PEER 2019 Annual Meeting
Seismic Resilience 25 Years after Northridge:
Accomplishments and Challenges

A Proposed Performance Based Seismic Design Process for Lifeline Systems

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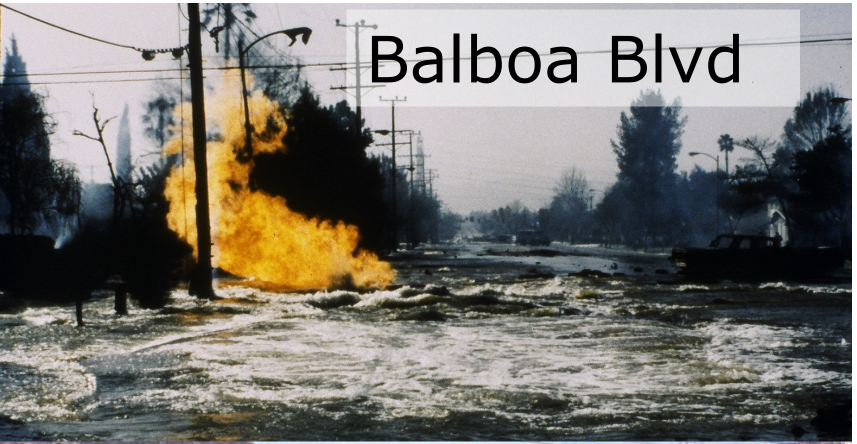
Lifelines Performance during 1994 Northridge Earthquake



Performance Categories & the 1994 Northridge Earthquake

Performance Category	Description
Services	Limit service outages and restore lost services rapidly
Life Safety	Preventing injuries and casualties from direct or indirect damages to water system facilities; includes safety matters related to response and restoration activities
Property Protection	Preventing property damage as a result of damage to water system components; also includes preventing water system damage.

Lifeline Systems were fairly resilient in limiting the loss of services and restoring them in a timely manner

Few lives were lost, and not likely related to lifeline system performance

There was some serious damage to private property caused by lifeline system damages

Damage to system components was costly

Lessons and Challenge

Can improve lifeline system performance

Performance could be worse for larger events, or similar events in other locations

The challenge is getting all the:

1. components within a system to perform consistently to meet a defined target objective, and

2. lifeline systems to perform consistently, relative to the needs of the other lifeline systems and the communities they serve

For all potential earthquake events.

To start we need a common platform to work from, initiating with a definition.

Infrastructure Resilience

<u>*Definition*</u> *(modified from Davis and Giovinazzi, 2015)*

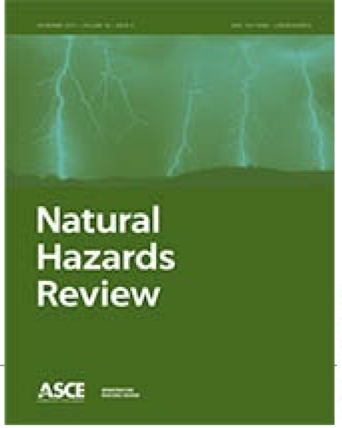
"A resilient infrastructure network is designed and constructed to accommodate hazard-related impacts with ability to continue providing services or limit service outage times tolerable for community recovery efforts."

Davis, C. A. and S. Giovinazzi, 2015, "Toward Seismic Resilient Horizontal Infrastructure Networks," 6th Int. Conf. on Earthquake Geotechnical Engineering, Christchurch, NZ, Nov. 1-4.

Performance Based Design

As Proposed for the Los Angeles Water System

Performance Based Seismic Design



Establishing Characteristics to Operationalize Resilience for Lifeline Systems

Craig A. Davis, Ph.D., P.E., M.ASCE[1]; Ali Mostafavi, Ph.D., A.M.ASCE[2]; and Haizhong Wang, Ph.D., A.M.ASCE[3]

Abstract: The purpose of this paper is to provide information useful for creating and maintaining resilient utility lifeline systems. In part, the information presented helps to answer the question: "What is a resilient lifeline system?" Seventeen characteristics of resilient lifeline systems are identified and categorized within organizational, technical, social, and economic domains. Each characteristic has a listing of achievement indicators. The achievement indicators are shown to define the space bounded by the resilience domains (organizational, technical, social, and economic), resilience properties (redundancy, resourcefulness, rapidity, and robustness), and the event cycle (planning, mitigation, response, recovery, and rebuild). The characteristics and achievement indicators define attributes needed for resilient lifeline systems and can be used as a checklist to allow lifeline organizations to better understand their current level of resilience and what they may undertake to improve. The difference between the current status and the target, defined by the characteristics, identifies the gaps in resilience needing to be filled. The gaps can be prioritized and implemented individually or as part of a lifeline system resilience program and are helpful for setting future directions and strategic planning. Example and case study applications are presented to show how the characteristics and achievement indicators can be operationalized into practice. For these reasons, one primary intended audience for this information is midlevel to high-level managers of lifeline system owners and operators who are interested in improving their system resilience. The characteristics and achievement indicators are also useful for identifying where research and development are needed to create further guidance on how to improve lifeline system resilience. As a result, another audience for this paper is lifeline system researchers and product developers. **DOI: 10.1061/(ASCE)NH.1527-6996.0000303.** *© 2018 American Society of Civil Engineers.*

Introduction

A useful tool to help lifeline systems achieve infrastructure resilience in support of the communities they serve.

By itself, PBSD does not create a resilient system, but it is an important instrument for achieving needed characteristics of resilient lifeline systems.

<u>To understand Lifeline System Resilience Characteristics:</u>

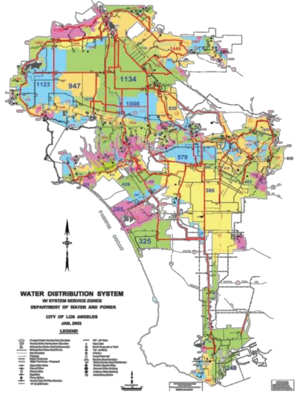
Davis, C.A., A. Mostafavi, and H. Wang (2018). "Establishing Characteristics to Operationalize Resilience for Lifeline Systems," ASCE Natural Hazards Review Journal, DOI 10.1061/(ASCE)NH.1527-6996.0000303.

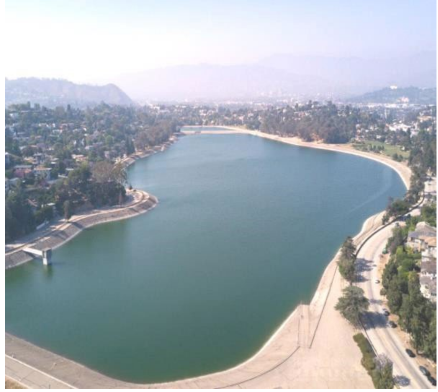
Undertaken as part of the ASCE Infrastructure Resilience Division

Performance Based Seismic Design

The remaining presentation is based on a recently adopted procedure developed for the LADWP Water System;

This can be generalized for other lifelines.




PERFORMANCE BASED SEISMIC DESIGN FOR LADWP WATER SYSTEM

JANUARY 2019

Prepared by:

Craig A. Davis, Ph.D, PE, GE




<u>Based on:</u>

LADWP (2019). "Performance Based Seismic Design for the LADWP Water System.

Davis, C.A., (2019). "A Proposed Performance Based Seismic Design Process for Lifeline Systems," 7ICEGE, ISSMGE, Rome, June.

Davis, C.A., (2017). "Developing a Seismic Resilient Pipe Network Using Performance Based Seismic Design Procedures," CTWWA/WRF/JWWA, 10th Wkshp on Water System Seismic Practices, Tainan, Taiwan, Oct.

What is Performance Based Seismic Design and How is it Applied to Lifeline Systems?

PBSD is a process that explicitly evaluates how a facility or system is likely to perform, given the potential hazard it is likely to experience, considering uncertainties inherent in the quantification of potential hazard and in assessment of the actual response (modified from FEMA, 2006).

