Resilience of Integrated Power and Water Systems

by Masanubu Shinozuka, Stepahanie E. Chang, Tsen-Chung Cheng, Maria Feng, Thomas D. O'Rourke, M. Ala Saadeghvaziri, Xuejiang Dong, Xianhe Jin, Yu Wang, and Peixin Shi

Research Objectives

The primary objective of this study is to develop an analysis procedure and a database to evaluate the performance of electric power and water supply systems before and after a major catastrophic event, such as an earthquake, an accidental or manmade disablement of system components. Furthermore, the procedure and database can be incorporated as an integral part of the overarching framework of MCEER's methodology that can be used to enhance the seismic resilience of communities. Based on our experience in the analysis of the seismic performance of the Los Angeles Department of Water and Power (LADWP) system after the Northridge earthquake, we believe that we have derived a useful set of data and gained significant knowledge on the system's robustness during and after a catastrophic event. In this context, the present study adds new foci on modeling the restoration process after earthquakes and integrates the performance of water and power systems using LADWP's systems as a testbed. This study is believed to advance the state-of-the-art on evaluating the seismic resilience of communities.

In this study, the performance analysis of LADWP's power system is presented first, emphasizing newly developed system resilience analysis. Next, an integrative analysis between power and water systems is presented, focusing on their interaction through the process of restoration.

Electric power is essential for virtually every urban and economic function. Failures of electric power networks and grids – whether from natural disaster, technological accident, or man-made disaster such as terrorist attack – can cause severe and widespread societal and economic disruption. In the 1994 Northridge earthquake that struck Los Angeles, some 2.5 million customers lost electric power. For the first time in its history, the entire city of Los Angeles was blacked out. Power outages were experienced in many areas of the western U.S. outside the earthquake region and as far away as Canada (Hall, 1995). On August 14, 2003, a blackout of unprecedented proportions rippled out from Akron, Ohio, across the northeastern U.S. and parts of Canada, affecting an area with a population of some 50 million (U.S.-Canada Power System Outage Task Force, 2003). In September of

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Previous Summaries

2001-2003:
Shinozuka et al.,
http://mceer.buffalo.edu/publications/resaccom/0103/01shinozuka.pdf

2000-2001:
Saadeghvaziri et al.,
http://mceer.buffalo.edu/publications/resaccom/0001/rpa_pdfs/04Saad2.pdf

1997-1999:
Shinozuka et al.,
http://mceer.buffalo.edu/publications/resaccom/9799/Ch7shino.pdf

2003, a power outage that began in Switzerland cascaded over a large region of Italy. Examples such as these indicate the importance of being able to anticipate potential power system failures and identify effective mitigation strategies.

Modeling the impacts of electric power disruption is, however, a highly complex problem. Many of the inherent challenges relate to the need to integrate across disciplines – not only civil, mechanical, and electrical engineering, but also economics and other social science disciplines. For example, one must assess how damage to individual pieces of electric power equipment affects power flow across the network. One must model how a damaged network would be repaired and how electric power would be restored over space and time. Additionally, one must capture how the loss of electric power would affect households, businesses, and other units of society, not only directly but also indirectly through the cascading failure of other utilities, typically water systems.

The LADWP's power system was used as a test-bed in this research. Figures 1 and 2 show LADWP's electric power service areas and the power supply at a typical time of peak demand. The areas not colored are serviced by Southern California Edison (SCE). Figures 3a-d show the distribution of residential population, daytime population, households and hospitals over LADWP's service areas, which is the data that will be used in the ensuing analysis. To study the seismic resilience of power systems, the fragility curves for electrical power equipment, such as transformers, circuit breakers, disconnect switches and buses in the transmission network, play a significant role and were developed on the basis of damage information from the 1994 Northridge earthquake. The present analysis also uses fragility information obtained from an inventory survey and analytical/laboratory studies performed by MCEER researchers. The seismic performance analysis of LADWP's power system was then carried out under actual and simulated earthquakes, using a net-

Perceived and actual users of the results from this research include utility engineers and managers, regulatory agencies, local, state, and regional emergency response agencies, civil, electrical, mechanical and systems engineers, and power equipment manufacturers. Typically, users include LADWP (Los Angeles Department of Water and Power) and SCE (Southern California Edison), California State Office of Emergency Services and Los Angeles City Office of Emergency Response.

work inventory database, available fragility information, and Monte Carlo simulation techniques. This is a unique research work in which the Western Electricity Coordinating Council's (WECC's) database is used for the systems analysis, in conjunction with the computer code IPFLOW (version 5.2b), licensed by the Electric Power Research Institute (EPRI).

To gain more complete understanding of the performance of LADWP's power system under the possible seismic scenarios in the study area, 47 scenario earthquake events (*http://shino8.eng.uci.edu/Secnario_Earthquakes/47Scenario.pdf*) were selected and corresponding peak ground acceleration (PGA) maps were generated. By including each scenario's associated annual "equivalent probabilities" of occurrence, they represent the full range of regional seismic hazard curves (Chang et al., 2000). Based on the power analysis results from these 47 events, the risk curves for system performance degradation, for example, reduction of power supply, households without power and reduction in GRP (Gross Regional Product) immediately after an earthquake in LADWP's service areas were developed.

A repair and restoration model was also developed, calibrating with the Northridge restoration data, to evaluate the restoration process of the power systems. The system restoration process was then simulated accounting for restoration of disabled transmission equipment, and restoration curves were developed.

