RU), defined as generic work teams containing repair crews, replacement components and tools are considered for assignment to damaged components. One RU is required to repair each damaged component (Ouyang, Dueñas-Osorio, & Min, 2012). In this study, it is assumed that the networks have their own RUs for assessment and repair. This assumption is logical since the resource units of each network are different based on their skills and needed equipment. However, the available RUs are limited and depend on the capacities and policies of the responsible companies.

Policymakers may consider the recovery of some networks a priority. Such priorities are considered in this study. The EPN components with the higher demand and importance are considered to be repaired first. Importance analysis can be considered as an alternative to prioritize damaged components. The EPN recovery policy followed in this study is generally as follows: the transmission line, the power sub-station, the distribution line to the water pump or the well that supplies Costco and Walmart, and the distribution lines that supply the downtown. The WN recovery policy is generally as follows: potable water wells, water tanks, pipelines that supply food retailers and residences. We assumed that the food retailers as well as bridges can be repaired simultaneously. A random repair time generated based on the statistics presented in Table 4, is assigned to damages components. A Monte Carlo simulation is implemented to propagate the uncertainties and compute the average and standard deviation bands of the restoration curves. Once a damaged component is repaired, the functionalities of the networks are computed, taking into account interdependencies as required, and the RU will move to the next assigned damage component. Since the networks are interconnected, even a component that is undamaged following the earthquake or has been repaired, may not be functional until all its suppliers are functional. The reader interested in a more thorough treatment and assessment of networks recovery should refer to (Bruneau & Reinhorn, 2007; Ouyang, Dueñas-Osorio, & Min, 2012; **?**).

Figure 9 shows the percent of available EPN components with one and two standard deviation bands over time. This figure is important for decision-support algorithms and policymakers, in that the number of damaged components determines the dimension of the decision-making problem and the number of required RUs for the EPN or any other network in time. The times to full recovery of EPN, $T_{\varphi(\mathbf{x}(t))(e)}$, and time to 75% EPN recovery, $T_{0.75}(e)$, are also represented in Figure 9b. The times required to restore electric power and water for each food retailer are presented in Figure 10, which indicates the vulnerability of each food retailer due to the unavailability of utilities and informs the periods of time that reliable backup utility systems should be provided.

[Figure 9 about here.]

[Figure 10 about here.]

The shape of the recovery trajectories and availability of utilities for each retailer depend on the location of each retailer in the community and more importantly to the recovery strategies. For instance, Walmart and Costco are next to each other and pretty close to the power substation; thus, they have the shortest time to regain electricity. Safeway, Nob Hill Foods, and Mi Pueblo, which are close together in downtown Gilroy, have roughly similar recovery times. The best recovery strategy is one that would minimize the time to achieve partial or full network resilience, $T_{\varphi(\mathbf{x}(t))(e)}$. However, this paper makes no attempt to seek the optimal recovery policy; this optimization is considered in the future work.

In what follows, the number of people that have electricity and potable water in the community are computed with one standard deviation band over time in Figures 11 and 12, respectively. The various sources of uncertainties along with occasional outliers in the simulated recovery paths make the broad band. Furthermore, the temporal metrics of recovery times for both networks are presented.

[Figure 11 about here.]

[Figure 12 about here.]

As noted in Figure 8, food security depends on availability, accessibility, and affordability. With this in mind, numbers of food-secure people have been calculated over the 36 urban grids as well as the community over time with respect to availability and accessibility in this subsection. For the sake of brevity, only three different grids (one in the south, one in the middle, and one in the north of the community), along with the entire community, are presented. Figure 13 shows the number of people, adults, children, and seniors that are food-secure in these three grids. Children include those ages 0-17, including those of preschool and school age, as indicated in (Harnish, 2014). Young children are especially vulnerable to food insecurity; policy makers should be conscious of the number of food-insecure children. Figure 14 represents the number of food-secure people with different age distributions at the community level. This figure is important to policymakers in that they can be informed when the community reaches a locally-defined desirable threshold.

[Figure 13 about here.]

[Figure 14 about here.]

6.2. The role of affordability

Affordability measures whether people have sufficient financial resources to purchase essential food items from food retailers. Prior to the occurrence of a severe hazard event when conditions of availability and accessibility are less important, affordability is the most significant issue for vulnerable populations. Affordability has a direct relationship with individual or household income. The annual median family income (MFI) for each area of the country is provided by the Federal Department of Housing and Urban Development (HUD). Gilroy has a lower median family income ($76,060 in 2012) than the median family income ($89,445 in 2012) of the surrounding area, which means that the role of affordability should receive special attention (Harnish, 2014).

A heat map of food-insecure people based on the poverty rates over the urban grids is shown in Figure 15. Figure 15 indicates that regardless of what happens due to the hazard as well as the recovery activities plans in the aftermath of the hazard, the number of people represented in Figure 15 remain in the food insecurity state. In other words, we assume that chronic food insecurity issues will return to pre-event levels.

[Figure 15 about here.]

6.3. Predicted recovery time

[Figure 16 about here.]

[Figure 17 about here.]

The food insecurity curves of the three different urban grids in terms of initial food-insecure people, along with that for the whole community, are presented in Figures 16 and 17, respectively. Figure 17 can inform policymakers how many emergency meals will be required and when the community reaches to the desired percentiles from food securities perspective. Table 5 summarizes the average number of days among the 36 grids to reach different percentages of food security. Noted that for about four days after the event every person in the city is considered food insecure. Furthermore, the community cannot reach to a complete food security status due to the affordability factor that considers the food insecurity of the households living in poverty who we assumed represented the level of chronic food insecurity prior to the hazard.

[Table 5 about here.]