The System is to be designed to match targeted objectives

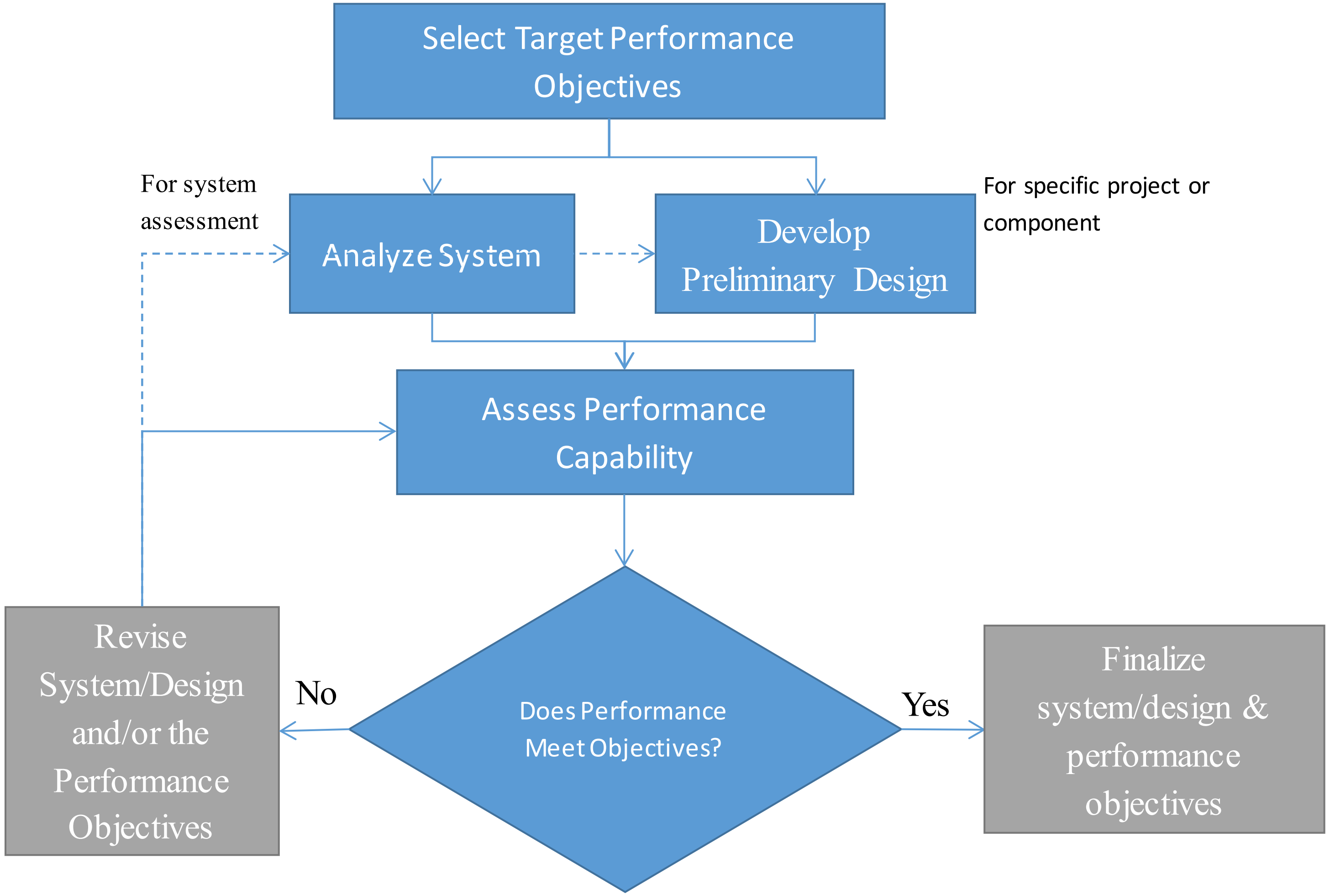
Components are designed to prepare system to meet the targeted objectives

Objectives are scaled relative to the probability and size of earthquake events

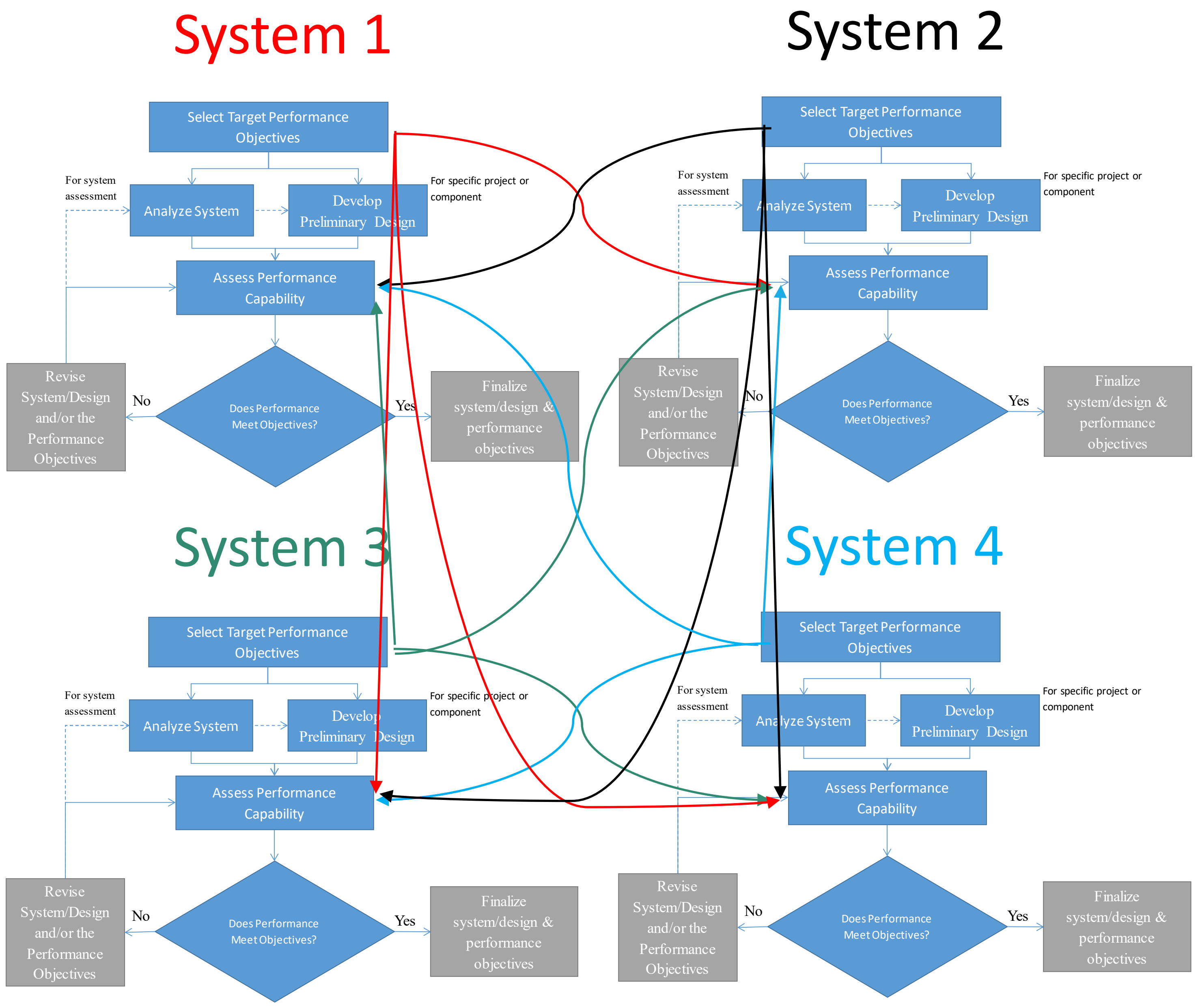
- The larger/less probable events will have more expected service losses and longer time to restore

System performance accounts for geospatial characteristics of the infrastructure and hazard systems, and their interactions

Performance Based Design Flow Diagram



Dependencies



This PBEE procedure is for single lifeline system

Each lifeline system performance is dependent upon other lifeline systems

Need for overarching set of goals so all lifeline systems can achieve a performance needed by the community

Draft Target System-Level Performance Criteria

Level	Hazard Return Period Criteria	Target System Performance	M_w Range
1	100 years	Limited damage to water system, no casualties, few to no water service losses. All customer services operational within about 3 days.	Less than 3.8 to 5.6
2	500 years[1]	Life safety and property protection. All customer services operational within about 20 days, except water quantity; rationing may extend up to 30 days.	4.6 to 8.0[1]
3	2,500 years[1]	Life safety and property protection. All customer services operational within about 30 days, except water quantity; rationing may extend up to 60 days.	5.4 to 8.2[1]
4	>2,500 years up to about 10,000 years	Life safety and property protection. All customer services operational within about 45 days, except water quantity; rationing may extend up to 12 months.	6.2 to 8.3[1]

[1]Highly active faults like the San Andreas have major to great earthquakes within Level 2 and 3 return periods. Performance criteria may need to be prudently relieved to a higher level; see procedure to assess potential modifications.

