4. Dependencies and Cascading Effects

The development of a specific community disaster resilience plan requires an understanding of the building and infrastructure system dependencies and the potential cascading effects that can occur. This chapter provides an overview of aspects of the physical interconnectedness of buildings and infrastructure systems to consider when setting performance goals for community recovery.

4.1. Introduction

To determine the performance needed for the selected clusters of the built environment and to protect a community from significant and non-reversible deterioration, an orderly and rapid process for managing recovery is needed that includes availability of a sufficient number of buildings in each of the designated clusters and infrastructure systems that support them. Each cluster's performance depends not only on its primary function, but also on the dependencies between clusters and the infrastructure systems that support them. These dependencies need to be addressed when setting performance goals to avoid potential cascading failures of multiple systems.

Cascading failures occur when a failure triggers failures of other components or systems. It can occur within one system, such as a power grid, when one component failure causes an overload and subsequent failure of other components in sequence. It can also occur between systems when the failure of one system causes the failure of other systems. For example, a multiple-hour loss of power in a community can cause failure in the cell phone system if there is no emergency power to maintain the cell towers.

Identifying the dependencies and potential cascading failures is the first step. Reducing the effect of dependencies and consequences, where possible, and setting performance goals that balance the role of dependent systems in community recovery is achieved through multiple approaches. For example, dependencies can be reduced by adding redundancy, increasing capacity, and installing weak links that constructively isolate portions of a system that do not need to be interconnected. Governance processes and public policies also play a key role in developing plans for mitigation, response, and recovery management of dependencies.

4.2. Dimensions of Dependency

Interactions within and between infrastructure systems are dependent on a number of factors. Traditionally, dependencies consider the physical and functional relationship between different systems (i.e., drinking water systems require electricity to operate pumps). However, this is only one dimension that illustrates system interaction. This section presents multiple dimensions of dependency considered in community resilience planning: internal and external, time, space, and source dependencies. It should be noted that due to the complex nature of infrastructure system interactions, these dimensions of dependency are not completely decoupled.

4.2.1. Internal and External Dependency

Disruption to the normal operating state of the built environment reveals that infrastructure systems are interconnected through a web of external dependencies. Additionally, within a given system (i.e., an individual service provider) operations are dependent on a similar web of internal dependencies. Failure of a single critical system component can result in cascading failures within an individual system, as in the case of lost electrical power to an estimated 50 million people in the 2003 Northeast Blackout (NERC 2004). External dependencies can also lead to cascading failures of other infrastructure systems, as in the shutdown of train service in and out of New York City and loss of cell sites after batteries were drained in the 2003 Northeast Blackout.

Internal Dependency

Within a given system, there are certain components that are critical to the successful operation of the system. An example of a critical component in a water system is a pump that delivers water to a water tower to distribute onto customers by gravity feed. If the pump stops working, then customers in the pressure zone served by that pump are without water – unless there is redundancy built into the system to supply water in another way. This pump example represents an infrastructure-related dependency internal to a single water utility. The pump would also be an internal dependency that affects operations within a single infrastructure system if it was part of a system that provided water to numerous water utilities from a wholesale water supplier. In addition to physical infrastructure-related internal dependencies, each infrastructure system depends on a number of other factors to sustain normal operations.

An example of infrastructure system interdependencies is shown in Figure 4-1 for emergency services. The example illustrates the dependencies that may exist between the services and buildings at the 'emergency services' level with the other infrastructure systems. Understanding of dependencies and potential cascading effects provides an informed basis for setting performance goals for community response and recovery.