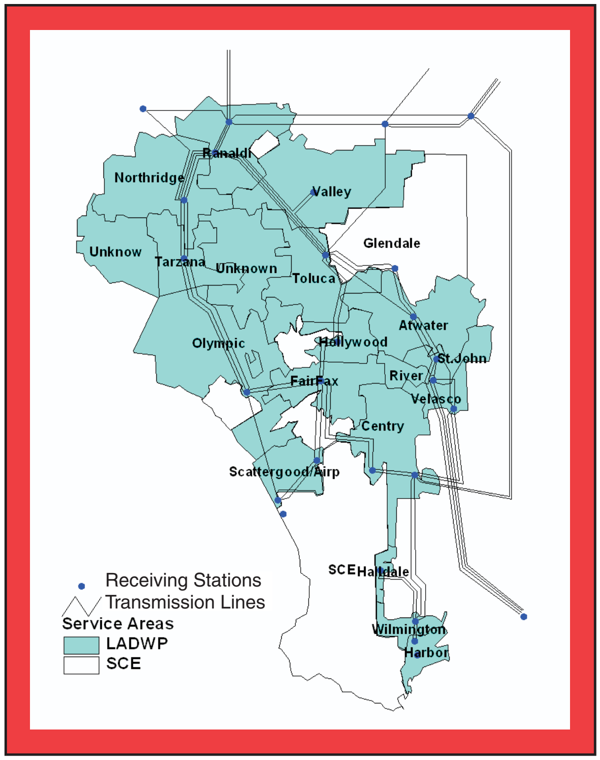


Figure 1. Transmission Network and Service Areas of LADWP's Power System

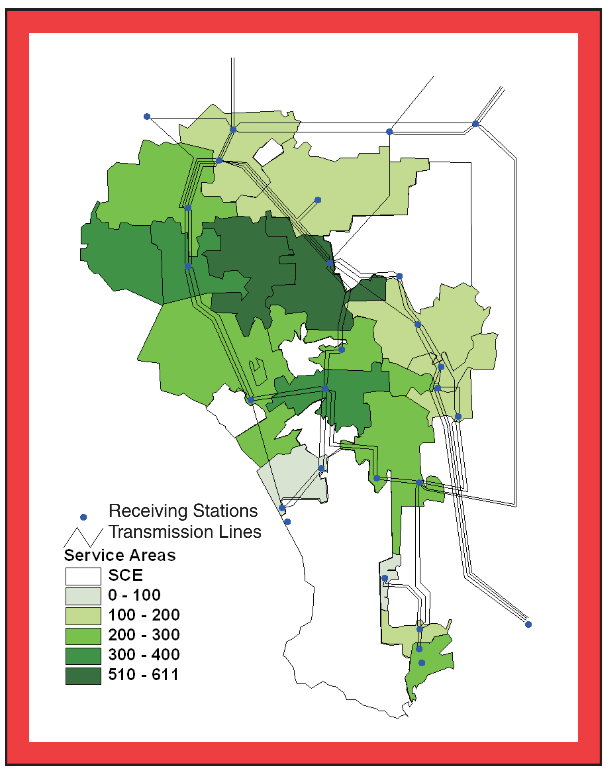
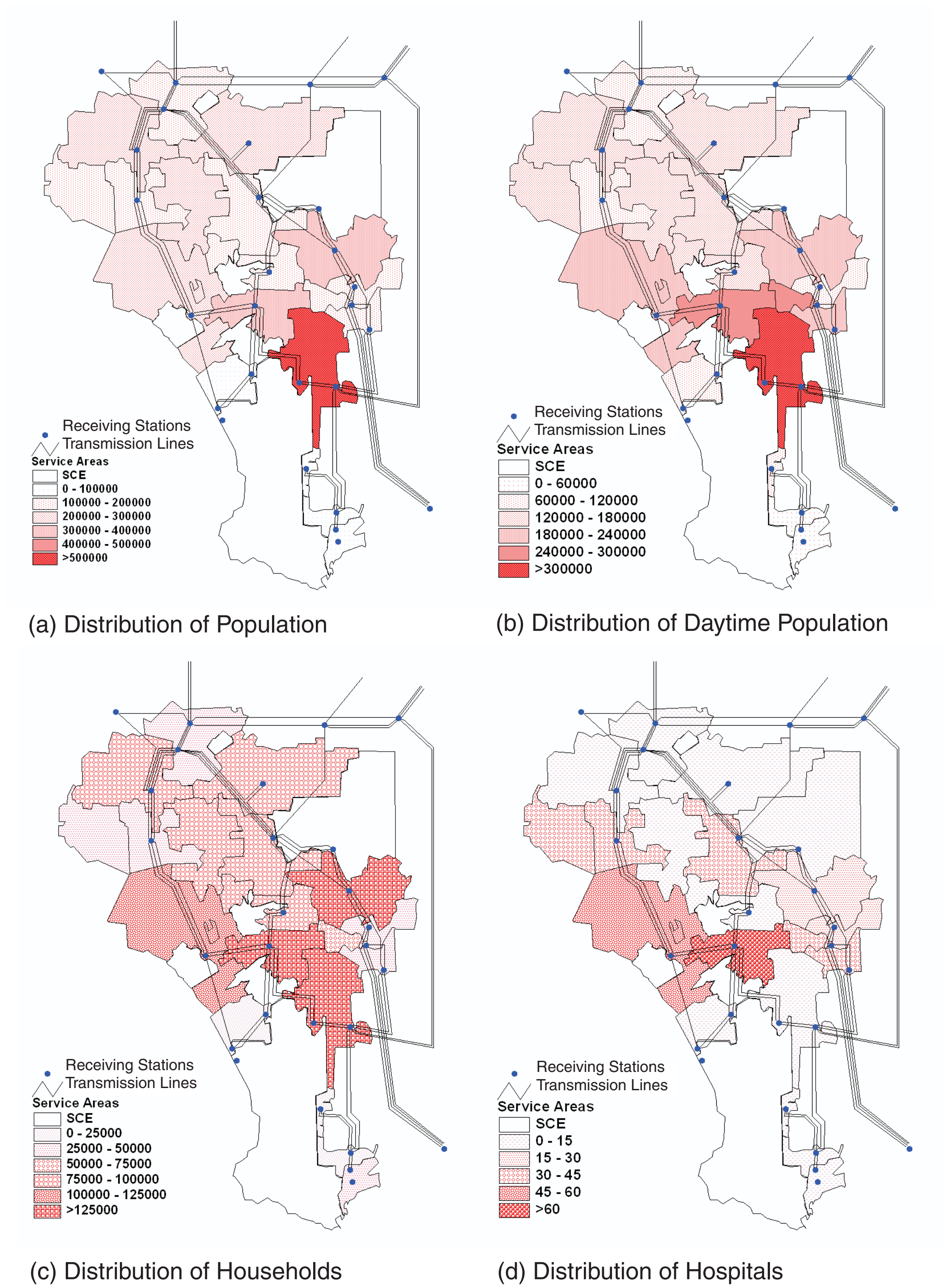


Figure 2. Electric Power Output for LADWP's Service Areas Under Intact Condition



■ Figure 3. Key Customers Distribution Data

Seismic Performance of LADWP's Power System

Collaborative Partners

Jon Mochizuki *and* ***Ron Tognazzini****, Los Angeles Department of Water and Power*

Nobuo Murota*, Bridgestone, Japan*

Scenario Earthquakes

For electric power and other urban infrastructure systems, evaluating potential impacts of damage is complicated by the fact that the networks are spatially distributed across a wide area. Risk analysis must account for how the system performs given that the hazard (e.g., earthquake ground motion) is not only spatially variant across a wide area but also, for any given disaster, spatially correlated. Hence, traditional probabilistic methods that can readily be applied for site-specific facilities such as individual buildings cannot be used for these spatially distributed networks.

The current study therefore analyzes system functionality and impacts in the context of scenarios of individual earthquake events, then combines the scenario results probabilistically to gain a complete understanding of the seismic performance of LADWP's power system. In total, 47 scenario earthquakes for the Los Angeles region were selected and simulated, as discussed later in detail. These scenarios were developed by Chang et al., 2000, applying a loss estimation software tool, EPEDAT, based on K. Campbell's attenuation law (Campbell and Bozorgnia, 1994), which was used to generate regional ground motion patterns for a given earthquake epicenter, magnitude, and depth (USC-EPEDAT, 1999). The 47 events include 13 maximum credible earthquakes (MCEs) on various faults in the Los Angeles region and 34 other events of magnitude 6.0 or higher. These scenario earthquakes are associated with annual "equivalent probabilities" of occurrence so that collectively, they represent the full range of the regional seismic hazard (Chang et al., 2000).

Transmission Systems

A utility power system consists of generating stations, transmission systems and distribution network. The present study focuses on transmission systems including receiving stations. Throughout the analysis, it is assumed that the transmission lines will not fail under seismic conditions. This assumption is generally acceptable for LADWP's system and allows one to concentrate on the receiving stations. There are many electric/mechanical components in receiving stations, such as transformers, circuit breakers, disconnect switches, lightening arresters, current transformers, coupling voltage transformers, potential transformer, wave trap and circuit switches. These components are integrated to transmission lines through buses at nodes. Transmission lines then serve as links between generating stations and distribution systems and lead to other power systems. In general, if the voltage between two buses is different, then there must be at least one transformer between them. Figure 4 models receiving stations and nodes. Fig. 4a is a model of a receiving station with four nodes, while Figure 4b depicts a node at which four

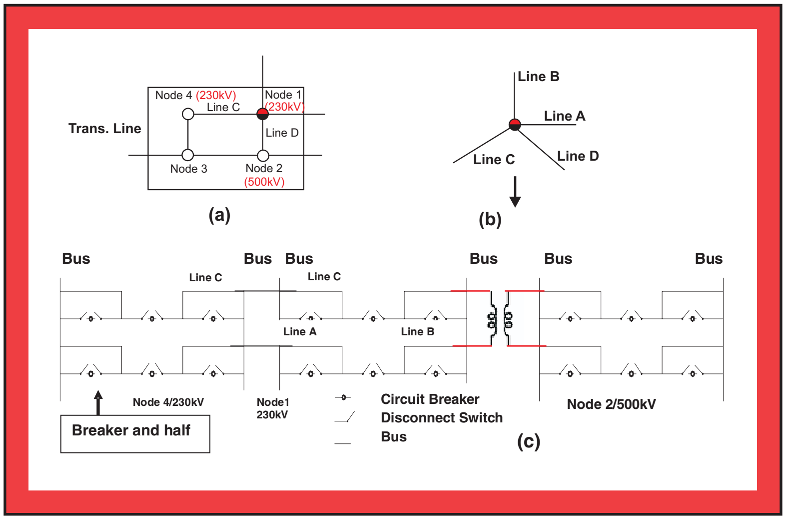


Figure 4. Models for Receiving Station and Node

transmission lines are connected. A node facilitates movement of electric power protected by buses, circuit breakers and disconnect switches. A node's configuration is complex and designed to be redundant to minimize the chance that the transmission lines become disconnected from the power network. A popular node configuration is shown in Figure 4c, which is known as a "breaker and half" model. This model is used in the present analysis.

Seismic Performance of Power System

LADWP's network is part of the large WECC power grid, covering 14 western states in the U.S., two Canadian provinces and northern Baja California in Mexico. The present analysis considers 52 receiving stations (some in LADWP and others in SCE power systems) within the WECC network (see *http://www.wecc.biz/main.html*). They are subjected to significant ground motion intensity under some of the 47 scenario earthquakes and consequential to LADPW's system damage. Using an ArcGIS platform, the map of 52 receiving stations in Figure 5 is overlaid on the map of peak ground acceleration (PGA) from the 1994 Northridge earthquake as shown in Figure 6(a) to identify the PGA value at the location of each receiving station. The fragility curves provided in Figure 7 were then used to simulate the damage state for transformers at each of the 52 receiving stations. Note that three fragility curves (labeled Case 1, 2 and 3) are given in Figure 7, where the Case 1 curve is obtained empirically from the Northridge earthquake damage data, Case 2 curve represents improvement of the Case 1 curve by 50% (in terms of median value) and Case 3 curve by 100%. These improvements are deemed possible on the basis of analytical and experimental studies by Feng and Saadeghvaziri (2001) and Dong