Earthquake Sources

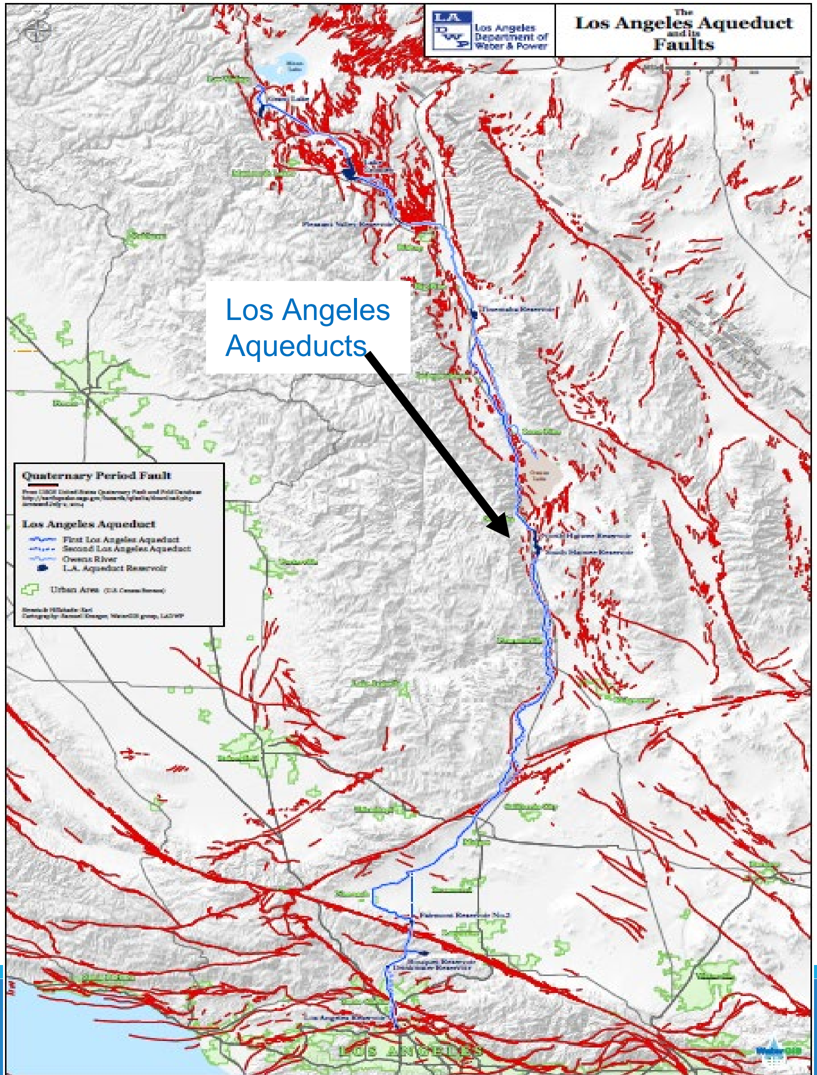
Over 40 faults

30 impact City

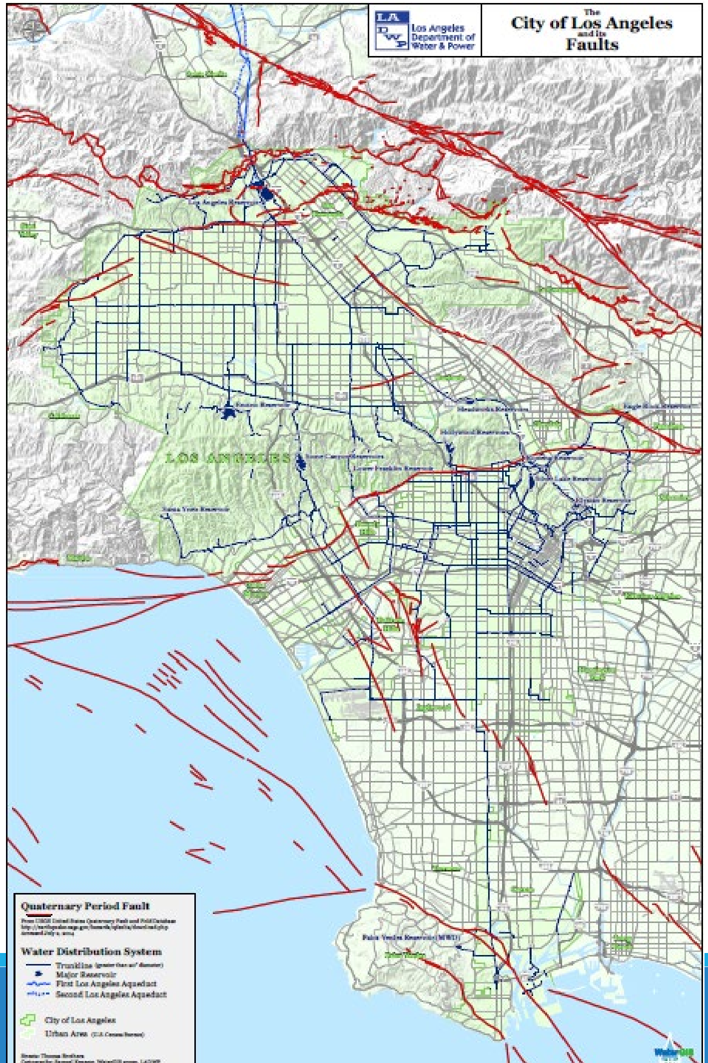
More than 20 rupture ground surface in LA

Identify the rupture magnitude probability for each Level 1 to 4 (UCERF 3).

Los Angeles Aqueducts

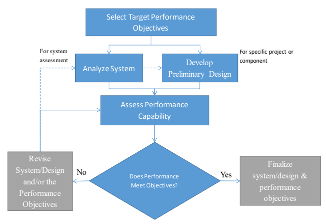


Los Angeles Metro Area



Why Include Level 4 Events?

- They are plausible
- When they occur, but were not considered, communities often find infrastructure performance to be unacceptable
  - May apply to entire event
  - May apply to specific hazard occurrence within the event
- Encourage everyone to think resiliently and cost-effectively improve serviceability after such events
  - New and innovative solutions can be brought forward
  - Higher criteria does not always equate to greater expense and longer projects
- Based on PBEE procedures, it does not require all designs to meet Level 4 criteria, but needs a check on the decision making to use or not to use



System Level Performance
Water System Service Categories

Water System resilience is dependent upon the amount of service losses suffered and time to reestablish

Service Categories	Description
Water Delivery	Able to distribute water to customers, but the water delivered may not meet water quality standards (requires water purification notice), pre-disaster volumes (requires water rationing), fire flow requirements (impacting fire fighting capabilities), or pre-disaster functionality (inhibiting system operations).
Quality	Water to customers meets health standards (water purification notices removed). This includes minimum pressure requirements.
Quantity	Water flow to customers meets pre-event volumes (water rationing removed).
Fire Protection	Able to provide pressure and flow of suitable magnitude and duration to fight fires.
Functionality	The system functions are performed at pre-event reliability, including pressure (operational constraints resulting from the disaster have been removed/resolved).

Does water come out of tap?