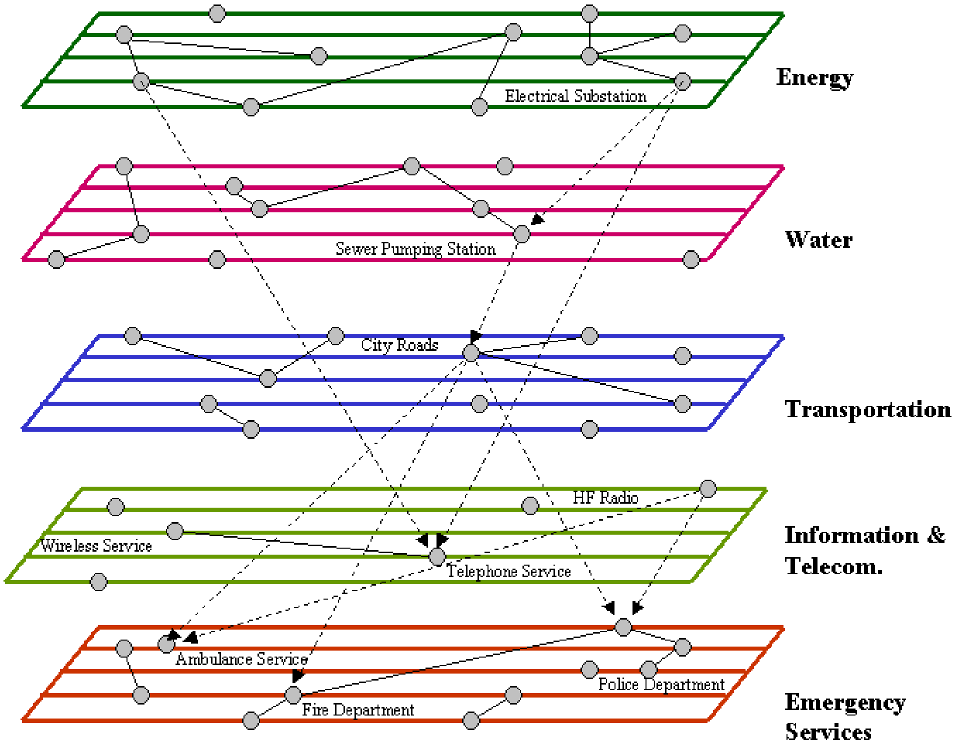

Figure 4-1. Example of Infrastructure Interdependencies for Emergency Services (Pederson et al 2006)

External Dependency

Infrastructure systems are typically dependent on other external systems for continued successful operation. The water pump described above is dependent on electrical power for operation; therefore, it is dependent on the energy system that is external to the water system. The pump may be able to operate for a short period with an emergency generator, but the generator would be dependent on refueling during an extended power outage. Refueling is in turn dependent on an available supply of fuel and a transportation system to deliver the fuel.

Figure 4-2 illustrates other examples of dependent relationship among infrastructure systems. These relationships can be characterized by multiple connections among infrastructure systems. The behavior of a given infrastructure system may be initially evaluated in isolation from other infrastructure systems, but community resilience planning requires understanding of the integraated performance of the physical infrastructure.

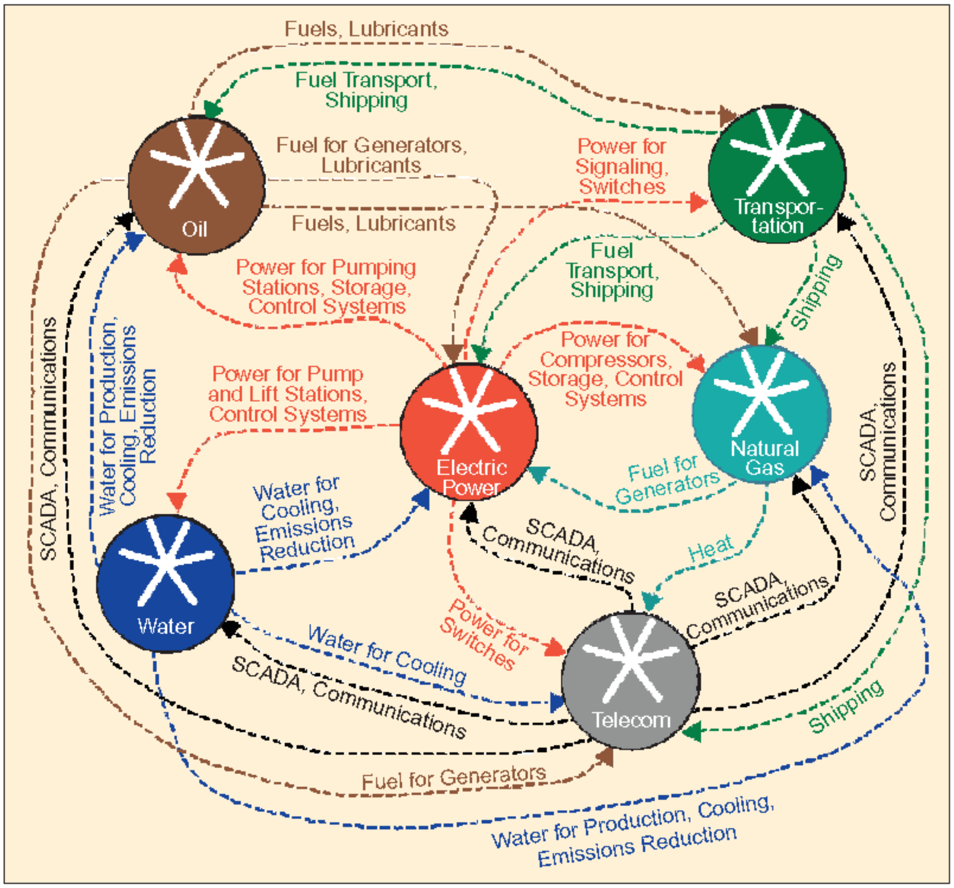

Figure 4-2. Example of External Dependency Relationship (Rinaldi et al 2001)