7. Conclusions

This paper presents a probabilistic framework for evaluating food-security related issues affected by damages to civil infrastructure caused by severe natural hazards. An illustrative community made up of an electrical power network, water network, highway bridges, residential grids, and food retailers is modeled to represent the direct and indirect consequences resulting from physical damages to interconnected infrastructure exposed to seismic hazards. The restoration and functionality of networks are quantified, immediately following the simulated earthquake until full restoration. The case study results also demonstrate the periods of time that each main food retailer suffers from the lack of main utilities of electricity and potable water. Food security metrics based on food availability, accessibility, and affordability are defined and quantified probabilistically either at the grid level or at the community level.

The proposed framework can be extended in future work to evaluate optimized policy interventions that mitigate negative impacts and expedite regional recoveries related to food security. We believe that the methodology can be extended to other hazards and communities. However, a more comprehensive definition of food security metrics should be considered. For example, the definition of availability could include the performance and serviceability of the wastewater system and telecommunication network. Further, a gravity model that can capture the effect of affordability and the income of level households would improve the model. Furthermore, an optimization framework to seek the optimal recovery strategies with respect to food security issues must be gained attention.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Table 1. Racial and Ethnic Composition of Gilroy (United States Census Bureau, 2010a).

Subject	Number	Percent
HISPANIC OR LATINO AND RACE		
Total population	48,821	100
Hispanic or Latino	28,214	57.8
Not Hispanic or Latino	20,607	42.2
White alone	15,335	31.4
Black or African American alone	709	1.5
American Indian and Alaska Native alone	180	0.4
Asian alone	3,265	6.7
Native Hawaiian and Other Pacific Islander alone	86	0.2
Some Other Race alone	58	0.1
Two or More Races	974	2

Table 2. Age distribution of Gilroy (United States Census Bureau, 2010b).

Age Group	Number	Percent
Preschool (0-4 years)	4,144	8.4
School (5-17 years)	10,839	22.2
Young Adult (18-24 years)	4,514	9.2
Prime Working (25-54 years)	20,717	42.4
Retirement (55-64 years)	4,509	9.25
Senior Citizen (65+ years)	4,098	8.4

Table 3. The number of employees of main food retailers (Harnish, 2014).

Food Retailer	Walmart	Costco	Target	Mi Pueblo Food	Nob Hill Foods	Safeway
No. Employees	395	220	130	106	100	130

Table 4. The expected repair times (Unit: days).

	Damage state			
Component	Minor	Moderate	Extensive	Complete
Residential buildings	2	30	90	180
Food retailers	5	30	120	240
Highway bridges	0.6	2.5	75	230
Electric sub-station	1	3	7	30
Transmission line component	0.5	1	1	2
Distribution line component	0.5	1	1	1
Water tanks	1.2	3.1	93	155
Wells	0.8	1.5	10.5	26
Pumping plants	0.9	3.1	13.5	35

Table 5. Mean time for grid to reach percentage of population that is food secure.

Percentile (%)	0	25	50	75
Mean Time (days)	4.0	12	42	410

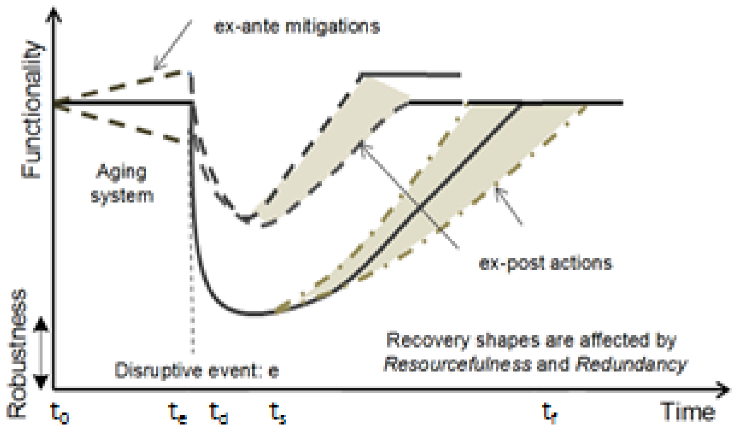


Figure 1. Concept of system resilience (adopted from McAllister (2013)).