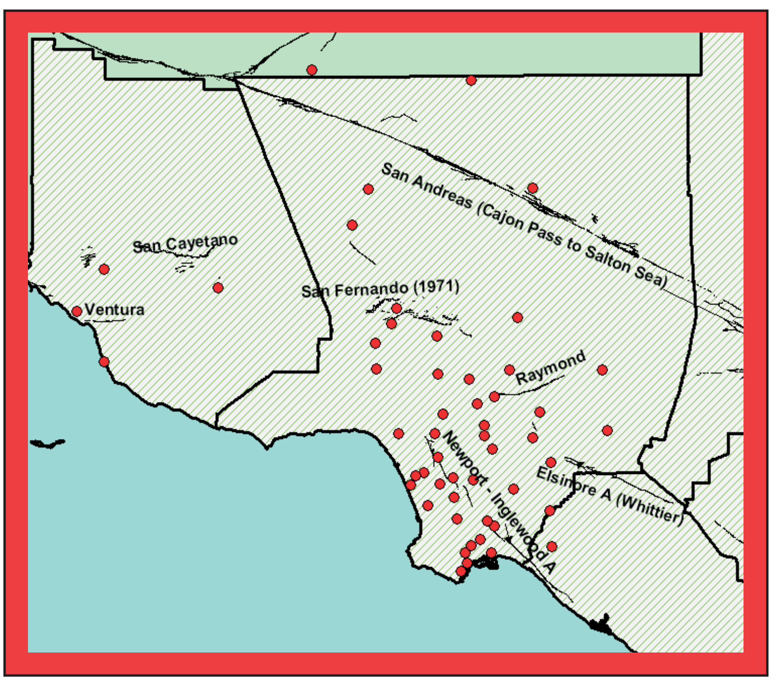
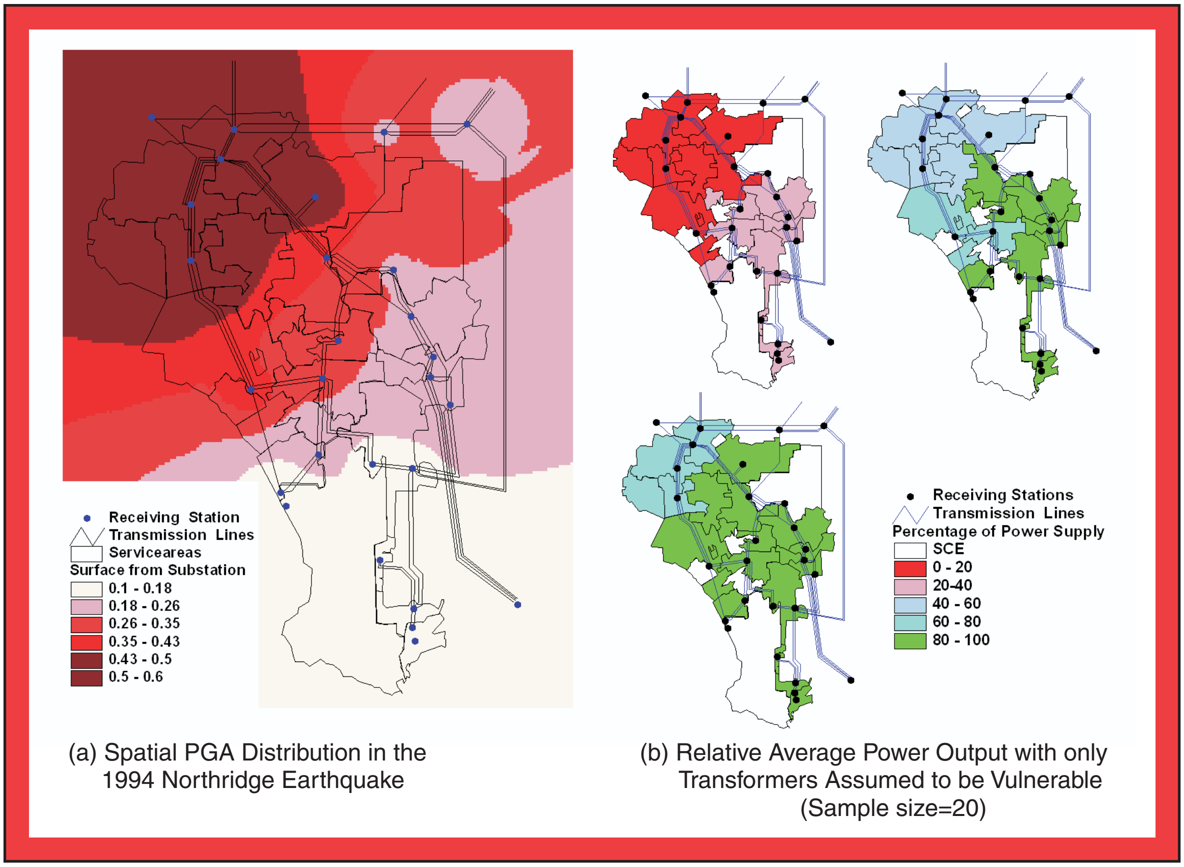


Figure 5. Locations of Earthquake Faults and 52 Receiving Stations

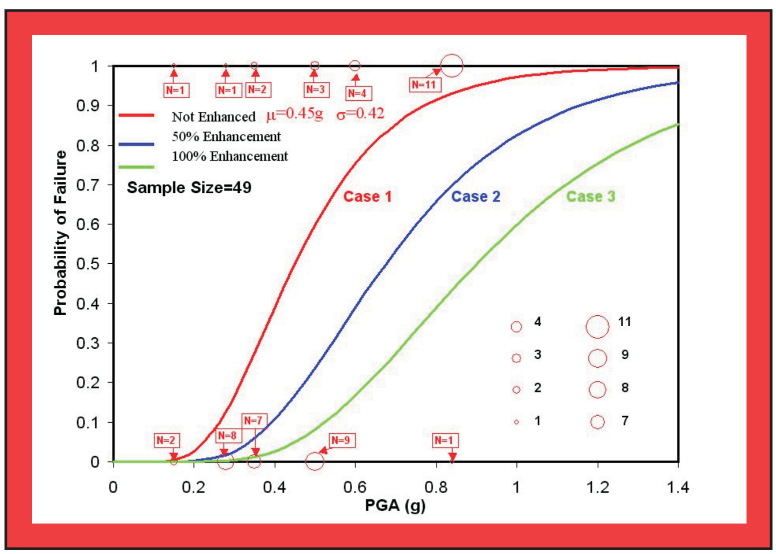


■ Figure 6. (a) Spatial PGA Distribution in the 1994 Northridge Earthquake and (b) Relative Average Power Output with only Transformers Assumed to be Vulnerable (Sample size=20)

(2002). For each system analysis, connectivity and power flow were examined with the aid of IPFLOW, where LADWP's power system was treated as part of the overall WECC system.

The analysis procedure for the seismic performance of the electric power network is described in the following steps and is also depicted in the flowchart in Figure 8. The entire process is tightly integrated with a GIS database involved in the analysis.

- For each of the 47 scenario earthquakes described earlier, spatial distribution of PGA is generated using the appropriate attenuation law.
- For each scenario earthquake, by Monte Carlo techniques,