Cascading Failures

Internal dependency-related cascading failures can affect power transmission, computer networking, mechanical and structural systems, and communication systems. External dependency-related cascading failures can affect all buildings and systems. Figure 4-3 and Figure 4-4 illustrate how internal and external dependencies resulted in cascading failures in the 2003 Northeast Blackout. Failures in physical infrastructure can also have cascading impacts on social institutions. For example, prolonged loss of critical services following a disaster may drive small businesses to relocate or go out of business entirely.

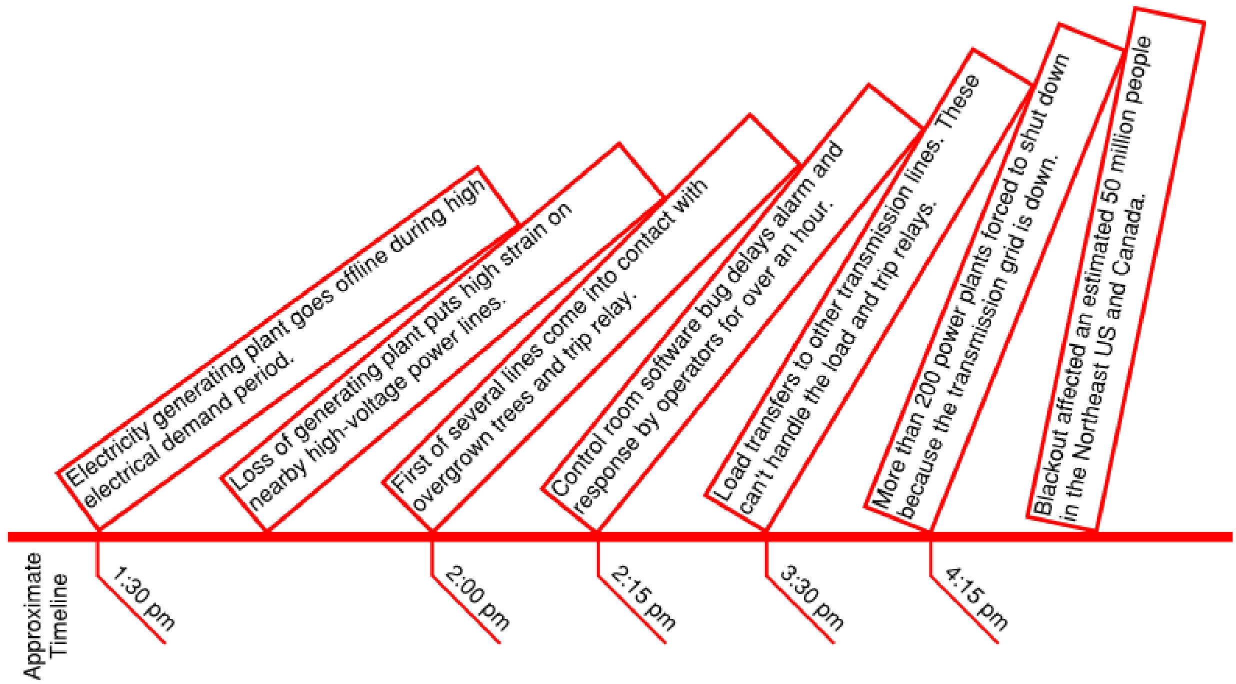

Figure 4-3: Power System Internal Dependence Cascading Failure in the 2003 Northeast Blackout

Figure 4-4: External Dependence Cascading Failure in the 2003 Northeast Blackout

4.2.2. Time Dependency

Recovery Phases

After a disaster, the time to restore critical services depends on how rapidly an infrastructure system and other systems required for its functioning can recover. Light-rail transportation systems, such as the Bay Area Rapid Transit (BART) system in the San Francisco Bay area, require electrical power for operation. No matter how resilient the light-rail infrastructure system, recovery of service depends on the restoration of electrical power.