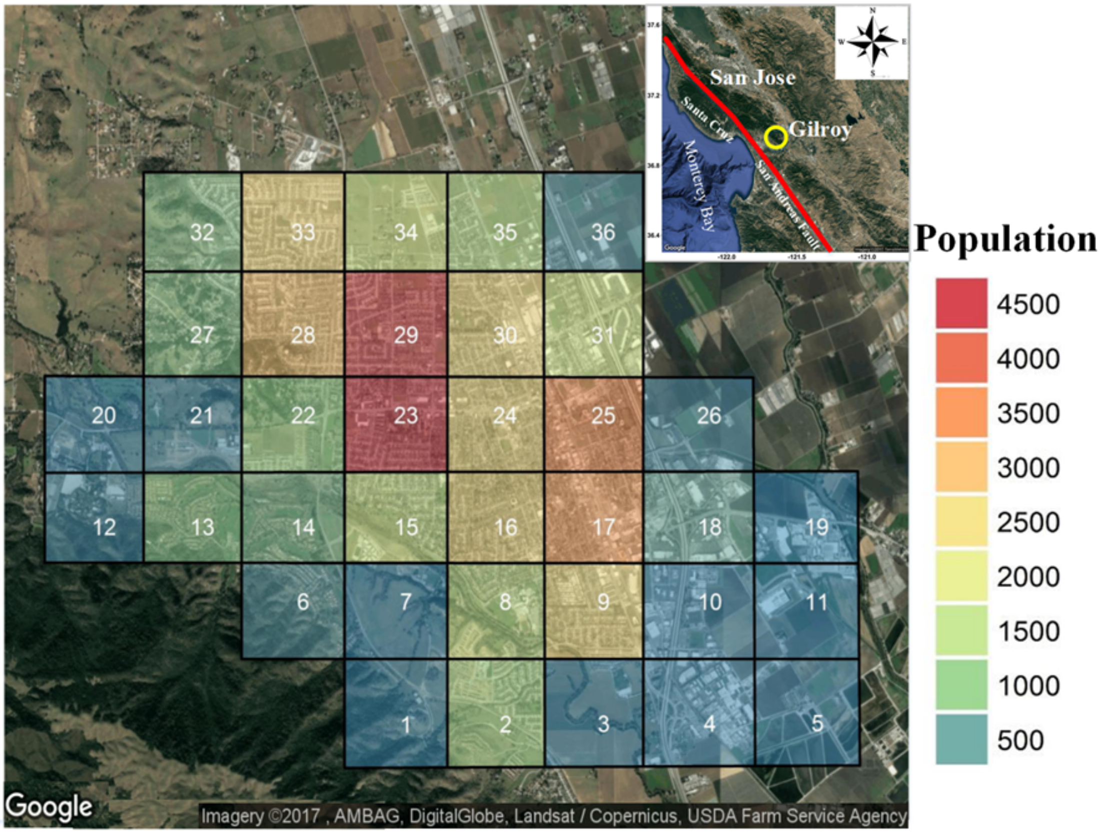


Figure 2. Gilroy position along with the population heat map over the defined grids.

Figure 3. Housing units over the defined grids.

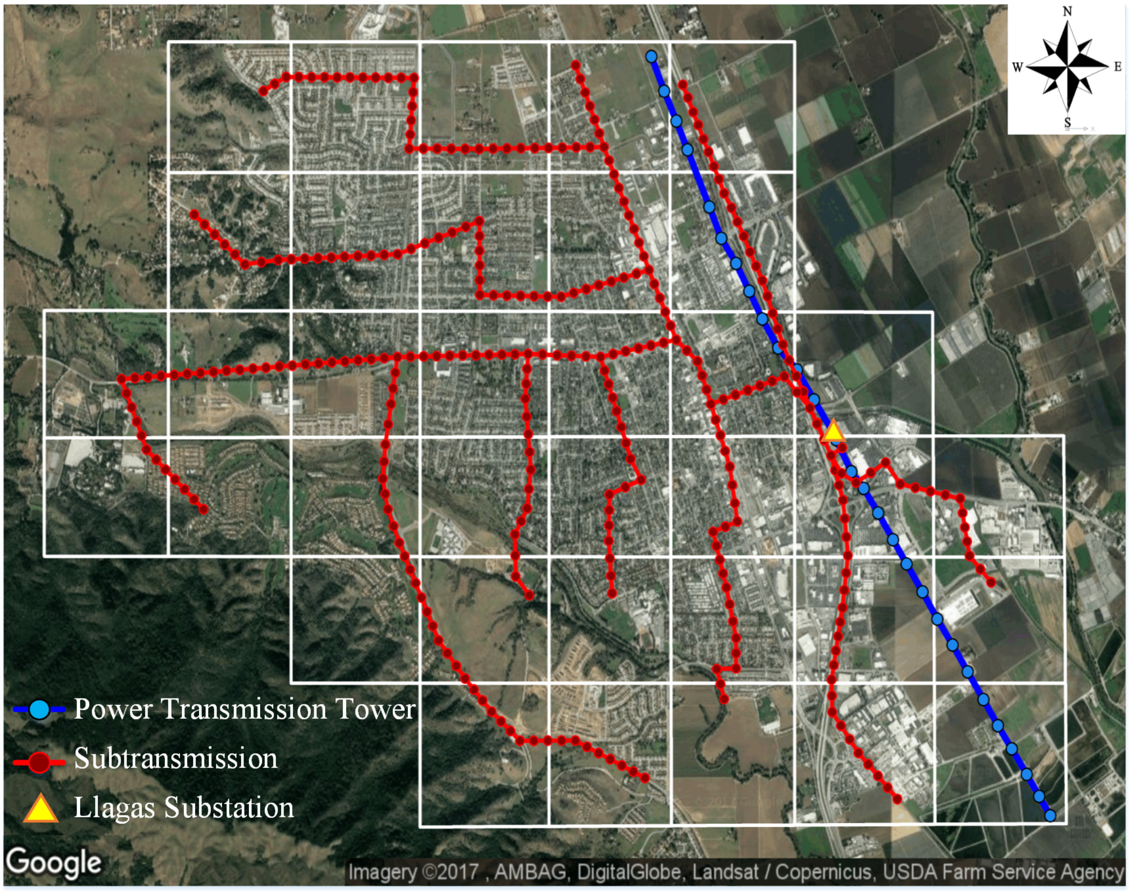


Figure 4. The modeled electrical power network.