■ Figure 7. Fragility Curves for Transformers With and Without Enhancement

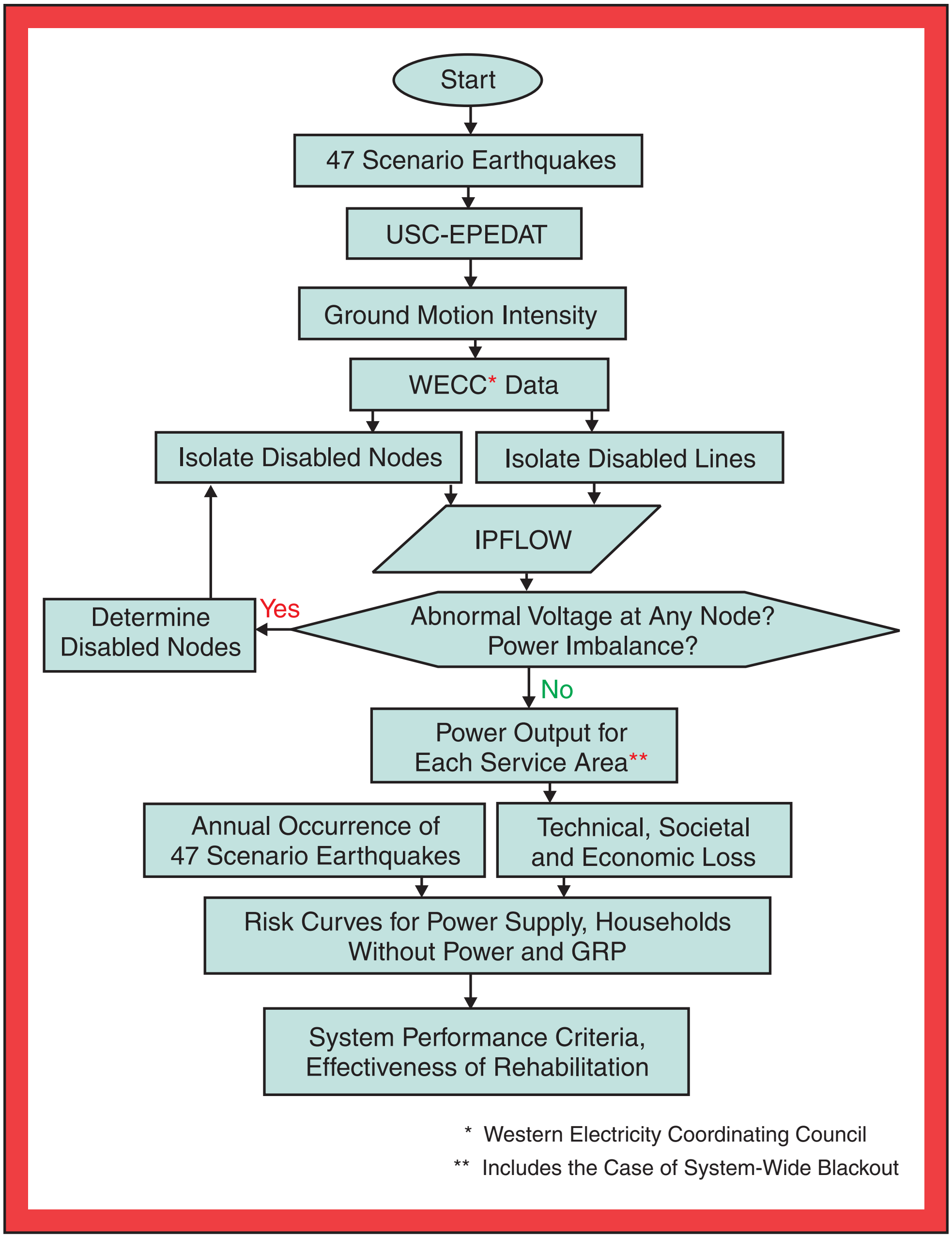


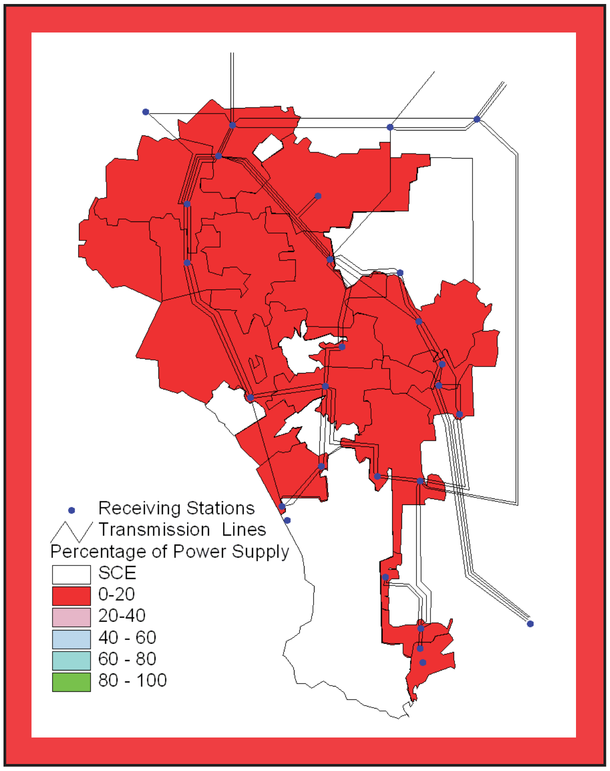
Figure 8. Flowchart for GIS-based Power Performance Analysis

the state of equipment damage is simulated using fragility curves for transformers with and without rehabilitation.

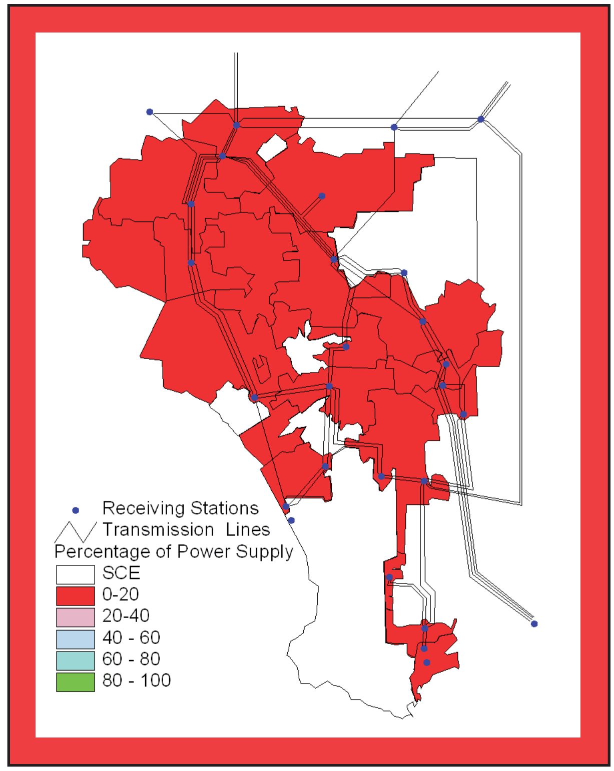
- The state of damage to the transmission network is simulated under each scenario earthquake.
- The power flow is calculated using the IPFLOW code, taking into consideration the following network failure criteria:

1. Imbalance of power: supply/demand ratio outside the range

$$1.05 \leq \frac{total\ supply}{total\ demand} \leq 1.1 \quad (1)$$



■ Figure 9. Relative Average Power Output with Transformers and Circuit Breakers Vulnerable



■ Figure 10. Relative Average Power Output with Transformers and Disconnect Switches Vulnerable

2. Abnormal voltage

$$\left|\frac{V_{intact} - V_{damaged}}{V_{intact}}\right| > 0.1 \qquad (2)$$

3. Frequency change (IPFLOW does not check this criteria)
4. Loss of connectivity

- The seismic performance of the power network is computed, e.g., in terms of percentage of power supply and households with power after the earthquake. This is done for the entire area of service as well as for each service area under each scenario earthquake. The percentage is relative to the performance under the intact system condition.
- A seismic risk curve is developed (which plots the annual probability that system performance will be reduced more than a specified level due to earthquake as a function of that level).
- System performance is examined relative to performance criteria, with and without rehabilitation (of transformers in this study).
- Effectiveness of rehabilitation is determined.
- In combination with regional economical analysis, risk curves are developed for the loss of Gross Regional Product (GRP).

Using Monte Carlo simulation techniques involving the fragility curves, the power flow analysis is performed 20 times under each scenario earthquake. Each simulation result represents a unique state of network damage. Figure

Links to Current Research

This study develops an analysis procedure that can be used to evaluate seismic resilience of critical systems taking their interaction and combined impact on communities in technical, organizational, economical and social dimensions.

6(b) shows the ratio of the average power supply of the damaged network to that associated with the intact network for each service area, when only transformers are considered to be vulnerable. The average is taken over all 20 simulations. The extent to which the rehabilitation of transformers contributes to improvement of system performance is evident if we compare the power supply ratio under Case 1 (not enhanced), Case 2 (50% enhanced) and Case 3 (100% enhanced).

In addition to transformers, functionality of circuit breakers, disconnect switches and buses are critical for basic operation of receiving stations. Figures 9 and 10 present the results of the seismic performance analysis when these components are also assumed to be vulnerable, using the same fragility characteristics as transformers. These results indicate that if the additional equipment are considered vulnerable, the LADWP suffers from the total blackout under the Northridge earthquake as we observed in January 17, 1994. More comprehensive results of the analysis involving these types of equipment will be presented later.

Economic Impact

The preceding analysis of systems performance can be readily extended from impacts on households to impacts on the regional economy. Here, direct economic losses are evaluated using a methodology that relates the spatial pattern of electric power outage to the regional distribution of economic activity (see Chang and Seligson, 2003; Chang, 1998).

Direct economic loss, L (dollars), is evaluated for each earthquake simulation and each mitigation condition as follows:

$$L = \sum_{s} \sum_{j} l_j \cdot d_s \cdot e_{sj} \qquad (3)$$

where l_j is a loss factor for industry j ($0 \le 1 \le 1$), d_s is a disruption indicator for service area s ($d = 1$ in case of power outage, $d = 0$ in case of no outage), and $e_{s,j}$ is daily industry j economic activity in area s (dollars). The disruption indicators d_s for each electric power service area derive directly from the power supply simulation results described previously.

The loss factors l_j reflect the dependency of each industry on electric power. They were developed empirically on the basis of survey data collected following the 1994 Northridge earthquake that struck the Los Angeles region. Specifically, a large survey of over 1,100 businesses was conducted by K. Tierney and colleagues at the Disaster Research Center of the University of Delaware (Webb et al., 2000). Data from this survey that were used in the current study included information on whether a business lost electric power, for how long, the level of disruptiveness associated with this outage, and whether or not the business closed temporarily in the disaster. Data on other sources of disruption (e.g., building damage, loss of water, etc.) were also used to estimate the net effect of electric power outage. For details on the methodology, see Chang and Seligson (2003). The loss factors range from a low of 0.39 for mining and construction to a high of 0.60 for manufacturing. These factors pertain to a one-day power outage.

Estimates of industry economic activity by service area, e_{sj}, were based on industry employment data. Employment by industry and zip code were obtained from the Southern California Association of Governments (SCAG) and aggregated, using GIS overlays, to the LADWP service areas. Employment was converted into output using estimates of output per employee in each industry. These productivity estimates were based on California gross state product (GSP) and employment data available from the Bureau of Economic Analysis (BEA).

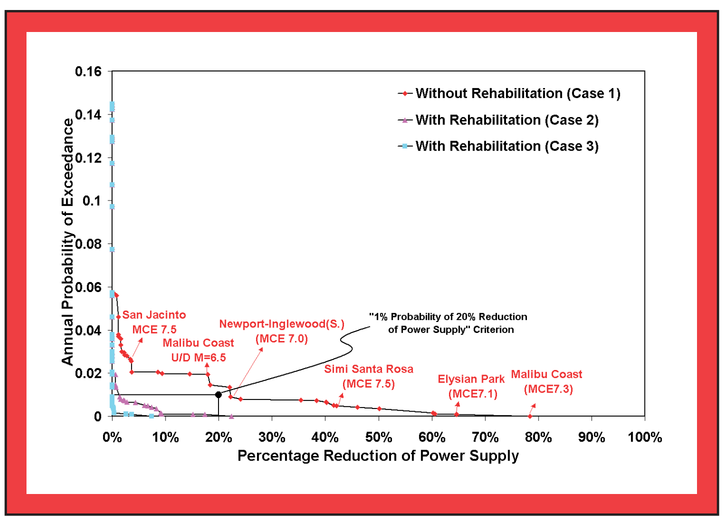
Loss results are expressed as the percent of gross regional product (GRP) in the LADWP service area that would be lost given electric power outage in each earthquake simulation. At this stage, results are assessed in terms of daily GRP loss. This can be interpreted as the loss that would be sustained if the outage pattern lasted for one day.