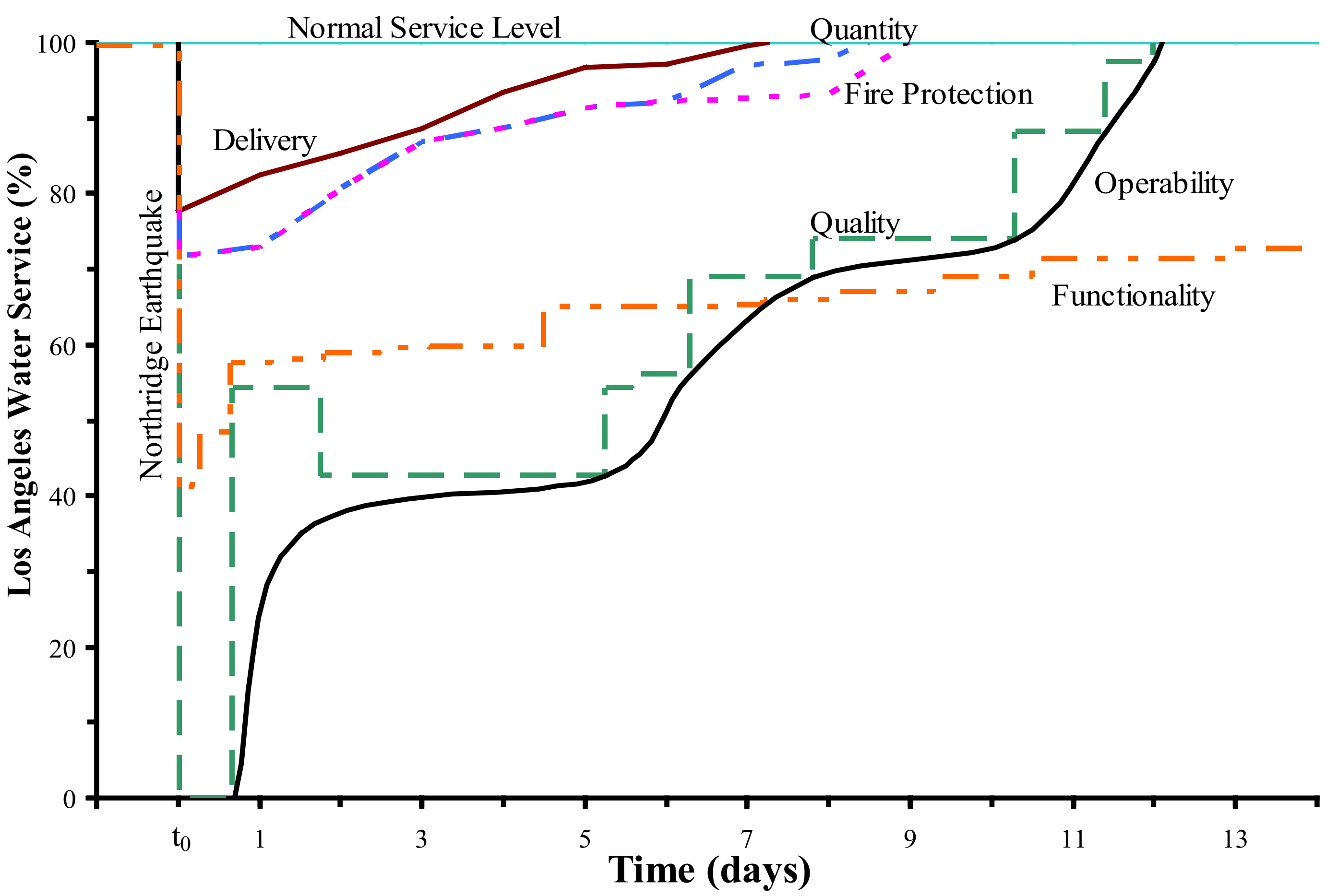
Is it safe to Drink?

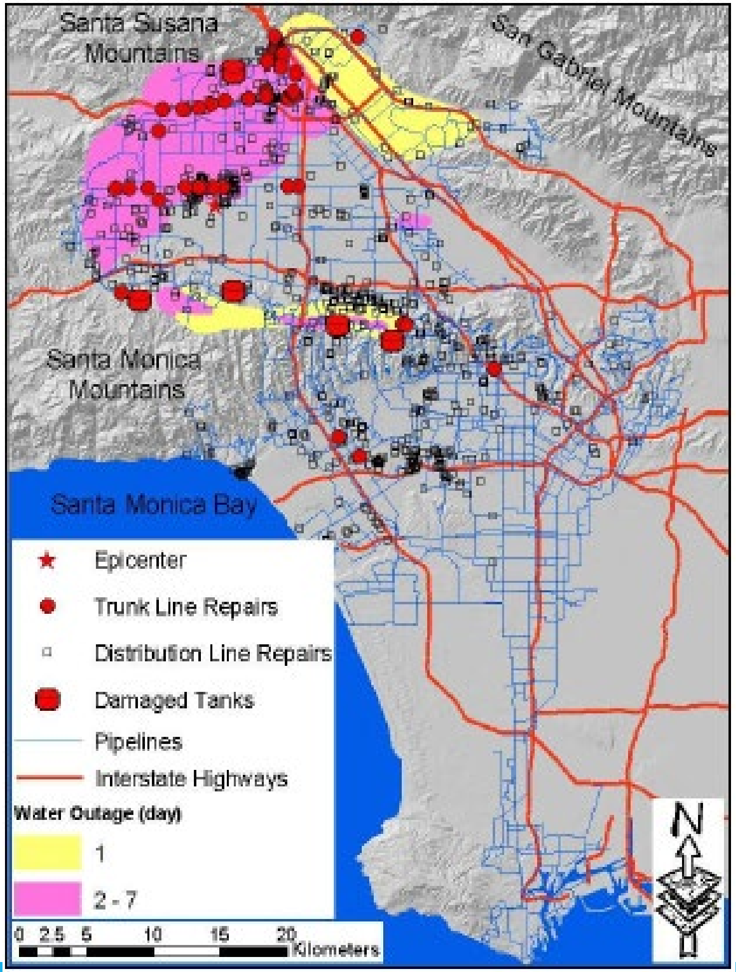
Can you get the amount you need?

Does Fire Dept. get what they need?

Is the water system in working order?

1994 NORTHRIDGE EARTHQUAKE, L.A., EXAMPLE WATER RESTORATIONS





OPERABILITY VS FUNCTIONALITY

Operability is achieved once water delivery, quality, quantity, and fire protection services are restored

- System is able to completely service customers at pre-disaster levels
- However, system may not be fully functional
- **e.g., LA Water restored operability in 12 days after repairing 8 of about 80 transmission line leaks/breaks**.
- **Measure of resilience in support of the community**

Functionality services describe the ability of a system to reliably perform.

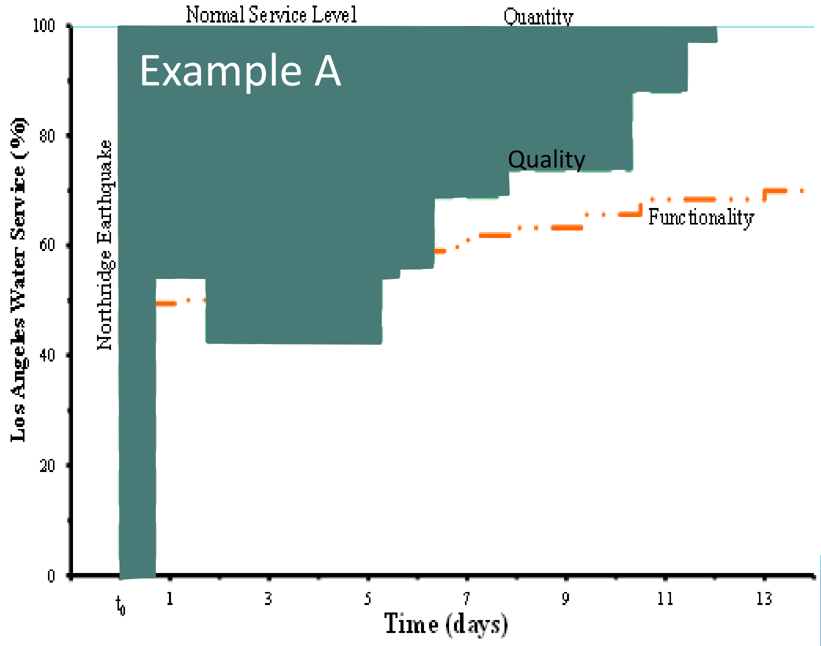
- A highly functional system can provide water delivery, quality, quantity, and fire protection services prior to completing all water infrastructure repairs
- Damage imposes constraints that do not allow the system to function with its pre-earthquake performance and reliability
- e.g., LA Water restored functionality in 9 years after repairing all necessary damaged facilities (some remaining damage deemed acceptable).
- **Measure of system resilience**

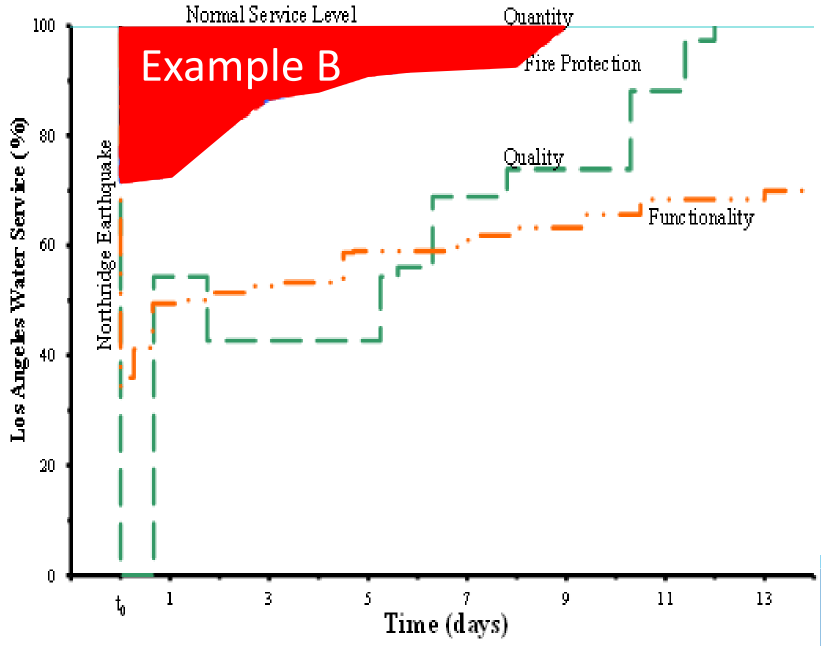
Water Accessibility Services

Accessibility Services: the provision of water to customers through alternate sources or locations when the network is unable to provide normal services