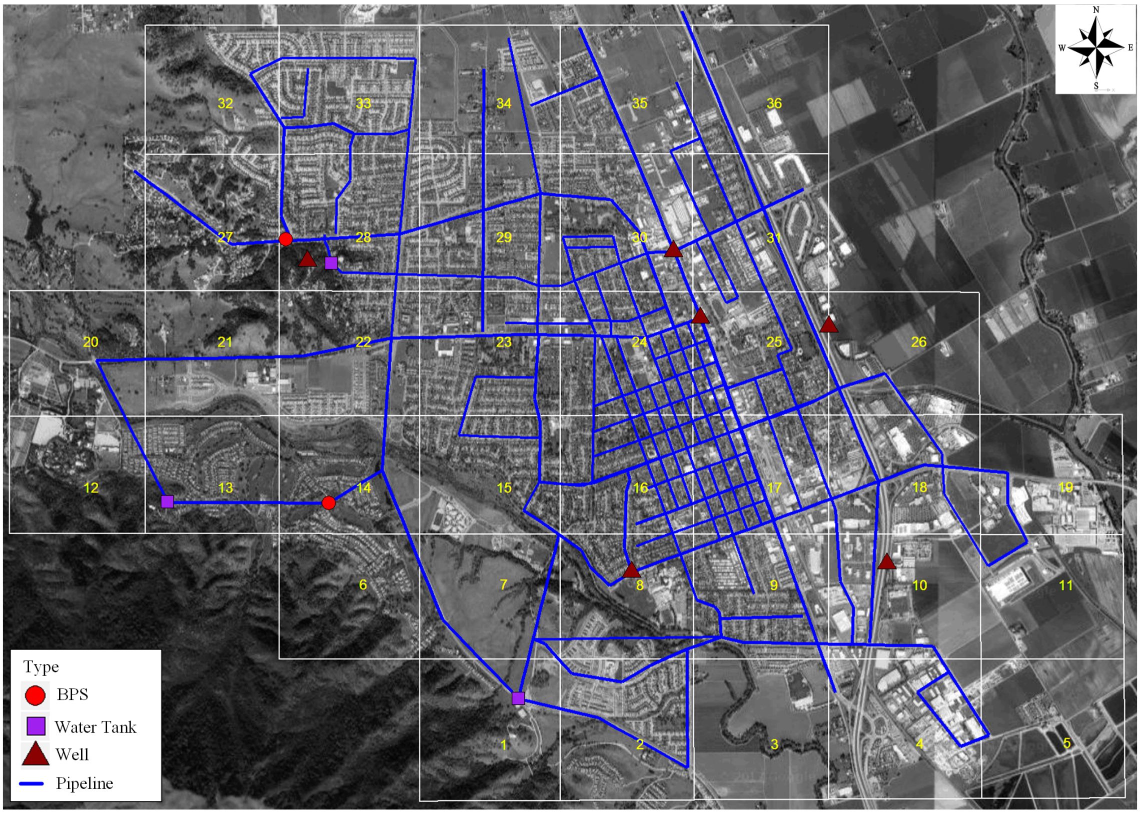
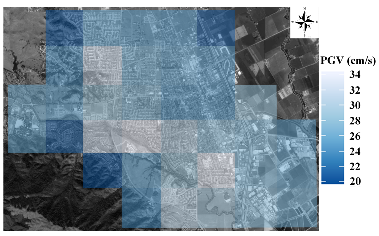


Figure 5. The modeled water network.

Figure 6. Main food retailers in Gilroy.

(a) Peak Ground Acceleration.



(b) Peak Ground Velocity.

Figure 7. Definition of food security in this study.