Risk Evaluation of Power Systems

Analysis using these probabilistic earthquake scenarios allows the estimation of "risk curves" that graphically summarize system risk in terms of the likelihood of experiencing different levels of performance degradation in disasters. Risk curves can be developed for performance parameters associated with different dimensions of resilience, including the technical (e.g., power supply in each service area), societal (e.g., rate of households without power supply), organizational (e.g., rapidity in repair and restoration efficiency), and economic (e.g., regional output or employment loss).

Risk Curves for LADWP's Power System

Reduction in power supply, households without power and reduction in GRP immediately after an earthquake are risk measures of technical, societal and economic concern, and the associated risk curves are plotted in Figures 11-13. These risk curves indicate the percentages of reduction in power supply, households without power and reduction in GRP immediately after earthquake, and are computed utilizing the results of power flow analysis and census data (Figure 3) on the spatial distribution of households across LADWP's service areas as shown below. As for the details of evaluation in GRP, readers are referred to Shinozuka and Chang (2004).



■ Figure 11. Risk Curves for Power Supply Reduction

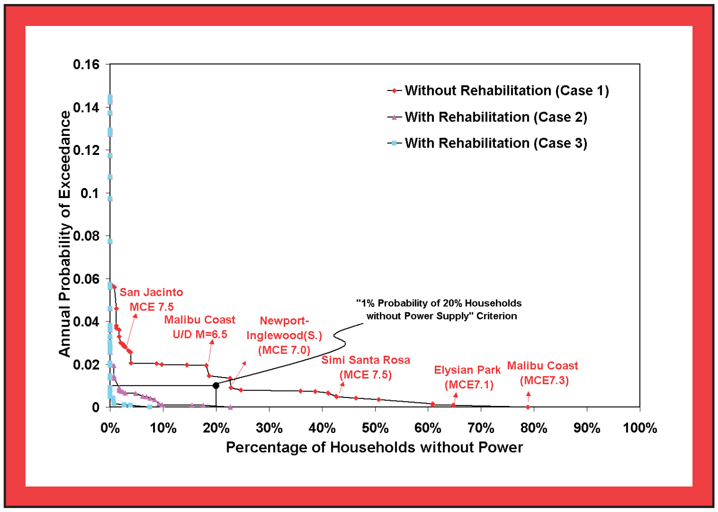
Related Web Sites

Professor Shinozuka:
http://shino8.eng.uci.edu

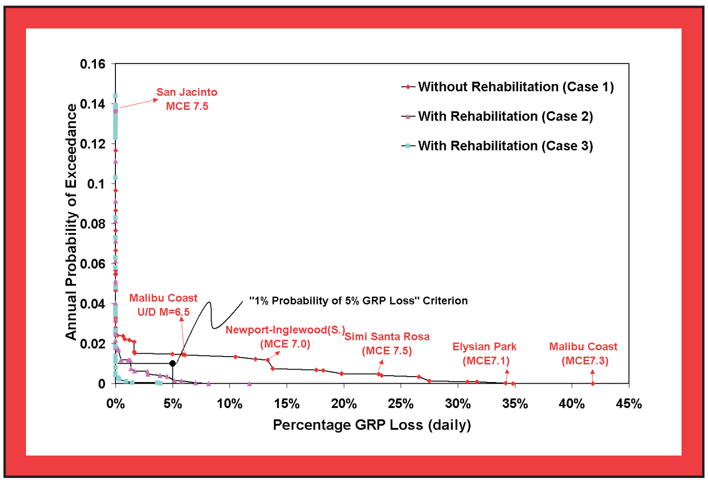
Shake Map Home Page:
http://quake.wr.usgs.gov/research/strongmotion/effects/shake/

Western Electricity Coordinating Council:
http://www.wecc.biz/main.html

Scenario Earthquakes:
http://shino8.eng.uci.edu/Secnario_Earthquakes/47Scenario.pdf



■ Figure 12. Risk Curves for Household Power Outage



■ Figure 13. Risk Curves for Economic Loss

Percentage P_w of power supply

$$P_w = \frac{\sum_{m=1}^{M} \frac{1}{N} \sum_{n=1}^{N} Pd(m,n)}{\sum_{m=1}^{M} P(m)} x100\% \quad (4)$$

Percentage P_{wo} of reduction in power supply

$$P_{wo} = 100\% - P_w \quad (5)$$

Percentage H_w of households with power

$$H_w = \frac{\sum_{m=1}^{M} \frac{1}{N} \sum_{n=1}^{N} Rd(m,n) \times Hshld(m)}{\sum_{m=1}^{M} Hshld(m)} \times 100 \quad (6)$$

Percentage H_{wo} of households without power

$$H_{wo} = 100\% - H_w \quad (7)$$

where m is the service area number (1,2,…,M), M=21 in this example; n is the simulation number (1,2,…,N); N equals 20 in this example; $Pd(m,n)$ is the power output in service area m under n-th simulation; $P(m)$ is the power output in service area m under normal conditions; $Rd(m,n)$ is the power output ratio in service area m under n-th simulation; and $Hshld(m)$ is the number of households in service area m.

The risk curves in this study plot the expected annual probability as a function of loss of system power supply in Figure 11, the percentage of households without power in Figure 12 and the reduction of GRP in Figure 13 after an earthquake. Each point in the figures represent one of the scenario events with their occurrence probabilities cumulatively added backward beginning from the scenario earthquake producing the largest percentage so that the risk curve represents a complimentary cumulative distribution function of the performance variable (such as percentage of power supply reduction). The risk curve approach is also useful for economic impact analysis, as well as cost-benefit analysis to determine the effectiveness of enhancement technologies (see the curves with solid triangles and squares) (Dong, 2002). Of equal importance is the use of the risk curve in relation to the verification of performance criteria.

System Performance Criteria

The performance criteria for power systems listed in Tables 1 and 2, demonstrate a possible format in which the criteria can be given. Table 1 lists criteria to be satisfied in pre-event assessment (e.g., through seismic retrofit), and Table 2, those in post-event emergency response (e.g., through disaster response planning). These tables also include performance criteria for water and acute care hospital systems. This general format for performance criteria for structures and lifelines has been provided by Shinozuka and Dong (2002) and Bruneau *et al.* (2003). In combination, they conceptually establish the degree of community resilience in terms of robustness, rapidity and reliability. Specific values (in percentages for robustness, rapidity in restoration, and reliability) are examples so that the concept can be better understood.

Data collection and modeling for rapidity in restoration are much more difficult to pursue (Shinozuka and Dong, 2002). Further research is needed to develop analytical models based on past experience so that performance criteria, such as those shown in Table 2, become meaningful in practice. However, a simulation was performed in this study and compared with the Northridge repair/restoration data. The results from this study provide a potentially successful method of pursuit in this area as demonstrated below in "System Restoration."

Similar tables for GRP associated with the same systems are currently being constructed. For the sake of discussion, robustness of the power system in terms of GRP has a criterion of 5% loss with an annual probability of 1%.

The solid circles in Figures 11-13 indicate example performance criteria for the electric power system in technical, societal and economic terms. In these cases, the criteria specify that percentage of reduction in power supply, of households without power and of

■ Table 1. System Performance Criterion I for Pre-event Assessment and Rehabilitation

	Robustness	Reliability
Power	A majority (at least 80%) of households will have continued power supply after earthquake	With a high level of reliability (at least 99% per year)
Water	A majority (at least 80%) of households will have continued water supply after earthquake	With a high level of reliability (at least 99% per year)
Hospital	A majority (at least 95%) of injured or otherwise traumatized individuals will be accommodated in acute care hospitals for medical care	With a high level of reliability (at least 99% per year)

■ Table 2. System Performance Criterion II for Post-Event Response and Recovery

	Rapidity in Restoration	Reliability
Power	A majority (at least 95%) of households will have power supply as rapidly as possible within a short period of time (3 days)	With a high level of reliability (at least 90% of earthquake events)
Water	A majority (at least 95%) of households will have water supply as rapidly as possible within a short period of time (3 days)	With a high level of reliability (at least 90% of earthquake events)
Hospital	All the injured and traumatized individuals will be accommodated in acute care hospitals as rapidly as possible within a short period of time (1 day)	With a high level of reliability (at least 90% of earthquake events)

GRP loss immediately after earthquake should not exceed, respectively, 20 %, 20 % and 5 %, all with 1 % annual probability. In these instances, Figures 11-13 show that the unmitigated system (Case 1) will not meet the stated performance criteria, but rehabilitated systems (both Cases 2 and 3) will satisfy the performance criteria.

