# **Title:** Have We Adequately Mitigated Cross-sector Interdependencies of our Critical Infrastructure?

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# Have We Adequately Mitigated Cross-sector Interdependencies of our Critical Infrastructure?

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## ABSTRACT

Each sector of critical infrastructure relies upon other sectors to function. For example, the water and medical sectors depend upon the energy sector. The energy sector in turn relies upon water. In all there are 16 critical infrastructure sectors as designated by the US Department of Homeland Security. The interdependencies among those sectors are complex and dynamic, making it very difficult to predict or quantify scenarios such as cascading infrastructure failures.

Our knowledge of cross-sector interdependencies will advance over time as the problem is studied by researchers and informed by experience. In the meantime, however, we must manage with the limited knowledge we already possess and supplement that knowledge with reasonable assumptions in the absence of hard, factual data.

This paper examines some important cross-sector interdependencies in order to understand the state of current knowledge and assumptions, to assess whether the assumptions are realistic and consistent across sectors, and most importantly, to determine whether available knowledge is being applied, i.e., whether our actions are consistent with our beliefs.

Knowledge and assumptions of cross-sector interdependencies can be revealed in at least five ways:

1. By published advice. For example, water utility customers may be advised by the water agency or other authority to plan on outages lasting up to a certain period of time.
2. By regulation. For example, hospitals may be required to store fuel and water to sustain a certain number of days or hours.
3. By stated intent. For example, if a water utility's emergency plan calls for storing fuel for up to 48 hours, the plan is revealing a key assumption about the contemplated duration of a power outage.
4. By experience. For example, if a water utility experiences several power outages of various durations, that experience becomes part of the working knowledge of potential cross-sector interdependencies.
5. By action. Action is perhaps the truest statement of belief. For example, if a utility invests in the ability to provide essential functions entirely off-grid, it's revealing an assumption about the grid's reliability and resilience.

A review of cross-sector planning assumptions reveals a general awareness of cross-sector dependencies in both directions, i.e., each sector that was studied generally shows awareness of at least some of its own dependencies and also shows awareness of other sectors dependent upon itself. However, some assumptions reveal a systemic optimism regarding the timeline for other sectors to restore service under extreme conditions. Additionally, practices are not always aligned with the best available knowledge, for various reasons including misaligned or missing incentives, cognitive bias and simple lack of awareness.

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# INTRODUCTION

The East Bay Municipal Utility District (EBMUD) is a water/wastewater utility in the San Francisco Bay Area of California, USA, providing water service to over 1.3 million people in a seismically active area.

As the owner-operator of important lifelines, EBMUD is concerned with providing reliability, security and resilience in the face of various hazards. Following a moderate 1989 earthquake that damaged the water system, EBMUD implemented a major seismic upgrade to its system, and continues to enhance seismic reliability.

While the work to improve the water system's seismic performance will likely continue in perpetuity, the goal of this paper is to broaden our outlook somewhat by examining whether larger-scale societal goals are likely to be met should a major disaster of any kind occur. The answer will depend not only upon the degree of damage to the water system, but also on the performance of other systems upon which the water system, and society itself, depend.

## Critical Infrastructure

Critical infrastructure is defined as the assets, systems and networks necessary to support our way of life. In its 2013 Presidential Policy Directive (PPD-21)[i], the US Department of Homeland Security (US DHS) identifies 16 critical infrastructure sectors:

1. Chemical
2. Commercial Facilities
3. Communications
4. Critical Manufacturing
5. Dams
6. Defense Industrial Base
7. Emergency Services
8. Energy
9. Financial Services
10. Food and Agriculture
11. Government Facilities
12. Healthcare and Public Health
13. Information Technology
14. Nuclear Reactors
15. Transportation
16. Water and Wastewater

PPD-21 called for an update of the plan known as National Infrastructure Protection Plan (NIPP). The scope of the update was to identify all critical assets, identify their vulnerabilities to all hazards, whether natural or manmade, and then prioritize them based on risk. The updated plan[ii] is known as NIPP 2013 and is designed to help operators of critical infrastructure reduce risk and improve system resilience.