Example A: Providing prepackaged water while portable water cannot be provided through the network

Example B: Aiding the Fire Department with alternate sources when water cannot be delivered through the network with sufficient volume and pressure





Community Resilience

Service restoration to critical customers, defined as:

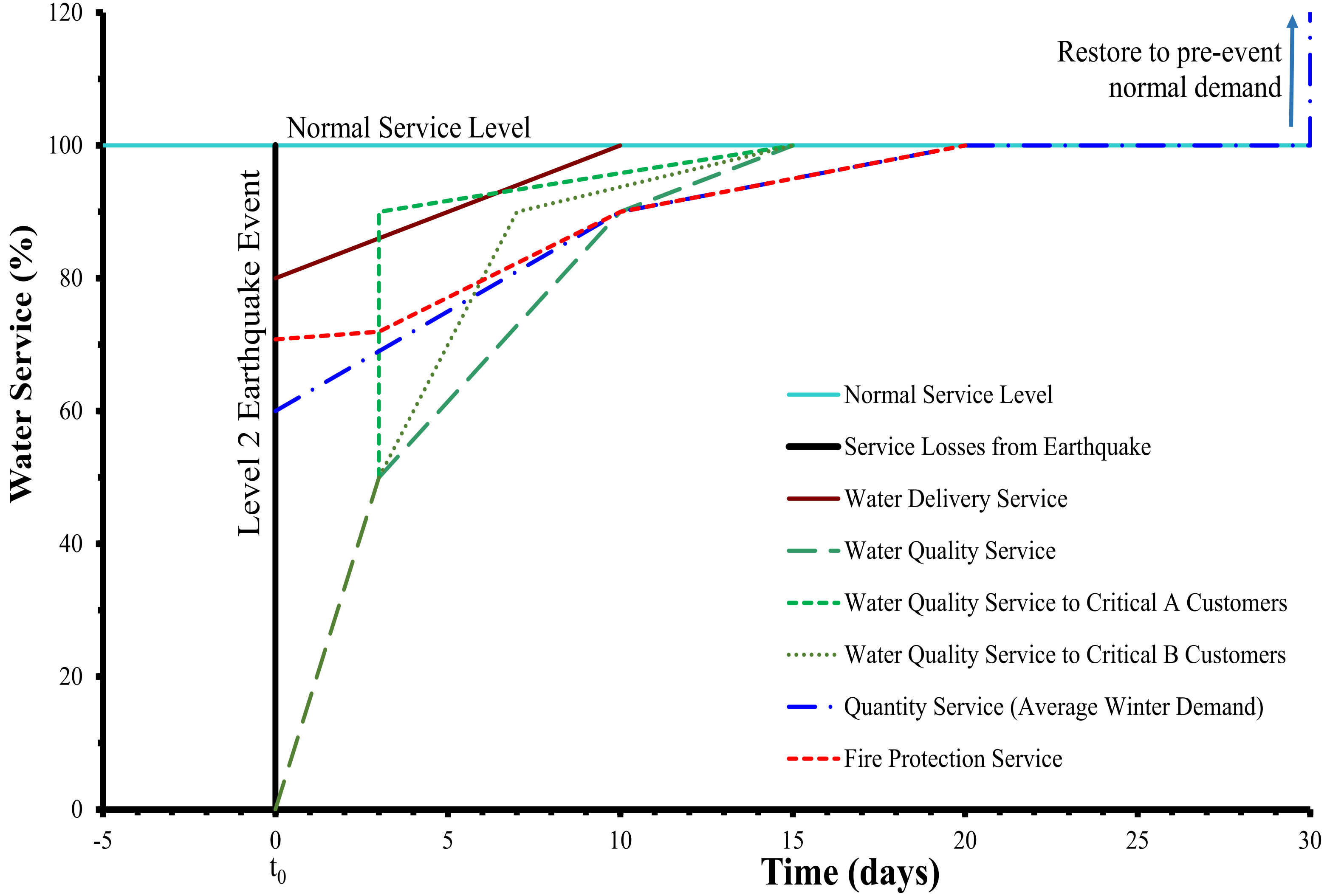
- Critical A Customers: public health and safety
  - Examples: Hospitals, Evacuation Centers Fire Department, etc.
- Critical B Customers: critical community resilience services
  - Examples: schools not used as evacuation centers, lifeline utilities not providing public health services, etc.

Draft Service Goals Level 2

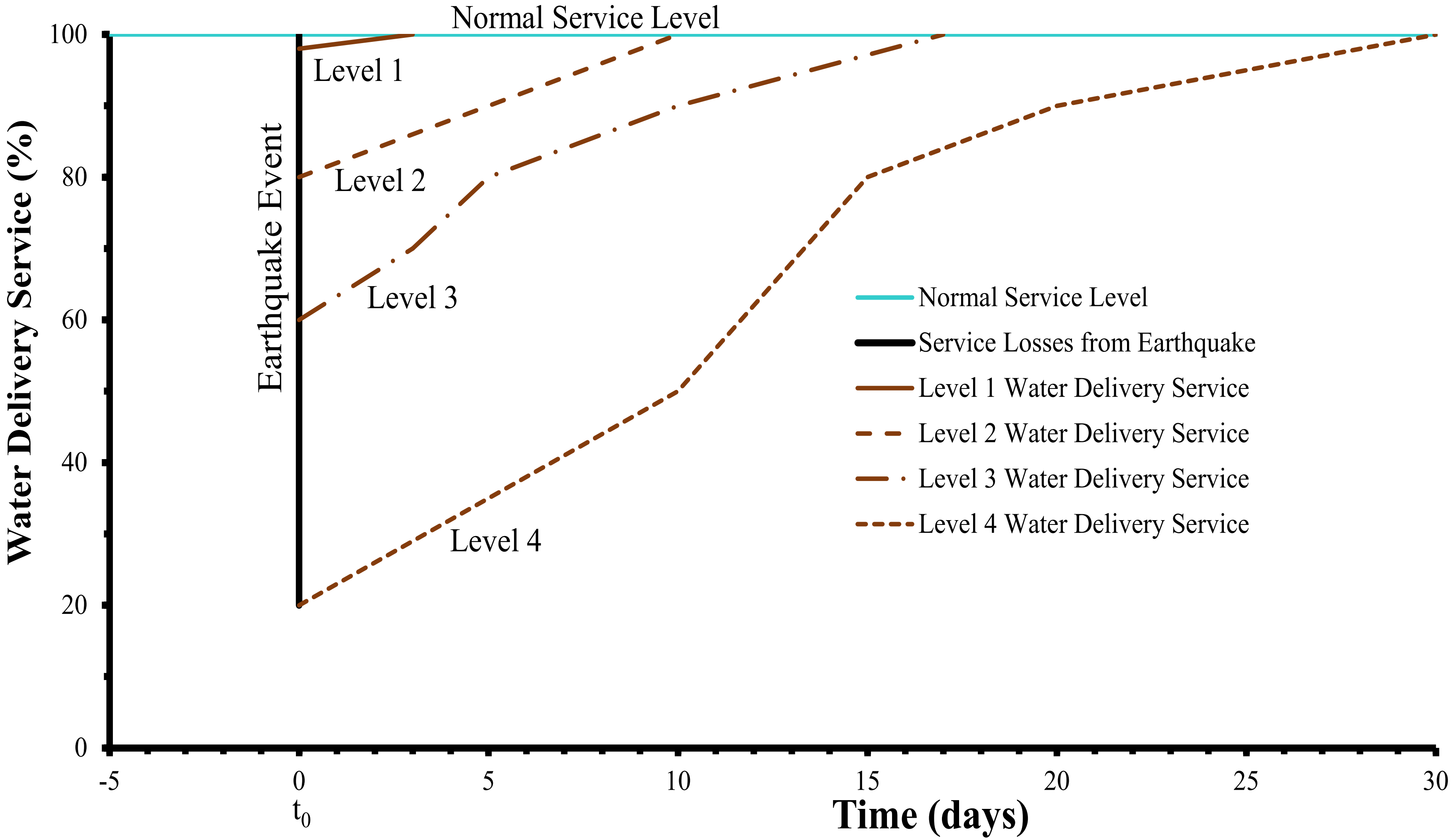
Service Category	Service Description	Target restoration time
Delivery[1]	Limit losses to approximately 20% of customers	0 days
	Restore to 90% of customers	5 days
	Restore to all customers	10 days
Quality[2]	Restore to 50% of customers	3 days
	Restore to 90% of customers	10 days
	Restore to all customers	15 days
	Restore to 90% of all Critical A customers[3]	3 days
	Restore to 90% of all Critical B customers[3]	7 days
Quantity	Implement city-wide rationing at average winter day demand (AWD)	0 days
	Limit losses below AWD to approximately 40% of customers[1]	0 days
	Restore AWD to 90% of customers	10 days
	Restore AWD to all customers	20 days
	Restore to pre-event normal demand	30 days
Fire Protection	Provide partial[4] services from pipe network within 5-miles distance of any delivery loss	0 days
	Provide partial[4] services from pipe network within 2-miles	3 days
	Restore to 90% of hydrants	10 days
	Restore to all hydrants	20 days
Functionality[5]	Limit system losses to approximately 40% (maintain 60% functionality)	0 days
	Restore system to 70%	7 days
	Restore system to 80%	60 days
	Restore system to 90%	180 days
	Restore system to 100%	360 days
	Improve system vulnerabilities identified	5 years
Emergency Accessibility	Provide 1 gallon per person per day potable water to domestic users within 5 miles from residence[6]	3 days
	Provide 2.5 gallons per person per day potable water to domestic users within 0.3 miles from residence[7]	7 days