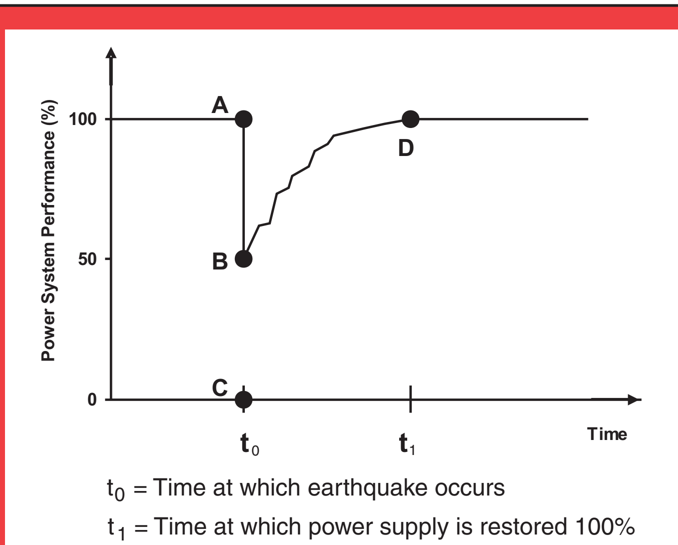


Figure 14. Power Supply as a Function of Time

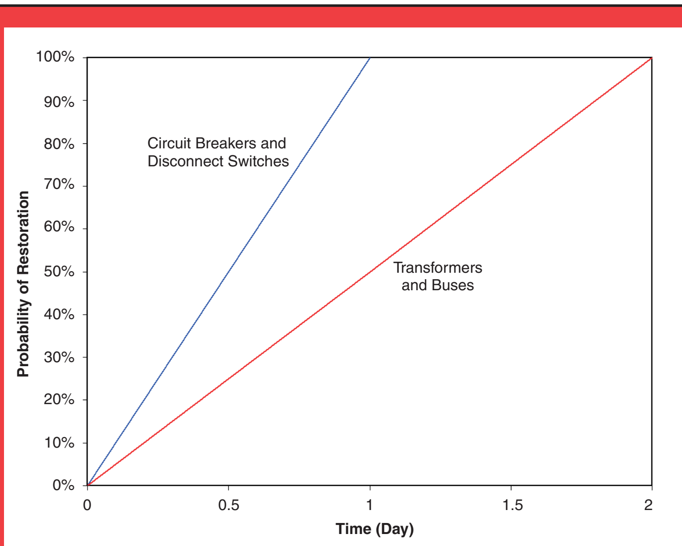


Figure 15. Restoration Curve for Transformers, Circuit Breakers and Disconnect Switches

Resilience Framework and System Restoration

Resilience is an important concept for the disaster management of infrastructure systems. Two key dimensions of resilience can be referred to as robustness and rapidity in restoration as described in the preceding sections. These can be expressed utilizing a restoration curve typically having characteristics as shown in Figure 14.

The curve plots system performance as a function of time. The reduction in performance from 100% at point A (time t_0) to 50% (in this example) at point B results from the damaging seismic impact to the system. The restoration curve starting from the initial distress point B, to the complete recovery point D (back to 100% at time t_1), demonstrates the process of restoration. Hence, the performance percentage corresponding to B (or B-C, with C associated with zero performance) represents robustness (Equation 8), and the elapsed time for the total restoration (t_1-t_0) can be used to quantify rapidity (Equation 9), although Equation 9 may admittedly be too simplistic.

$$Robustness = B - C \quad (in\ percentage) \qquad (8)$$

$$Rapidity = \frac{A - B}{t_1 - t_0} \quad (average\ recovery\ rate\ in\ percentage\ /time) \qquad (9)$$

It has been demonstrated that the restoration for power systems tends to be rapid compared with that for water, gas and transportation systems. Figure 15 shows the assumed repair or replacement curves for the LADWP system after the Northridge earthquake. The curve plots the probability of damaged equipment being restored (repaired or replaced) as a function of time (in days). This model may indeed represent organizational effectiveness in the sense that it asserts that LADWP has the capacity to repair/replace all the damaged components within 2 days, with each damaged component given equal chance to be repaired/replaced in the interval of 2 days. It is postulated that circuit breakers and disconnect switches are more rapidly restored with uniformly distributed probability density over the first one day period, and transformers and buses over the first two days. This not only reflects the relative ease with which each component is repaired /replaced, but also the cost of its replacement. The resulting curve indicates, for example, that a damaged transformer can be replaced or repaired within a half day with a probability of 25%. This is merely an assumption on which we initiate and gain numerical insight for the restoration simulation. In reality, a transformer probably cannot be replaced or repaired with such rapidity unless the degree of damage is slight, i.e., less than moderate. As for the fragility information, we use Figure 7 (Case 1) for transformers, Figure 16 for circuit breakers and Figure 17 for disconnect switches and buses. The fragility curves for circuit breakers and disconnect switches are also developed from the Northridge damage data. Then, a power flow analysis is performed as outlined in earlier sections, adding an extra layer of Monte Carlo simulation where damaged components are restored in accordance with the restoration curves assumed in Figure 15. The resulting simulation of restoration (in % of households) is represented by four points in Figure 18, which underestimates the speed of restoration (in % of customers) actually observed in the aftermath of the Northridge earthquake. The difference between household- and customer-based percentage restoration is assumed to be negligible here. Figure 18 also includes simulated restoration

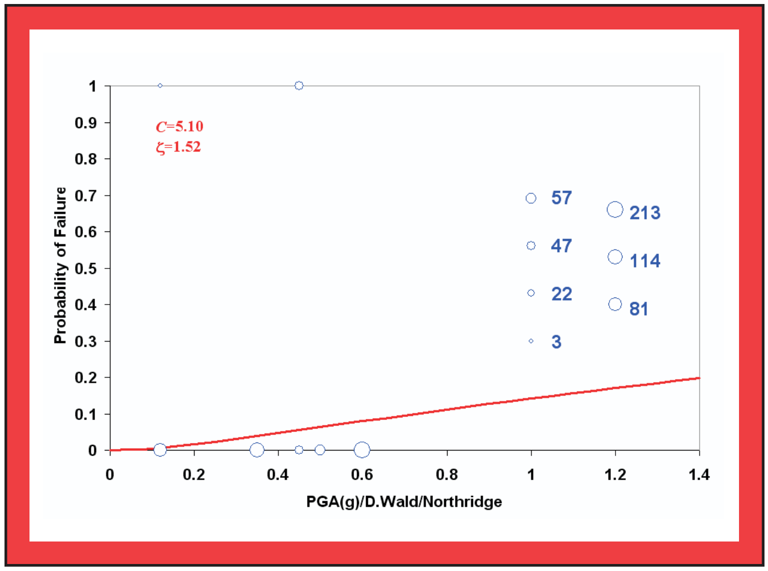


Figure 16. Fragility Curve for Circuit Breakers

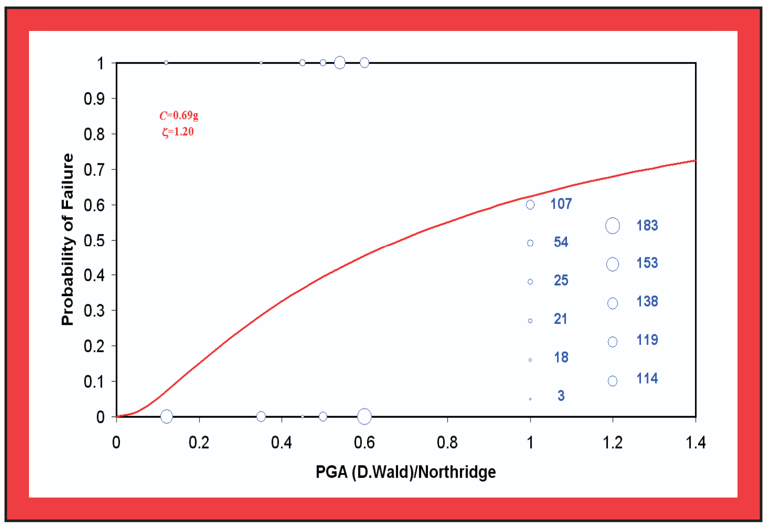
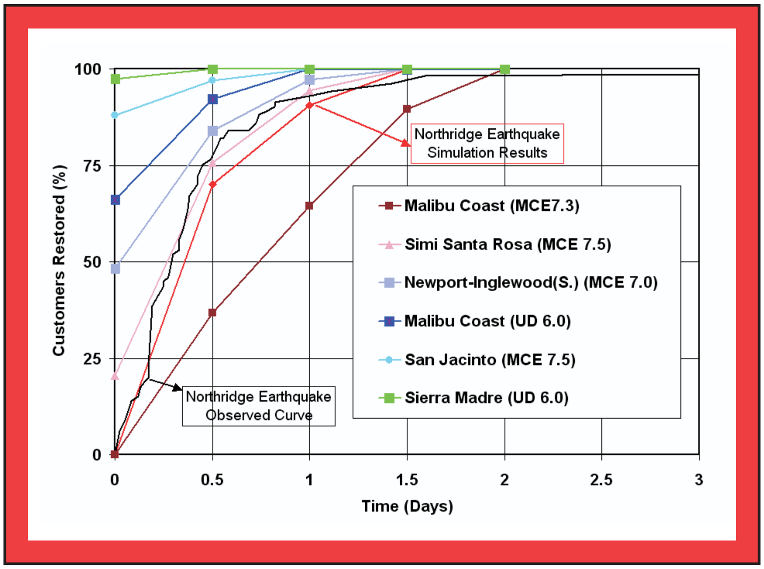
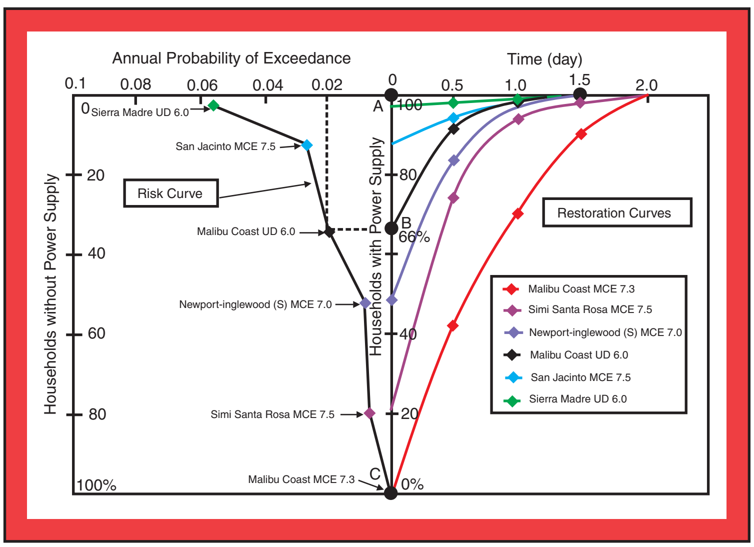