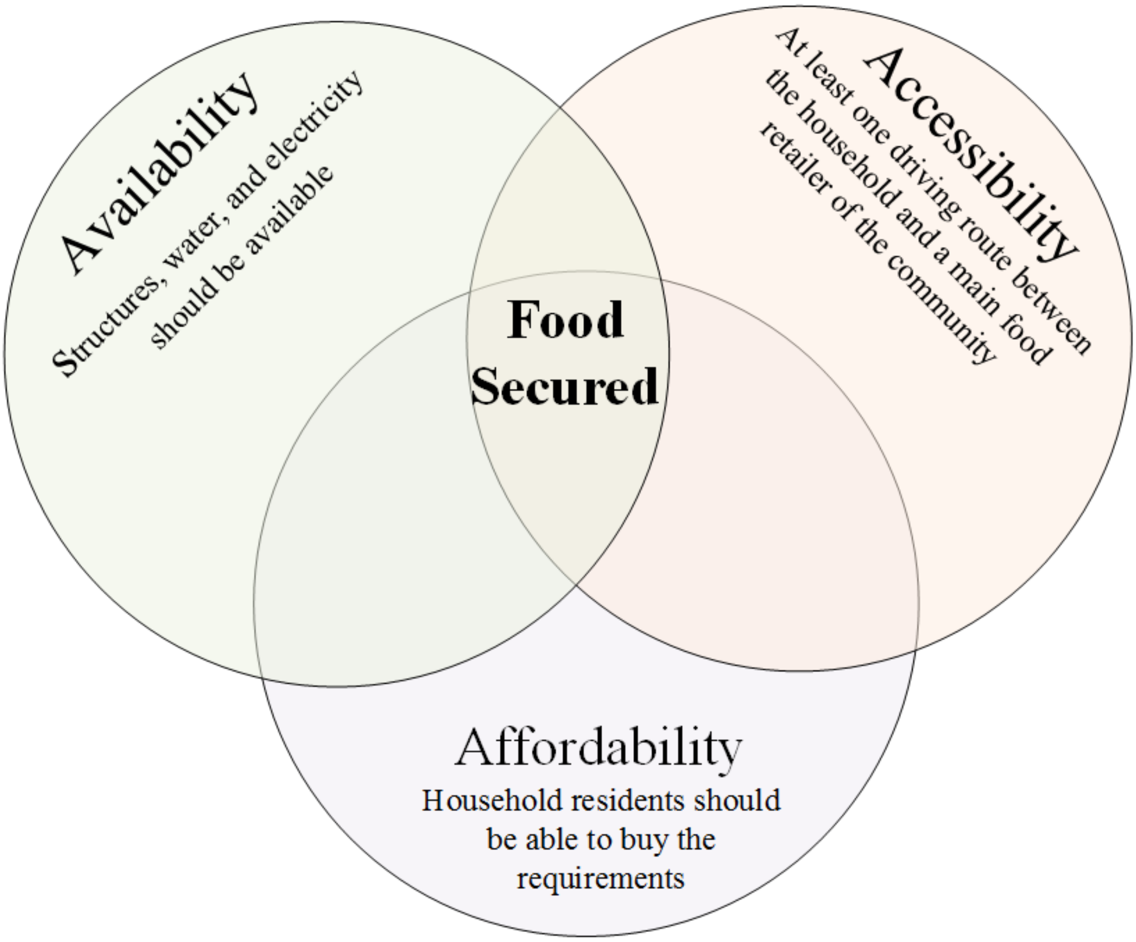
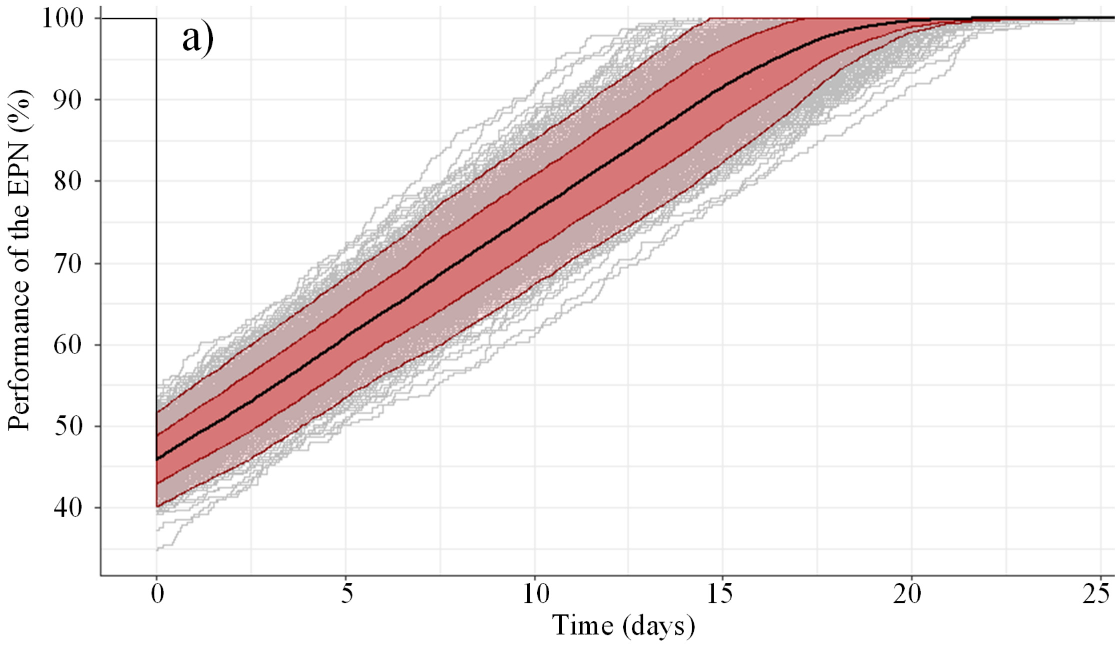
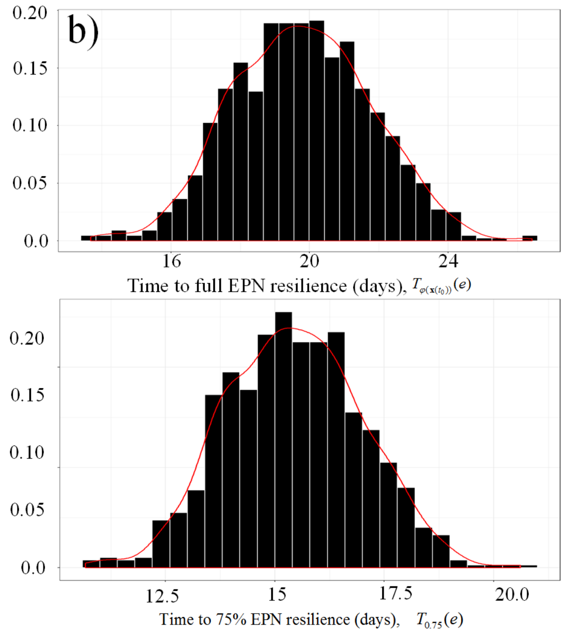


Figure 8. Definition of food security in this study.



(a) The percent of available components over time.



(b) Times to full recovery and 75% recovery.

Figure 9. The Electrical Power Network recovery and temporal metrics.