[1]System is able to contain flow and minimize continued service losses in 1 day or less (i.e., drainage losses are constrained, and the system does not have significant continued drainage). For quantification purposes, delivery services are met when flow reaches about 20% of average winter day (AWD) demand.
[2]Water quality may be effectively lost to all customers out of precaution taken by issuing city-wide public notification for water use (e.g. Boil Water Notification). This has occurred in past earthquakes in LA (e.g., Davis et al., 2012).
[3]Critical customers and facilities are described in Appendix B.
[4]May not meet hydraulic requirements for pressure and volume, but sufficient flow to be used with in-line pumping and hauling.
[5]Functionality can be measured using Davis (2014b) or other similar evaluation methods.
[6]Rough estimate of distance based on expected area of delivery service loss, current water bladder plan, and assumed additional support from other organizations such as FEMA, Red Cross, and other volunteer organizations.
[7]Volume and distance estimates based on recommendations from World Health Organization (2005). Volume includes use for consumption (drinking and food preparation), personal hygiene, and laundry.

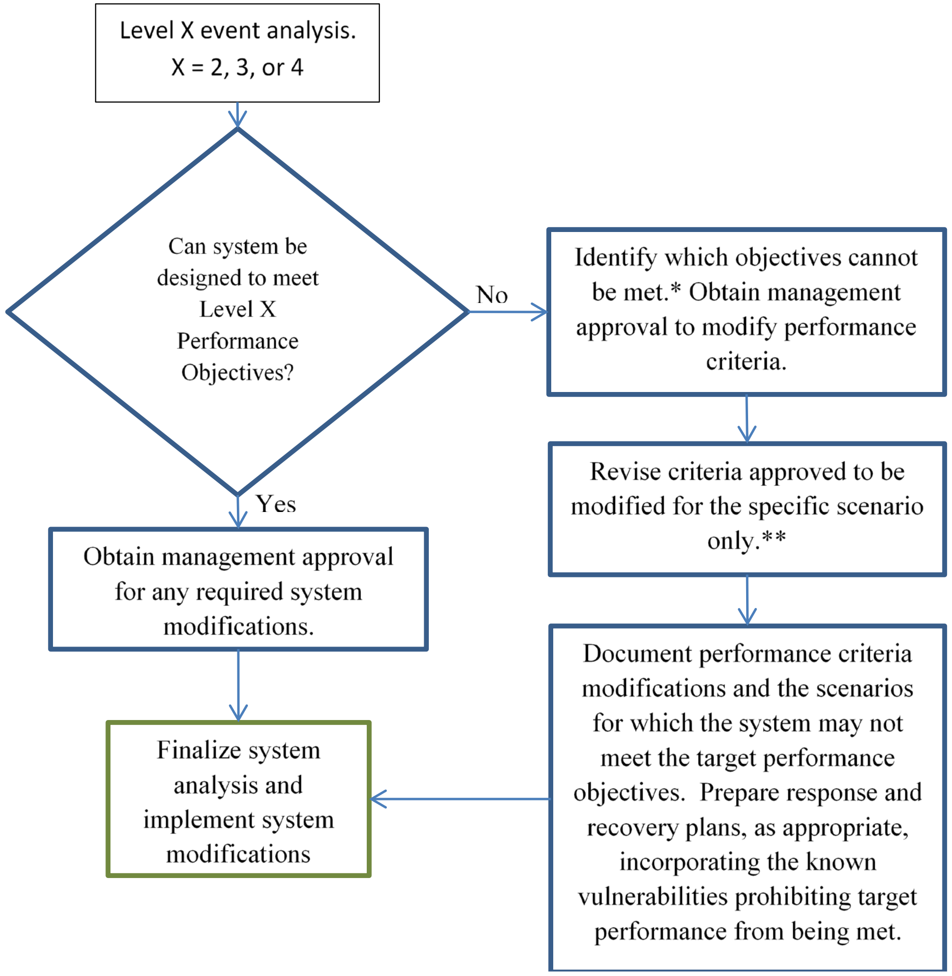
Draft Service Goals – Level 2



Draft Delivery Service Restorations



Work flow for Modifying Levels 2, 3, and 4 Target Performance Objectives



*Some basic service categories may meet the target performance objectives, while others may not. Only propose modifications to those basic service categories which cannot meet the target performance objectives.

**When evaluating which performance, the system may technically or cost-effectively be able to meet, start with assessing the next level target performance criteria. For example, if the system is unable to meet Level 2 performance objectives (Table 2) for a Level 2 San Andreas Fault Event, then check to see if the Level 3 target performance objectives (Table 3) can be met for the Level 2 event; if not, then check the Level 4 target performance objectives (Table 4). If the system is unable to technically or cost effectively meet the Level 4 objectives, then determine alternate number of basic service category losses restoration times to propose and justify for approval. This procedure may need to be applied for different major to great earthquakes.