There may also be operational dependencies that impact a utility provider's ability to perform repairs. Crews typically rely on the transportation network (roads and bridges) to access repair sites, liquid fuel for trucks and equipment, cellular phones for communication, availability of repair supplies through the supply chain, etc. Disruption in any one or a combination of these systems can increase delays in recovery of service.

The resilience framework defined in Chapter 3 organizes the community resilience plan around three phases of recovery using four categories of building clusters. The nature of the critical dependency issues is different for each of these phases. The first phase, focused on immediate response and labeled as "short-term", is expected to last for days and requires critical facilities and provisions for emergency housing. The second, intermediate recovery phase, is expected to last for weeks to months and includes restoration of housing and neighborhood-level services, such as schools. The third, the long-term recovery phase, focuses on full recovery of the community's economic and social base. Each phase has a unique set of dependencies, as is introduced below.

Short-Term Recovery Phase

During the short-term phase (days), the normal operation of infrastructure systems may be impaired. Individual system operators will activate their emergency response plans. Internal dependencies (such as staff, operations center, data, repair supplies, etc.) and key external dependencies (such as transportation) will be critical in defining the pace of the initial response. A well-defined governance process, between and among government emergency managers and system providers, will be essential to coordinate system restoration priorities that are best for the community, especially when the recommended restoration sequence might not be optimal for an individual system provider. A report by the City and County of San Francisco Lifelines Council indicated that a top planning and preparedness priority for system providers is to develop communication and employ priority decision-making strategies to aid in post-disaster response (CCSF Lifelines Council 2014).

Critical facilities, as defined in Chapter 3, are a small number of building clusters and supporting infrastructure systems that need to be functional immediately after an event to organize and direct the emergency response and provide a safe environment for emergency responders. During this early phase, the degree of dependence on other infrastructure systems depends on their ability to operate with emergency power, an independent communication network, and possibly onsite housing and subsistence for the staff. Critical transportation routes need to be established prior to the event and made a high priority in post-event cleanup and debris removal. Critical routes enable replenishment of onsite supplies including fuel, water, food, medical supplies, etc. Performance goals for recovery need to represent an appropriate balance between having the needed supplies on hand to operate independently for a short period and defining achievable restoration times.

For example, the stored water at some hospitals can only supply drinking water for three to four days. This supply may only represent about 5% of the total water usage, whereby some hospitals' total water usage may exceed 300,000 gal/day. Many hospitals do not currently have onsite storage capacity for wastewater and have limited storage capacity for medical waste. These dependencies would likely impair hospital functionality after a hazard event. In California, the Office of Statewide Health Planning and Development is implementing requirements to provide three days of an operational supply of water (including water for drinking, food preparation, sterilization, HVAC cooling towers, etc.), wastewater storage, and fuel for emergency generators (CBC 2013).

The timing of a disaster may also impact the resources available for response. Availability of hospital beds is often seasonally dependent. During the winter respiratory season, many hospitals operate at or near capacity, limiting the number of patient beds available for disaster response (even after discharge of less critical patients and canceling elective procedures).

The need for temporary housing for emergency responders and displaced individuals and animals, as discussed in Chapter 2, is often met by using schools, shelters, hotels, conference centers, residences that are safe to shelter-in-place, etc.. Food, water, security, and sanitation needed to protect public health are usually provided at centralized locations. During the short-term recovery phase, there is a limited need for transportation, power, and communication. For example, current thinking for earthquake resilience says that it is best for residents to shelter in their homes, neighborhoods, or within their community. Recovery performance goals should consider such options.

The inability to provide sufficient temporary housing can lead to a mass exodus from the community that could cascade into a loss of residents and ability to restore the economic base of the community. Performance goals need to realistically estimate the number of displaced residents and emergency responders that need to be accommodated, and the availability of adequate facilities within or adjacent to the community.

Intermediate Recovery Phase

In the intermediate recovery phase (weeks), the dependency focus is expected to shift more to external dependencies (electricity, liquid fuel, transportation, etc.) along with key internal dependencies (funding for payroll and repair supplies, contractors, etc.).

Restoring fully-functional neighborhoods is key to maintaining the workforce needed to restore the economic vitality of the community after a hazard event. During this period, special attention must be paid to the needs of the disadvantaged and at-risk populations who require a higher level of assistance. Functioning residences, schools, and businesses are needed rapidly enough to give the population confidence to stay and help to support community recovery. If people are unable to shelter in their neighborhoods, the small neighborhood businesses they depend on will likely lose their client base and have to be relocated or close. This, in turn, may cascade into delays for recovering the community's economy.