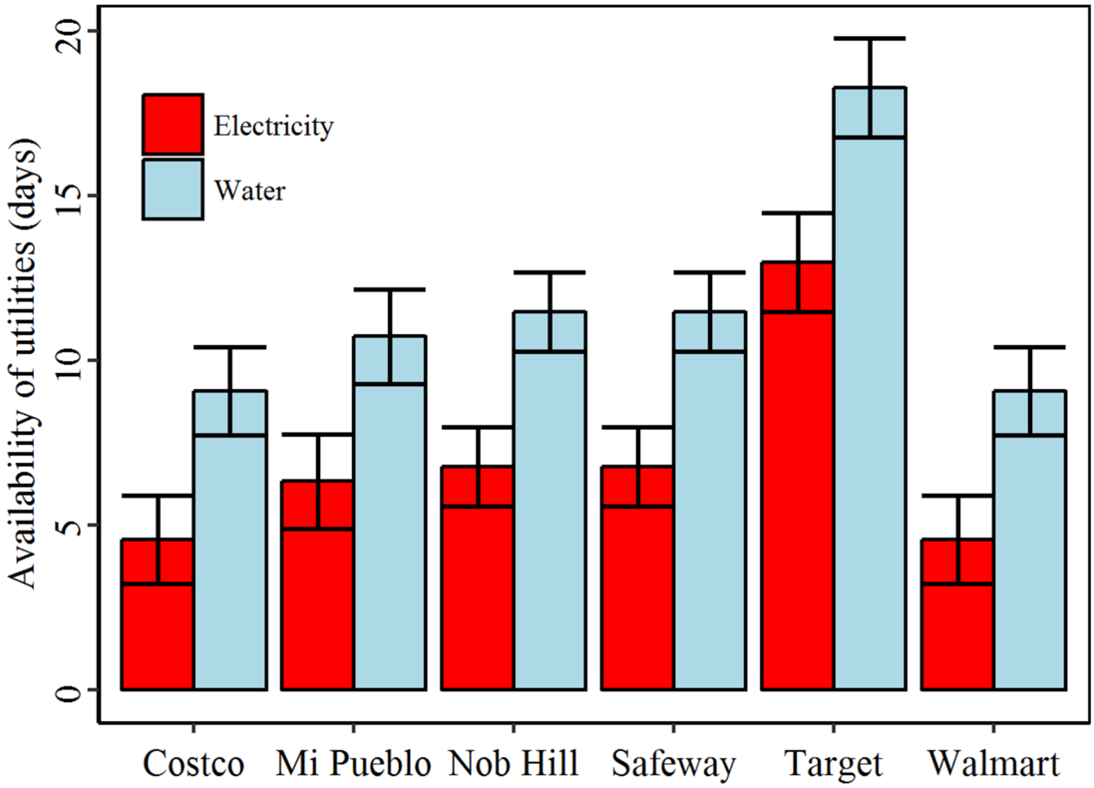


Figure 10. Time to availability of electricity and water for each main food retailer.

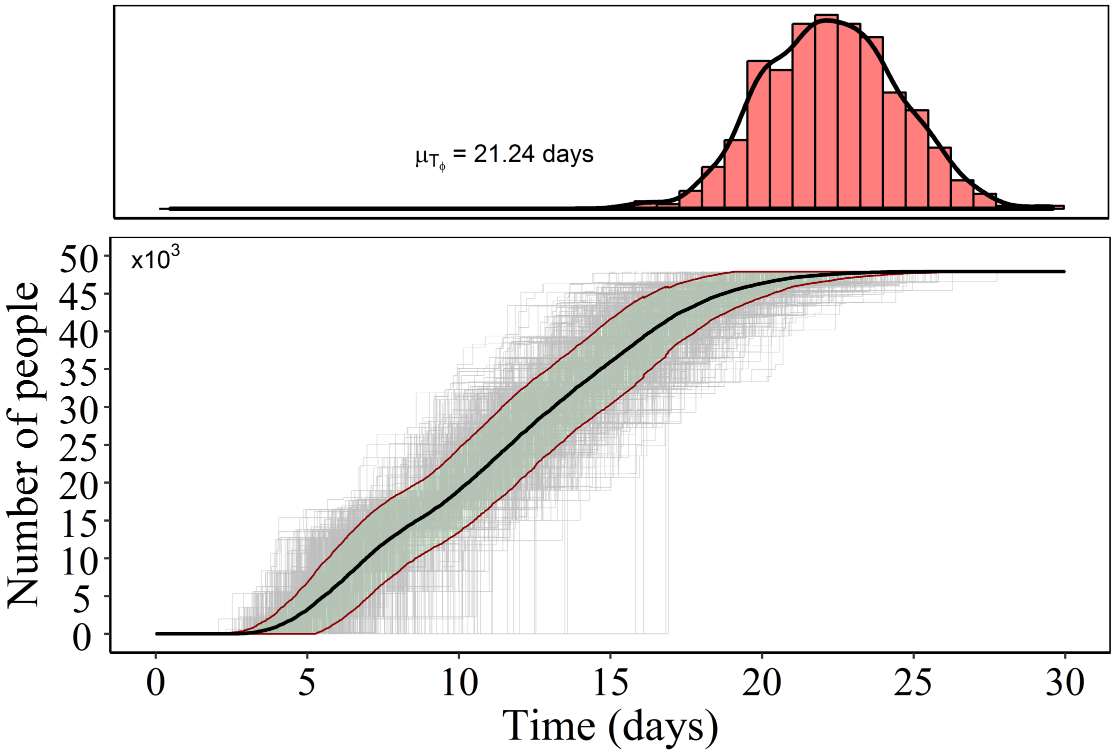


Figure 11. Recovery trajectories with mean and full times recovery distribution for electrical power network.