Figure 17. Fragility Curve for Disconnect Switches and Buses



■ Figure 18. LADWP Power System Customers Restoration



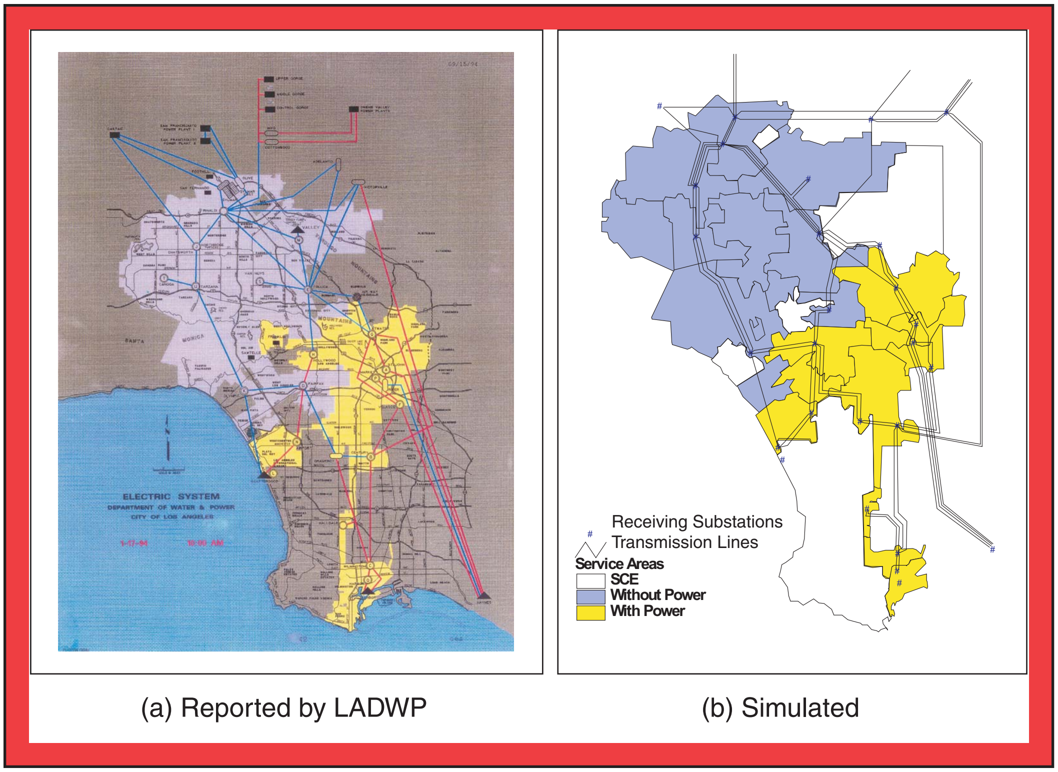
■ Figure 19. Risk Curve and Restoration Curves for LADWP''s System

curves for two other less damaging scenario earthquakes. Note their shapes are, in essence, the same as the curve BD in Figure 11. We note that power system restoration procedures may repair or replace damaged components in an order reflecting the priority established by the utility for the purpose of accelerating the entire network restoration. If such a procedure were taken into consideration, the simulation performed here might have more closely agreed with the empirical curve. The simulated states of restoration as time proceeds can be depicted in GIS format. Figure 20 (a) shows a snapshot at 6 hours after the earthquake of this spatio-temporal progression of restoration process as reported by LADWP, whereas Figure 21(b) shows the simulated version of the state of restoration at the same time.

Water and Power Systems Integration

Figure 21a shows the LADWP electric transmission network superimposed on the major highway system and topography of Los Angeles. Figures 21b and 21c show the pump stations for water distribution and groundwater wells, respectively.

The water distribution system contains 73 pump stations, many of which use several pumps in parallel, resulting in 284 pumps throughout the system. As indicated in Figure 21c, the water distribution system contains an additional 151 pumps for groundwater wells. Of significance is the Van Norman Complex in northern San Fernando Valley, which operates with two pump stations.

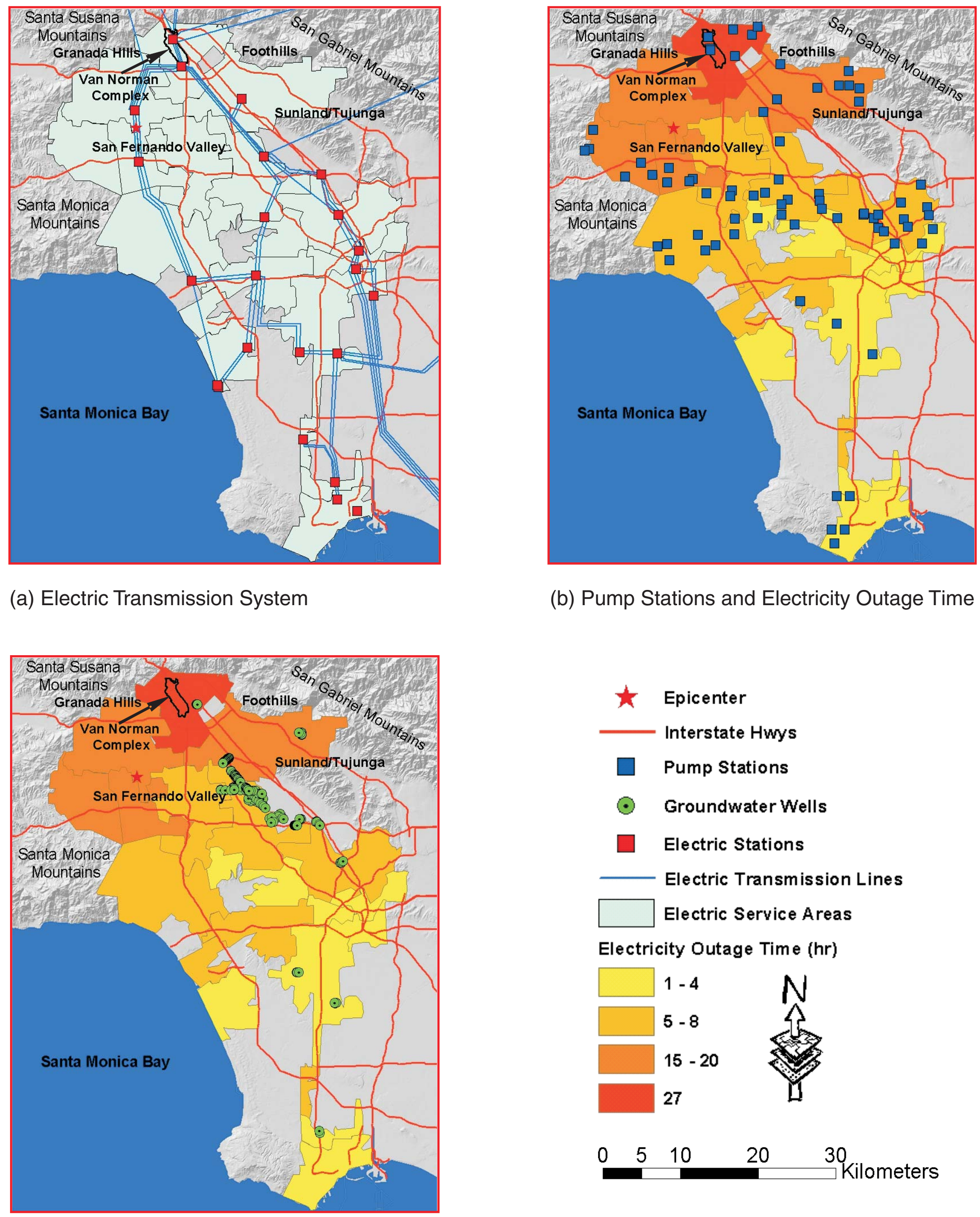


■ Figure 20. State of LADWP Power Supply Restoration at 6 hours after the Northridge Earthquake

Pump stations and groundwater wells generally performed well during the 1994 Northridge earthquake. The damage to these facilities was minimal, except for the loss of pumping capacity due to interruption of electric power (Lund and Cooper, 1995). Most pump stations have emergency backup internal combustion generators or pump units to provide at least the capacity of one electric pump unit. The emergency capacity, however, is less than the pumping capacity with normal electric service at most of the stations. The post-earthquake capability of pump stations to operate at a normal level of service was therefore related to the restoration of electric power.