The needs of commercial services, such as banking, are critical to recovery of a community. If the primary economic engine of a region is based on a manufacturing plant that requires water, wastewater, and power operating within two weeks after an expected hazard, then the intermediate recovery phase must address these dependent systems. The intermediate recovery plans should consider other factors, such as for parents to return to their jobs, schools and daycare facilities will need to be back in operation.

The condition of the built environment that supports residences, neighborhoods, and businesses is one key factor that determines recovery time. Significant structural damage to buildings and infrastructure systems cannot be repaired within a few weeks; it takes months or longer, depending on the damage. Buildings need to be safe to use while being repaired for minor damage or temporary facilities will need to be provided, especially for damaged residences. The transportation, energy, water, wastewater, and communication systems that support these facilities need to be restored within the same timeframe.

Long-Term Recovery Phase

In the long-term recovery phase (months), it is anticipated that utility services will be restored (at least with temporary fixes). If a community is in the early stages of developing its resilience, the recovery time may take longer due to needed repairs or rebuilding. As a community develops a 'mature' resilience, a similar event should cause less damage and have shorter, less costly recovery times. The key dependencies at this point are related to supplies, equipment, and resource availability for repairs and reconstruction.

Restoring a community after a major event will provide a significant, short-term stimulus to the economy from the accelerated construction activity and provide an opportunity to improve the built environment according to a community's resilience plan, financed by government, insurance companies, large businesses, private savings and developers. In order for the recovery process to successfully improve community resilience, a governance structure needs to be in place that approves reconstruction rapidly and in accordance with the community's interests. Any stall or stalemate in the decision-making process will delay the construction activities needed to restart the economy.

It is important that communities develop a plan before a disaster on how to manage the logistics of recovery. For example, logistics include an expedited building permit process and adequate resources for building inspections during a post-disaster construction boom. They also include land use planning decisions that will guide rebuilding. If the process is delayed, then people and businesses may move out of the region and the opportunity to build back a better, more resilient community is lost. The Oregon Resilience Plan indicated that businesses are only able to accommodate approximately two to four weeks of business interruption before they would need to relocate or go out of business. This is particularly troubling to a state like Oregon where a large portion of the economy relies on small businesses and where the current expected level of resilience for a Cascadia Subduction Zone earthquake does not meet this four-week time window. Japan experienced small business losses because of delayed decisions in land use planning to rebuild in the tsunami-impacted region after the 2011 Tohoku earthquake (Mochizuki 2014).

4.2.3. Space Dependency

Disaster Impact Region

Different types of disasters result in variation in the geographic area of impact. Hurricanes or a Cascadia Subduction Zone earthquake may impact a large multi-state region, while tornados may only impact a portion of a community. Communities need to consider the potential geographic area of impact for their expected hazards as part of the planning process. The Oregon Resilience Plan (OSSPAC 2013) was developed for a scenario Cascadia Subduction Zone earthquake that would likely impact a region including Northern California, Oregon, Washington, and British Columbia. The plan discusses a strategy where the central and eastern portions of the state would provide assistance to the Willamette Valley/I-5 Corridor region (area including the state's largest population centers) and then the Willamette Valley/I-5 Corridor would provide assistance to the coastal region. Other mutual aid assistance would likely be mobilized from Idaho, Montana, and other adjacent states. This is in contrast to a Midwest tornado, which may cause significant devastation to a particular community, but assistance in response and recovery is available from the surrounding communities.

Location of Critical Infrastructure

The physical location of infrastructure within a community impacts how it is expected to perform in a disaster. For example, wastewater treatment plants are often located close to rivers or the ocean for system operation reasons, but this makes them particularly vulnerable to flooding, sea level rise, and tsunami hazards. In the resilience planning process, communities need to consider how the expected hazard and location of existing infrastructure impacts expected system performance. Communities should also adopt land use planning policies that consider the dependence between physical location and system performance, when evaluating upgrades to existing facilities, construction of new infrastructure, and rebuilding after a disaster.