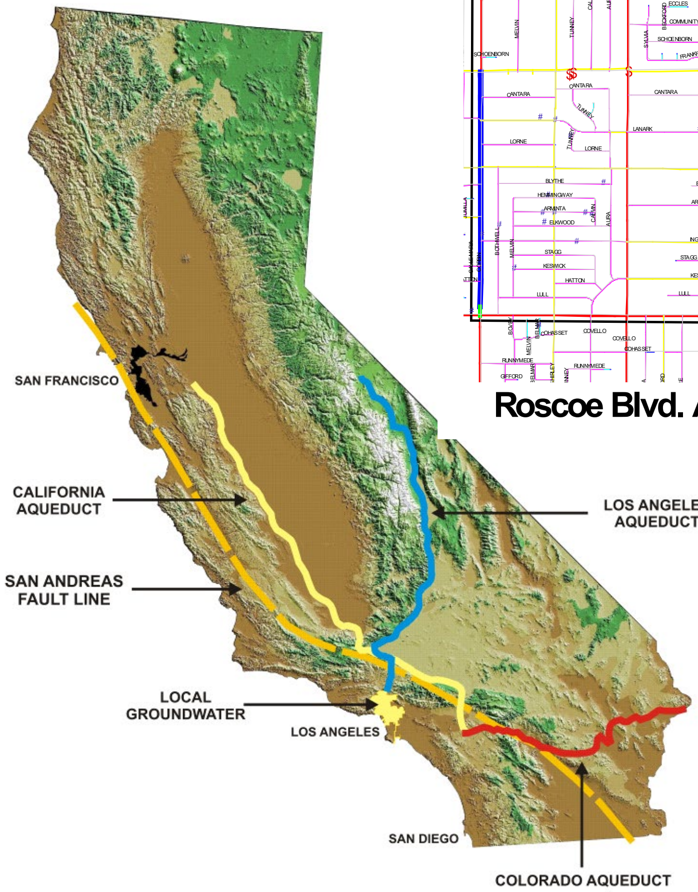
WATER SUBSYSTEMS

Water System is made up of multiple subsystems having their own characteristics

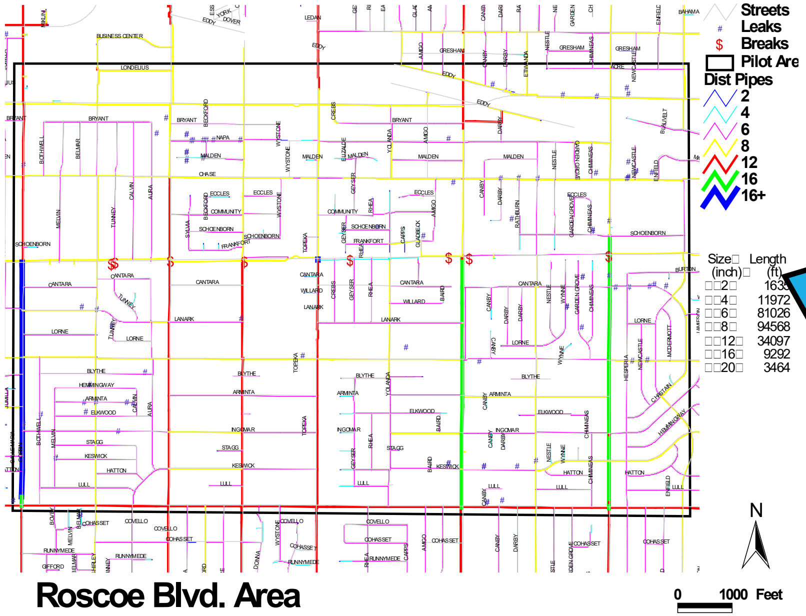
Subsystems	Description	Typical Facilities/Components
Raw Water Supply Systems	Systems providing raw water for local storage or treatment including local catchment, groundwater, rivers, natural and manmade lakes and reservoirs, aqueducts.	Reservoirs, pump stations, wells, pipelines, canals, tunnels, dams, levees, raw water intersystem connections. This may also include pertinent storm water capture facilities.
Treatment Systems	Systems for treating and disinfecting water to make it potable for safe use by customers.	Treatment plants, ultraviolet treatment processes, filtration systems, settling basins, chlorination stations.
Transmission Systems	Systems for conveying raw or treated water. Raw water transmission systems convey water from a local supply or storage source to a treatment point. Treated water transmission systems, often referred to as trunk line systems, convey water from a treatment or potable storage point to a distribution area.	Medium to large diameter pipes (>20”), tunnels, reservoirs and tanks, pumping stations, valves and regulating stations. This also includes treated water intersystem connections.
Distribution Systems	Networks for distributing water to domestic, commercial, business, industrial, and other customers.	All pumping stations, regulating stations, tanks and reservoirs, valves, and piping not defined as part of other subsystems forming a network from connections at the transmission systems to points of service.
Recycled Water Systems	Systems for producing, disinfecting, conveying, and distributing recycled water to customers.	Treatment plants, pumping stations, regulating stations, tanks, valves, and piping.

Los Angeles Department of Water and Power

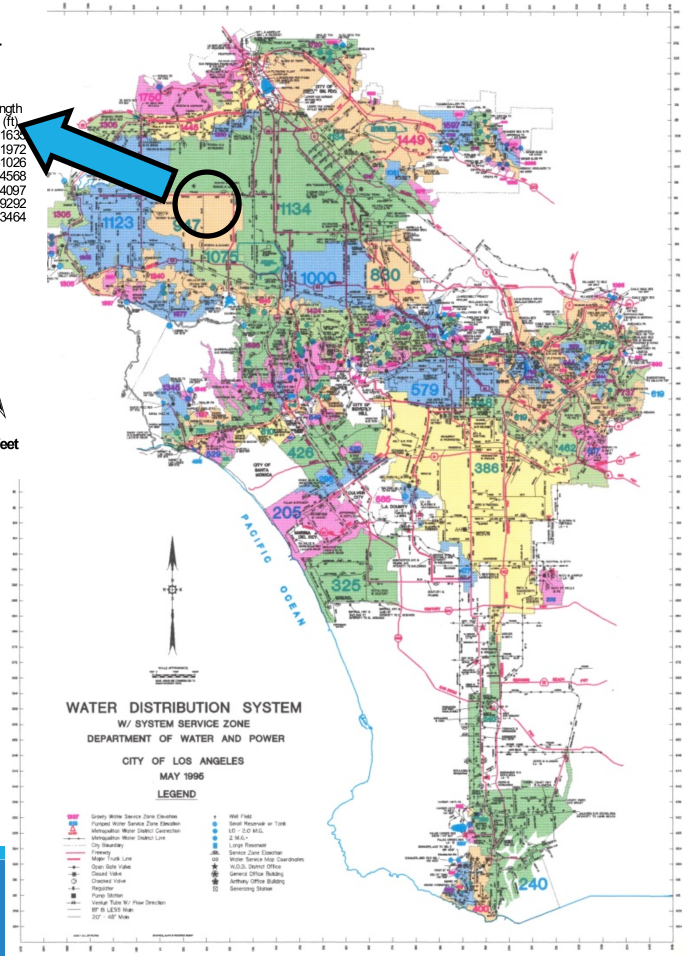
Supply



Distribution



Transmission



Component Level Design

Each component must be designed and constructed in a manner to provide the targeted system performance