LADWP (1994) provided information about the electric power system restoration after the Northridge earthquake, which was incorporated into a combined GIS for water and electric power, and evaluated in light of other data sources (Schiff et al.,1995; LADWP, 1994; EERI, 1995). Figure 21 shows the LADWP electric transmission system, as well as the time for power restoration, superimposed on pump stations and groundwater wells. Power was restored first in the southern portion of the service area, and then was expanded gradually to the north. The outage time in the Central City areas was less than several hours. In contrast, the outage for much of San Fernando Valley lasted 15 to 27 hours.

The restoration of electricity was accomplished by reinstatement of power in the least damaged, southern portion of the network at the same time that inspections and repairs were initiated in the most heavily damaged northern part

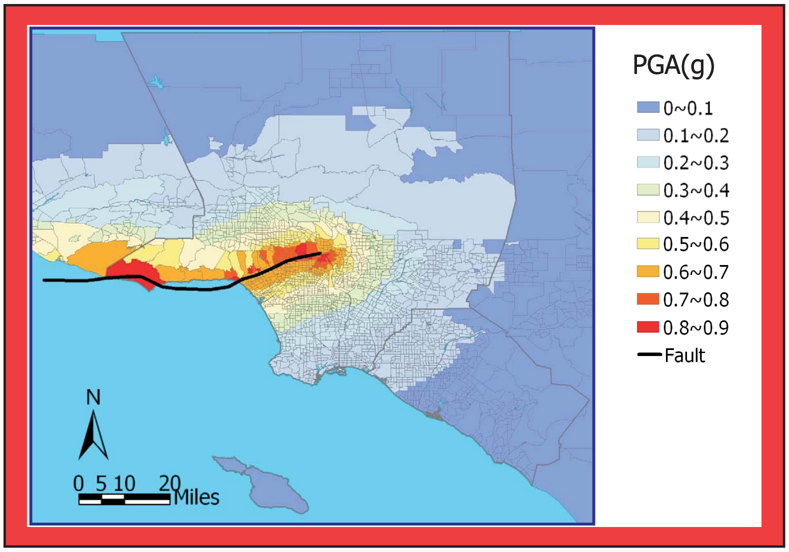


(a) Electric Transmission System

(b) Pump Stations and Electricity Outage Time

(c) Groundwater Wells and Electricity Outage Time

■ Figure 21. Water Distribution and Electricity Power System Interaction After the 1994 Northridge Earthquake



■ Figure 22. PGA Distribution (Malibu Coast M7.3)

of the network. In general, restoration proceeds from locations outside the most heavily damaged areas where the opportunity for power resumption is highest. This progression from areas of lesser to greater damage also supports a general resumption of services that helps in the repair of components with highest damage.

Electric service to most pump stations and groundwater water wells was reinstated by noon following the main shock. Electricity outage at the Van Norman Complex lasted as long as 27 hours. Emergency power to run the smallest of the two pump stations at the Complex at full capacity was provided during that time by internal combustion units. Even after electric power was restored to both pump stations at the Complex, the ability to convey water was impeded by earthquake-induced damage to major trunk lines.

MCEER investigations of earthquake effects on the combined water and power systems, as illustrated in this case history assessment, show the spatial interaction of both networks. GIS-assisted modeling illustrates both the temporal and spatial aspects of combined system performance, and helps to formulate future strategies for coordinated service reinstatement.

Figures 21a and 21b can also be demonstrated by utilizing the spatio-temporal restoration map of the power supply reported by LADWP for the Northridge earthquake as in Figure 20a. The method of simulation for the restoration process which was developed in Figure 20b can be used for one of the Maximum Credible Earthquakes, Malibu Coast M7.3, with a PGA distribution as depicted in Figure 22. The progression of the restoration process is then shown in Figure 23, in which the state of the restoration is demonstrated in GIS format immediately after and at 12 hours, 24 hours and 48 hours after the earthquake. This restoration simulation as exemplified in Figure 23 is pivotal in the pre-event assessment of restoration and related recovery processes.

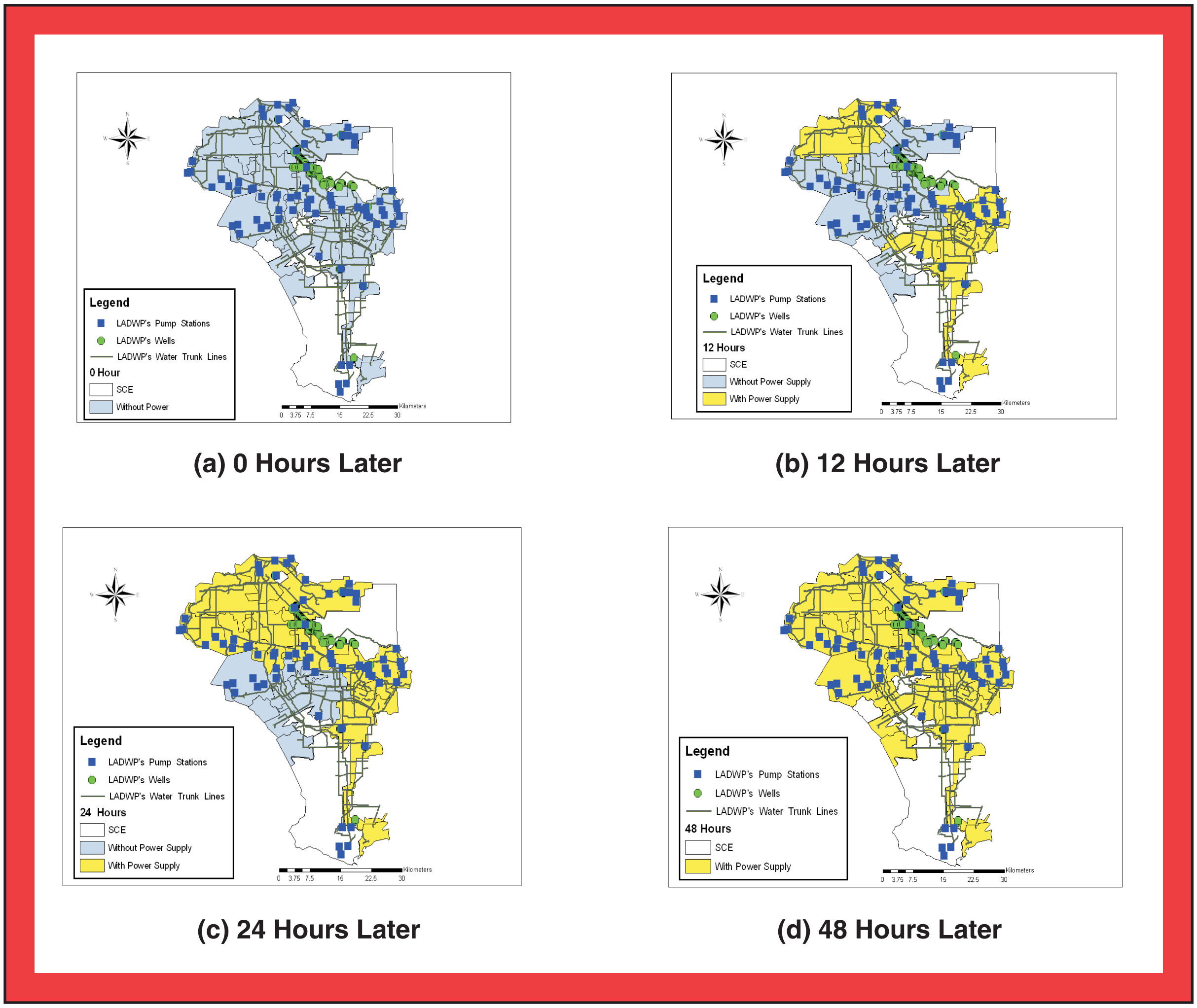


Figure 23. Pump Stations with Power Supply after Earthquake (Malibu Coast MCE 7.3)

Conclusion and Future Research

This research integrated the data and methods developed by the authors over many years, including the GIS inventory data of the LADWP electric power transmission system, multiple scenario earthquakes representing the Los Angeles area seismic hazard, fragility characteristics of system components with and without seismic retrofit, and systems analysis techniques using WECC's database and EPRI's IPFLOW computer code. This integration leads to the capability to evaluate the performance of power systems and the consequences of system interruptions caused by earthquakes. In addition, the research developed and proposed a form of performance criteria that can be quantitatively mapped into the response space, in terms of the technological, economic, organizational, and social dimensions of disaster resilience. A model of the system restoration process was recently added for the purpose of pre-event simulation in order to assess the economic loss resulting from system disruption. Research on integrative water and power performance has been initiated concentrating on the pump stations vulnerable to the interruption of power supply. Joint performance of power systems with other critical systems, such as emergency response organizations, medical care systems (e.g., acute care hospitals) and highway transportation systems is a critical issue to be addressed more comprehensively from the viewpoint of community resilience, and is currently being studied.

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