Co-location

Infrastructure systems are often co-located along transportation or other utility corridors. The close proximity of these different systems can lead to unintended damage to these co-located systems. Infrastructure system pipelines and conduits are often co-located on bridges at river or other crossings and can be significantly impacted by earthquake and inundation (flood and tsunami) hazards. Figure 4-5 shows an example of where bridge support settlement during the 2011 Christchurch New Zealand earthquake caused a sewer pipeline, supported by the bridge, to break and spill raw sewage into the river below. Telecommunications wires are often supported by electrical power poles, so if the pole breaks, both systems are impacted. Water and wastewater pipelines are often co-located near other buried infrastructure under or adjacent to roadways. Failure of pipelines may result in damage to the roadway (i.e. sinkhole from water main break or collapsed sewer pipeline) and impacts to traffic when repairs are being made. Co-located infrastructure not only results in potential damage to multiple systems, but also often requires significantly more coordination between service providers during repair.

Figure 4-5: Example of Infrastructure Co-location (Source: Eidinger & Tang, 2014)

4.2.4. Source Dependency

Communities depend on goods and services that may or may not be available locally. Disasters that impact the source of these goods and services can have far-reaching downstream impacts.

In the Pacific Northwest, Oregon is dependent on refineries in the State of Washington for a supply of liquid fuel. A Cascadia Subduction Zone earthquake would likely disrupt refinery operation and limit available liquid fuel supplies in Washington and Oregon. Similarly, a Gulf Coast hurricane could damage offshore drilling platforms and oil refinery facilities, disrupting the liquid fuel supply for the hurricane-impacted region and larger portions of the US.

Regional utility systems provide another example of source dependency. The Tennessee Valley Authority (TVA) supplies power to over 150 municipal utility companies and several large industrial users in Alabama, Kentucky, Mississippi, and Tennessee. A disaster, such as an ice storm, impacting one or more TVA power generation facilities or transmission lines, has the potential to disrupt electricity over a large geographic area.

A disaster, such as a wildfire, can impact the drinking water supply due to high post-fire sediment loads. These sediment loads can cause damage to reservoirs and treatment plants that result in higher treatment costs to remove suspended solids from drinking water. The impact of sediment is highest in the burned area, but data from the Southern California wildfires in the fall of 2003 indicated increased sediment loads at treatment plants up to 100 miles from the fire (Meixner and Wohlgemuth 2004).

4.3. Planning for Infrastructure System Dependencies

As part of the community resilience planning process, utility providers, businesses, and others should be encouraged to refresh or develop their own emergency and continuity of operations plans and identify internal dependencies. As organizations are conducting internal resilience planning activities, they should also compile a list of external dependencies and they impact their operations. After each infrastructure system identifies their external dependencies, the next step is to engage all infrastructure systems along with community and business leaders to discuss the current expected performance of infrastructure for the range of disasters expected, external dependencies, and expected service restoration times for each infrastructure system.

It is critical that all stakeholders are in these discussions, including elected officials, emergency managers, first responders, service providers, business leaders, civic organizations, and disaster services organizations, etc. For discussion of external dependencies, the definition of community might need to be broadened, as utilities often serve a larger area than just one local population.

Understanding the dependencies within and between physical infrastructure systems is a new and developing area of planning related to resilience and recovery from significant disruptions. However, there is an immediate need for a process to identify the interdependencies for a resilience framework and an empirical method based on historical data seems to be the most achievable at this point. Such a method was used by the City and County of San Francisco Lifelines Council in 2013 and it can be applied to other communities. San Francisco reported their findings and recommendations in February 2014 (CCSF Lifelines Council 2014). Their process followed these steps:

1. Form a service provider council of private and public infrastructure owners and provide a quarterly forum for them to meet, share current planning activities, and discuss response and recovery issues, their interdependencies, and methods to improve the existing conditions.
2. For the extreme level of all prevailing hazards, characterize the expected level of damage in terms related to infrastructure system performance from the view of the infrastructure provider. Figure 4-6 illustrates the restoration times estimated by the providers in the San Francisco study.
3. For each infrastructure system, document the planned response and restoration process, likely dependencies on other systems, and the understanding of other system dependencies on them.
4. Process the information and determine overall interactions between systems and the related dependencies. Identify areas with potential for cascading effects, occurrences of co-location, overlaps, and hindrances related to restoration and recovery plans. Table 4-1 illustrates the dependencies identified in the San Francisco Study.
5. Develop a series of recommendations related to the next steps needed to better define the needs, advance collaborative planning where needed, prioritize the needed mitigation projects and identify funding sources for pre- and post-event needs.