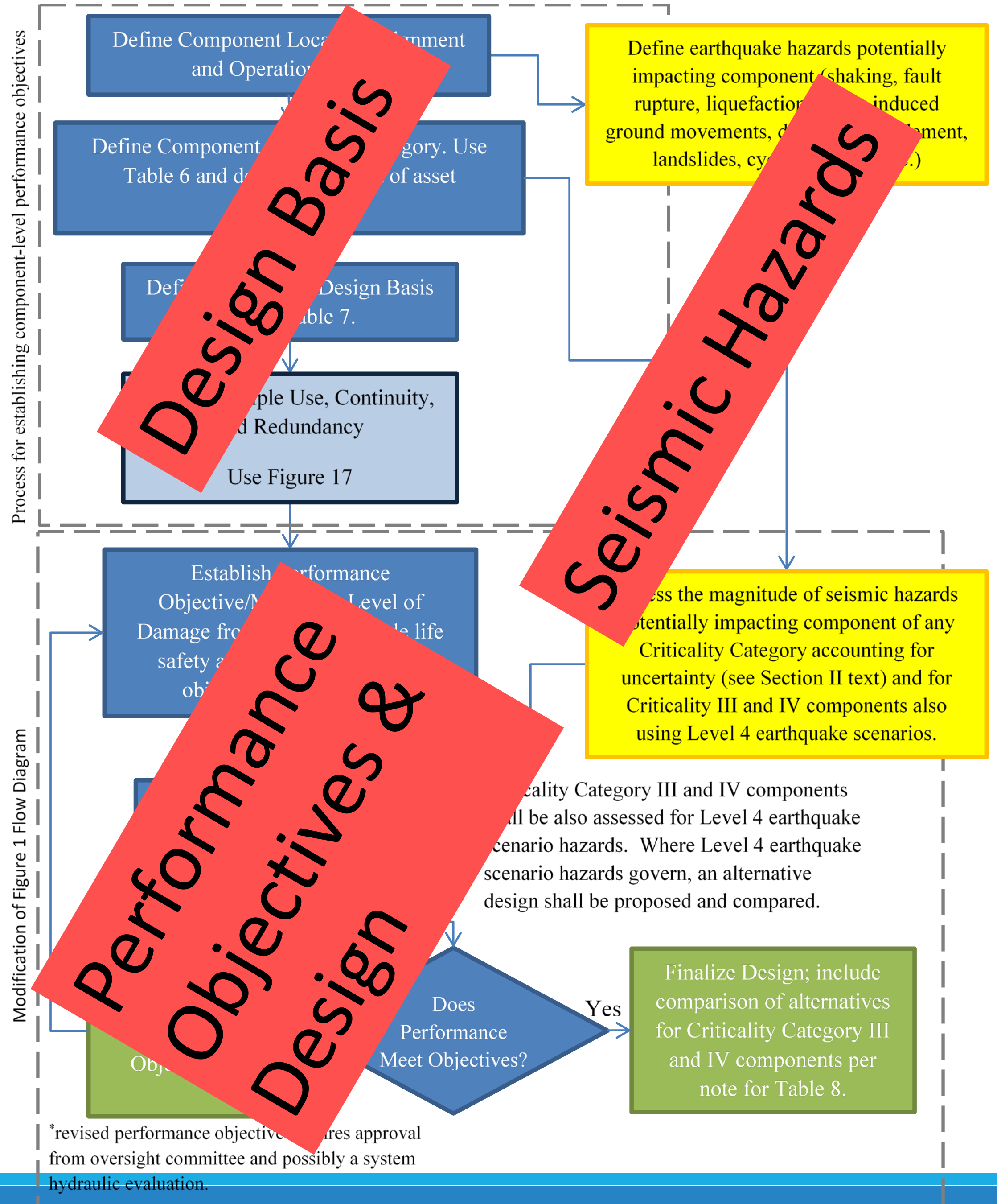


Figure 16

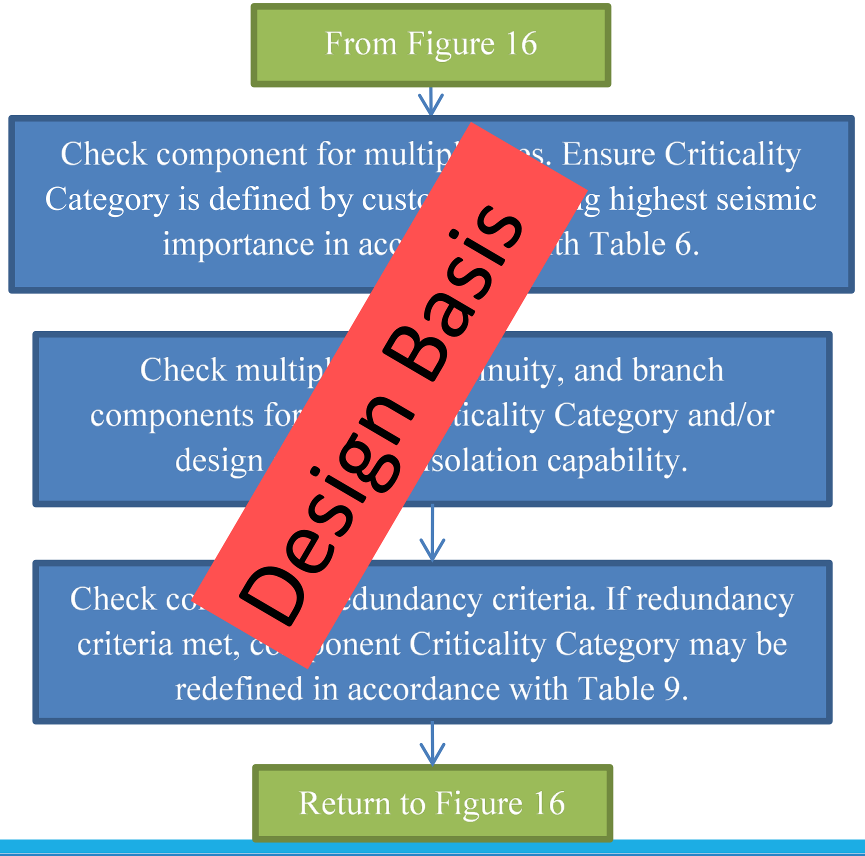


Figure 17

Criticality Categories

Each component is to have a designated Criticality Category I, II, III, or IV

The design of each component for defined hazard return period in table below is expected to aggregate to the desired system-level performance

Criticality Category	Description	Design basis hazard return period (years)
I	Components that present very low hazard to human life in the event of failure. Not needed for post-earthquake system performance, response, or recovery.	72
II	Normal and ordinary components not used for water storage, pumping, treatment or disinfection. They provide water for typical residential, commercial, and industrial use within the system and include all components not identified in Criticality Categories I, III, and IV.	475
III	Components, mainly pipelines, providing water to services that represent a substantial hazard or mass disruption to human life in the event of failure. Failure of these components may result in significant social or economic impacts. **Critical B Customers**	975*
IV	Components needed to provide water to essential facilities for post-earthquake response, public health, and safety. This includes components needed for primary post-earthquake firefighting. These components are intended to remain functional during and following an earthquake. **Critical A Customers**	2,475*

*Note: Also check against Level 4 earthquake scenario hazards,

Redundant Components

	L_R		
Criticality Category	0 [P]	1 [P, S]	2 [P, S, A]
I	I	I, I	I, I, I
II	II	II, II	II, II, II
III	III	III, II	III, II, II
IV	IV	IV, III	IV, III, II

L_R = Redundancy Factor
[P] = primary component
[S] = secondary redundant component
[A] = additional component

- Criticality Category may be reduced based on increased reliability, as long as performance criteria is met
- This redundancy factor shall not be applied to any component which:
    1. Otherwise are required to have a higher Criticality Category based on life safety or other factors,
    2. Are exposed to common cause failures, such as:
        a. A leak or break in one component may lead to damage on other redundant components,
        b. Components are exposed to the same permanent ground deformation hazards (i.e., pipes cross same fault, landslides, liquefaction zones, etc.).
    3. There are foreseeable plans to remove the designated primary redundant component from operation, in which case multiple redundant components shall be designated to be the same highest-level Criticality Category for their intended use.
- Level III still checked against Level 4 earthquake hazard scenarios

Component Performance Objectives

Component performance objectives are established through definitions of maximum tolerable damage

Each designation of minor, moderate, high, and severe damage have corresponding definitions

Designs for Criticality Category III and IV components are to be checked against Level 4 earthquake scenario hazards.

Increasing Performance →

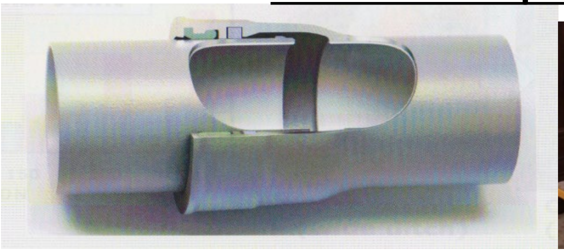
Increasing Event Intensity ↑

Hazard Return Period (yrs)		Criticality Category			
		I	II	III	IV
Level 4 Event Scenario*		Not Applicable	Not Applicable	High to Severe	Moderate to High
	2,475	Very Severe	Severe	High	Moderate
	975	Severe	Moderate to High	Moderate to High	Minor to Moderate
	475	Severe	High	Moderate	Minor
	72	High	Moderate	Minor	Very Minor

<u>Level 4 risk assessment</u>: Present recommendations to management including cost differentials and the potential consequences for not mitigating impacts from the Level 4 events

Technologies needed to Implement PBSD Next-Generation (Resilient) Pipelines

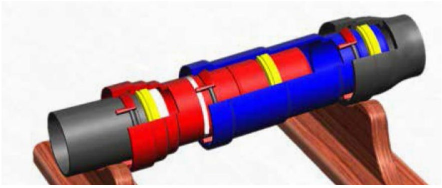
Ductile Iron Pipes



Kubota Earthquake Resistant Ductile Iron Pipe

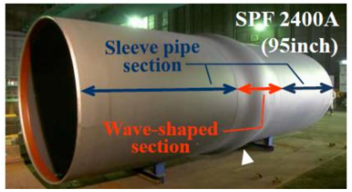
US Pipe TR-Extreme

American Ductile Iron Pipe



Mcwane Ductile

Steel Pipes

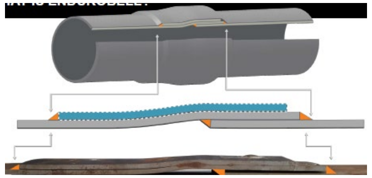


JFE Steel Pipe for Fault Crossings

Butt Welded Joints

Welded-Lap bell and spigot joints

Fiber wrapped joint



EnduroBell

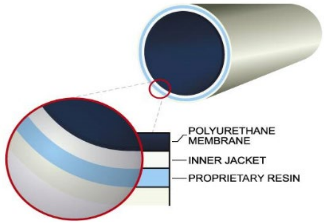
Steel wrapped joint

Plastic Pipes

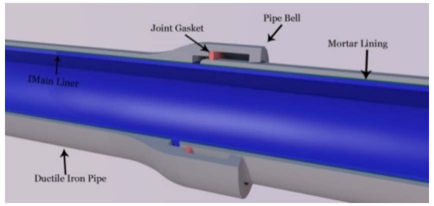
PVC

HDPE

In-Situ Linings



Aqua-Pipe



In-Situ Form

Use to create seismic resilient pipe network

PEER PBEE Methodology

The PEER Methodology is applicable to the described procedure at the system and component levels.

For building components, the methodology has been well defined.

Fragility models are lacking for many other lifeline system components

At the system level, service category losses and their restorations need to be tracked.

System can be assessed probabilistically using entire range of possible events

- Must include probabilities of wide range of permanent ground movements
- Assess system service losses relative to target performance using median values of all possible lost services and restoration times between the best case and the worst-case conditions.

Summary

A Performance Based Seismic Design procedure for lifeline systems has been proposed

Implementation of the PBSD procedure incorporates many of the characteristics needed for a resilient lifeline system

Established target objectives for safety, property protection, and basic lifeline system services

Allows for modification if designs cannot meet performance targets (with management approval)

Provides for efficient design to more extreme events by assessing Level 4 scenario benefits

- Designing to higher level events does not always cost more
- Some cases have provided greater resilience at lower cost

More work is needed to develop methodologies for

- Assessing geotechnical hazards consistent with PBSD application
- Incorporating system interdependencies