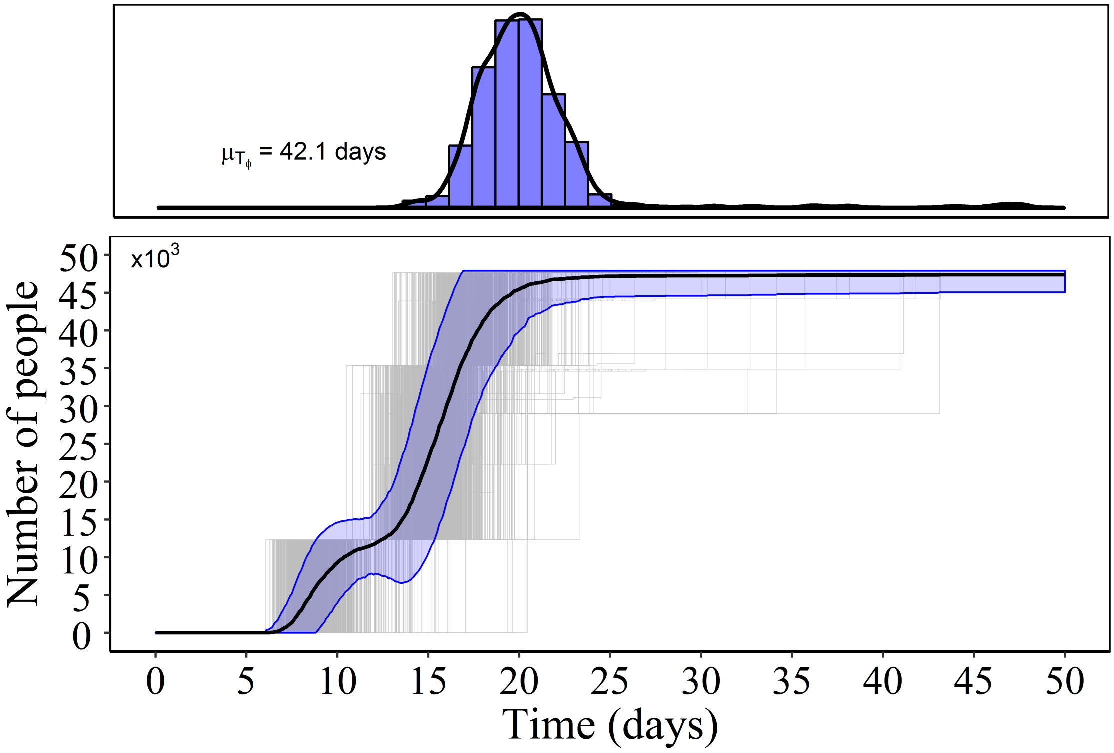


Figure 12. Recovery trajectories with mean and full times recovery distribution for water network.

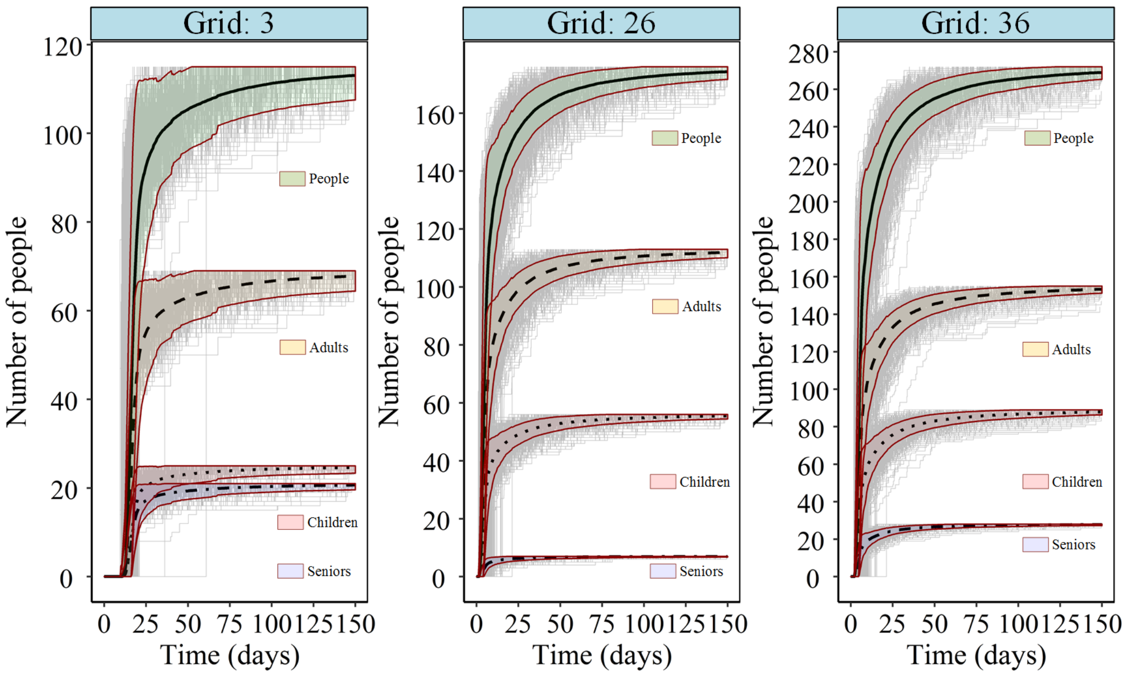


Figure 13. The number of food-secure people with $\pm\sigma$ over three different grids.

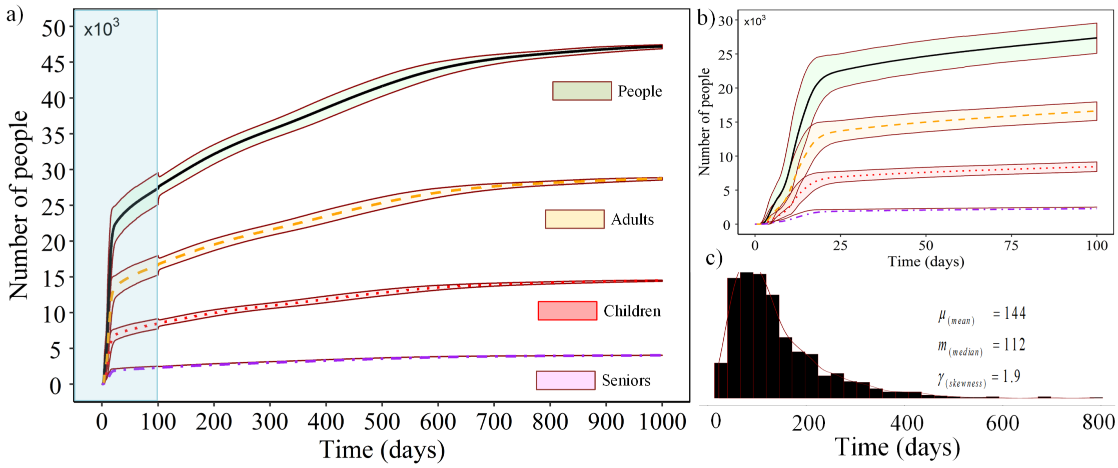


Figure 14. Total number of food-secure people at the community level with $\pm\sigma$ b) over the first 100 days c) times to full food security recovery.