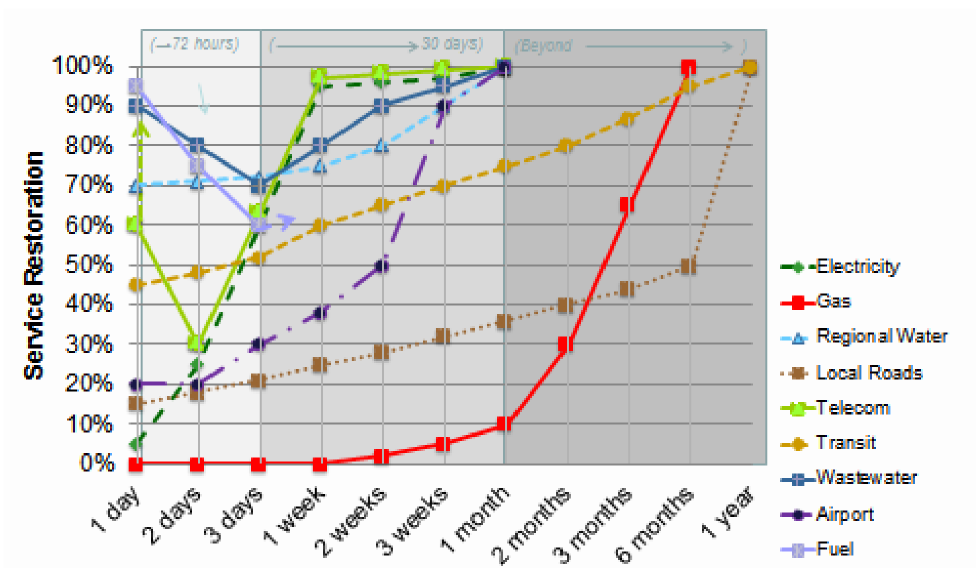

Figure 4-6: Potential Service Restoration Timeframes following a Scenario M 7.9 Earthquake on the San Andreas Fault. (CCSF Lifelines Council, 2014)

Table 4-1: Infrastructure System Dependencies following a scenario M7.9 earthquake on the San Andreas Fault. (CCSF Lifelines Council, 2014)

The overall interaction and dependency on a particular system (read down each column)

Infrastructure System Operators' dependency on other Infrastructure systems (read across each row)

	Regional Roads	City Streets	Electric Power	Natural Gas	Telecom	Water	Auxiliary Water	Waste-Water	Transit	Port	Airport	Fuel
Regional Roads	General	Restoration Substitute	Restoration	Restoration	Restoration	Restoration		Restoration	Substitute		Restoration	Restoration
City Streets	Substitute Restoration	General	Co-location, Restoration	Co-location, Restoration	Co-location, Restoration	Co-location, Restoration	Co-location, Restoration	Co-location, Restoration	Co-location, Restoration	Co-location, Restoration		Restoration
Electric Power	Restoration	Co-location, Restoration	General		Restoration	Co-location, Restoration	Co-location, Restoration	Co-location, Restoration		Co-location	Restoration	Restoration
Natural Gas	Restoration	Functional, Co-location, Restoration	Substitute	General	Restoration	Co-location, Restoration	Co-location, Restoration	Co-location, Restoration		Co-location	Restoration	Restoration
Telecom	Restoration	Co-location, Restoration	Functional, Restoration	Restoration	General	Co-location, Restoration	Co-location, Restoration	Co-location, Restoration			Restoration	Restoration
Water	Restoration	Restoration	Restoration		Restoration	General				Co-location		Restoration
Auxiliary Water	Restoration	Functional, Restoration	Restoration		Restoration	Functional, Restoration	General			Co-location, Restoration		Restoration
Waste-Water	Restoration	Co-location, Restoration	Functional, Restoration		Restoration	Functional, Restoration		General		Co-location, Restoration		Restoration
Transit	Substitute, Restoration	Functional, Substitute, Co-location, Restoration	Functional, Restoration		Restoration	Co-location, Restoration	Co-location, Restoration	Co-location, Restoration	Co-location, General	Co-location, Restoration		Functional, Restoration
Port	Restoration	Co-location, Restoration	Co-location, Restoration		Co-location, Restoration	Co-location, Restoration	Co-location	Co-location	Co-location	General		Restoration
Airport	Restoration		Restoration		Restoration	Restoration		Restoration	Co-location, Restoration		General	Functional, Restoration
Fuel	Restoration	Restoration	Functional, Restoration		Restoration	Restoration				Restoration	Restoration	General

Legend:

- (Yellow) Significant interaction and dependency on this infrastructure system for service delivery and restoration efforts
- (Green) Moderate interaction and dependency on this infrastructure system for service delivery and restoration efforts
- (Blue) Limited interaction and dependency on this infrastructure system for service delivery and restoration efforts

Key to terms used in the matrix:

Functional disaster propagation and cascading interactions from one system to another due to interdependence

Co-location interaction, physical disaster propagation among infrastructure systems

Restoration interaction, various hindrances in the restoration and recovery stages

Substitute interaction, one system's disruption influences dependencies on alternative systems

General interaction between components of the same system. (All systems would have general interaction issues, but some issues are more crucial for the system's potential disruption and restoration.)

Figure 4-7 shows a map of Portland, Oregon with a GIS overlay of infrastructure systems that are contained in the Earthquake Response Appendix to the City's Basic Emergency Operations Plan (City of Portland 2012). The city used this information to coordinate the potential spatial dependencies of the city's infrastructure. Eventually these tools may include systems modeling functionality that could enable scenario-based assessment of infrastructure system depencencies or be used as a tool to prioritize post-disaster infrastructure repairs and optomize restoration of all infrastructure systems.

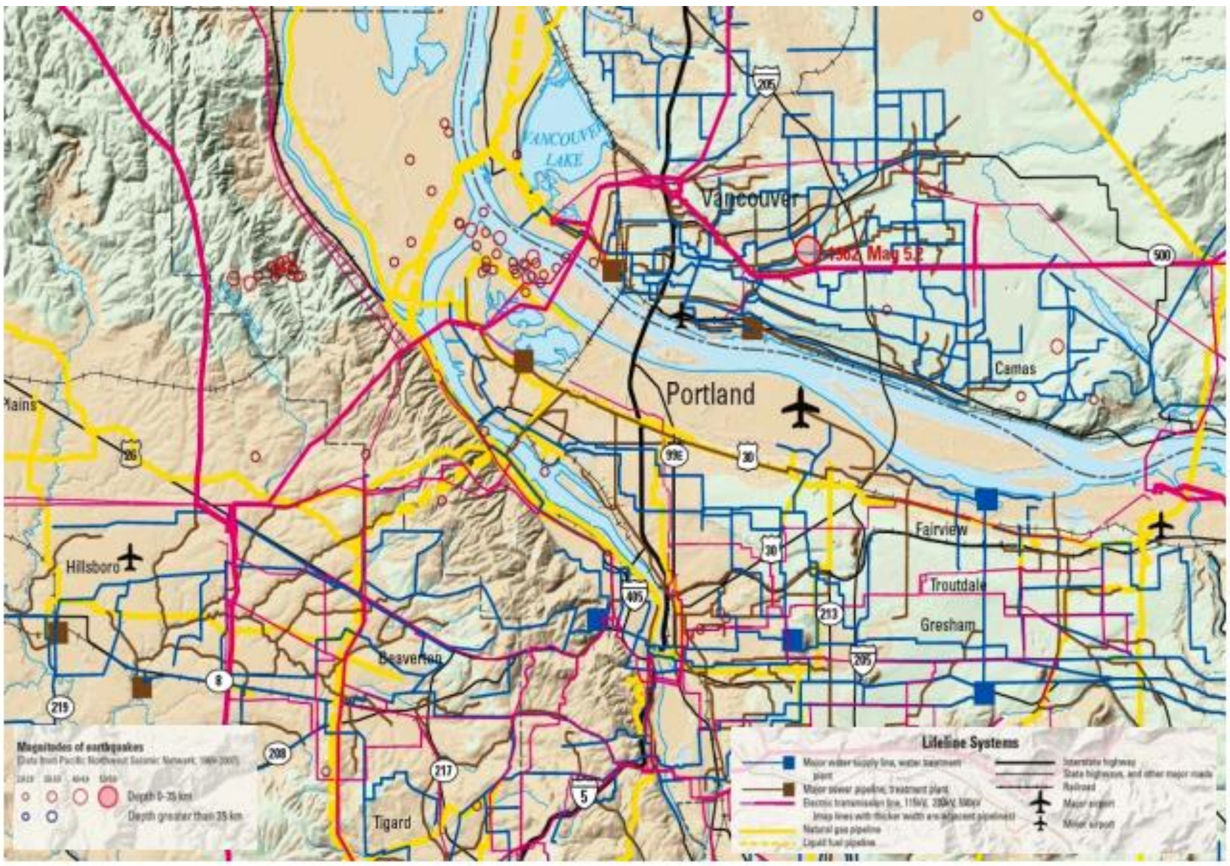

Figure 4-7: GIS Map of Infrastructure Systems around Portland, Oregon (City of Portland, 2012)

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