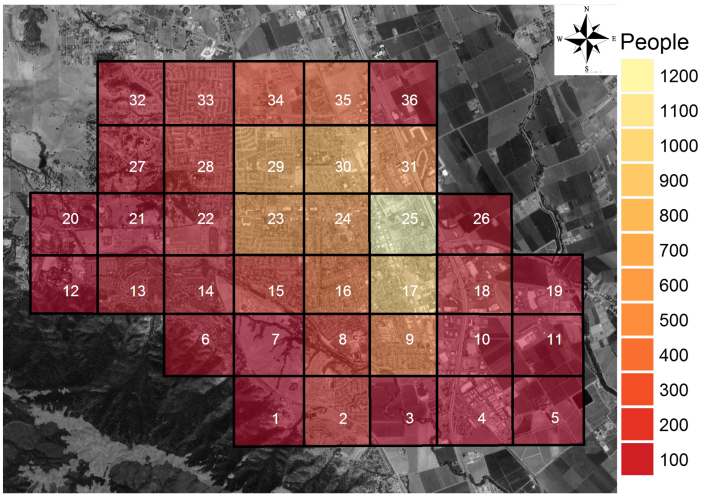


Figure 15. The map of pre-event food-insecure people over the defined grids.

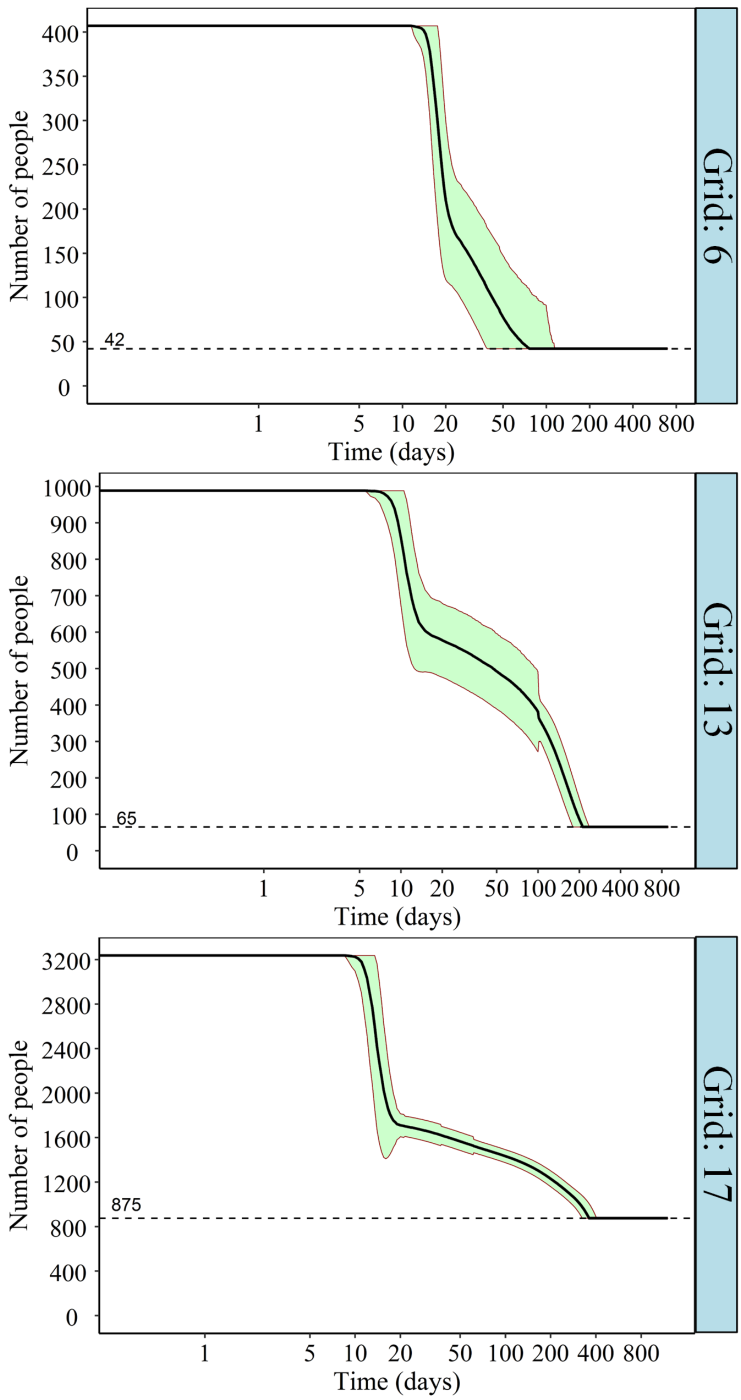


Figure 16. The number of food-insecure people with $\pm\sigma$ over three different grids.

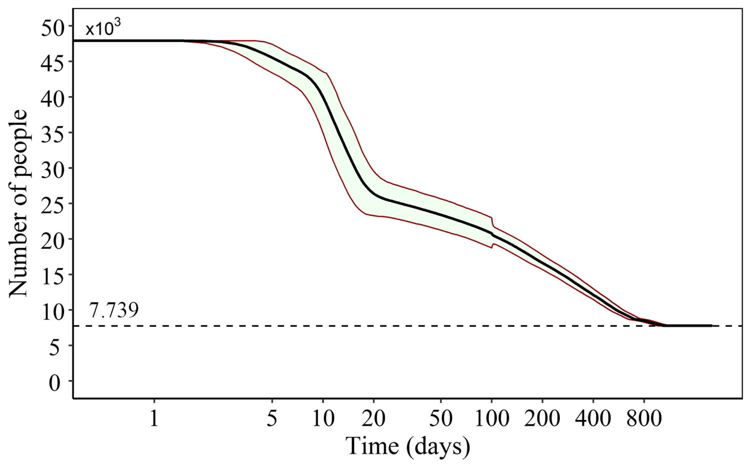


Figure 17. Total number of food-insecure people at the community level with $\pm\sigma$.