## Infrastructure Interdependencies and Cascading Effects

NIPP 2013 rests on seven explicit "tenets", of which two are:

- "Understanding and addressing risks from cross-sector dependencies and interdependencies is essential to enhancing critical infrastructure security and resilience"
- "Gaining knowledge of infrastructure risk and interdependencies requires information sharing across the critical infrastructure community."

Consistent with the tenets listed above, the NIPP has included in its 12 "calls to action" to:

- “Analyze infrastructure dependencies, interdependencies, and associated cascading effects”; and
- “Identify, assess, and respond to unanticipated infrastructure cascading effects during and following incidents”.

Infrastructure systems are often highly complex. Vulnerabilities to various hazards, even when considering only direct impacts, may be very difficult to gauge. For example, it is very difficult to predict with confidence which pipes will be broken during a specific scenario earthquake; predicting which pipes will be broken by *any* earthquake scenario is still more uncertain. Even if we knew which pipes would be broken in a given event, quantifying the resulting loss of system function, societal impact, and time to repair is a major task even without considering indirect impacts based on cascading effects or infrastructure inter-dependencies across sectors.

Adding cross-sector interdependencies and cascading effects to the modeling effort might appear to raise the level of uncertainty to such an extent as to defy analysis. Opinions are divided on whether quantitative risk modeling of complex adaptive systems exposed to a range of natural and manmade hazards can practically be done with any confidence. The 1975 WASH-1400[iii] report quantifying the risks of nuclear power was one of the earliest such attempts. The value of quantitative modeling has been debated ever since, and opinions have seesawed. In 1975, most reviewers thought that WASH-1400 had understated risks; however, by 1985, many scientists opined that prior risk assessments had greatly overstated risk.[iv] The popularity of that view lasted only a few months, until the 1986 Chernobyl disaster. Perceptions of risk again then gradually subsided, and the nuclear industry was seen to be on the verge of a renaissance until the 2011 nuclear accident at Japan’s Daiichi plant which was triggered by an earthquake and tsunami.

The limits of risk quantification have been recognized as applying to a wide array of complex systems beyond nuclear energy: in 2010 the National Academy published a report casting doubt on popular risk quantification tools, particularly those that sought to precisely quantify risk posed by acts of malice[v]. Other skeptics such as Nicholas Taleb[vi] have for many years opined that important aspects of the world are fundamentally unpredictable, i.e. that there will always be “black swans” that shape our destiny. Nonetheless, there is intense interest in analyzing and modeling infrastructure interdependencies, based on the idea that improved knowledge of our exposure to interdependencies and cascading effects, despite inevitable gaps and flaws in that knowledge, can help us mitigate adverse effects.

Over time the ongoing studies of inter-sector dependencies and cascading effects will likely continue to produce actionable insights. In the meantime, this paper sets a far less ambitious goal:

> To examine whether *currently available* knowledge regarding interdependencies is being applied to practice and, if not, to understand why.

Where existing knowledge is not being applied, modifying our practices to bring them into compliance with best available knowledge might be a cost-effective way to rapidly improve our resilience since it doesn’t depend upon new fundamental research.

After providing an overview of some interdependencies that are important for water utilities, this paper examines the current state of knowledge about selected interdependencies.

Then it provides information about the degree to which that knowledge is applied to practice. Finally it explores possible reasons for the gaps between knowledge and practice.

## OVERVIEW OF INTERDEPENDENCIES

As the study of interdependencies has received more attention in recent years, terminology to classify inter-dependencies and related phenomena has been developed. For purposes of our discussion, the following definitions are used:

*Interdependency* is a condition whereby systems either rely upon one another for their function, or the failure of one is likely to lead to failure of the other. An example of the first type of interdependency is that a water pumping plant requires electricity. An example of the second type of interdependency is that a subway tunnel may flood and be unusable if the water main above the subway breaks.

*Common-cause failures* are not the result of interdependencies, but rather are infrastructure failures of different systems directly owing to a single cause. For example, a flood may directly damage the electrical supply system, the road network, and the water supply system.

Dependencies can manifest themselves in two ways: *cascading failures* are those where a disruption in one system causes a failure in the other system; *escalating failures* are those where a failure in one system exacerbates an independent failure of the other system.

One snapshot of a few key infrastructure interdependencies is shown below (from Rinaldi[vii]):

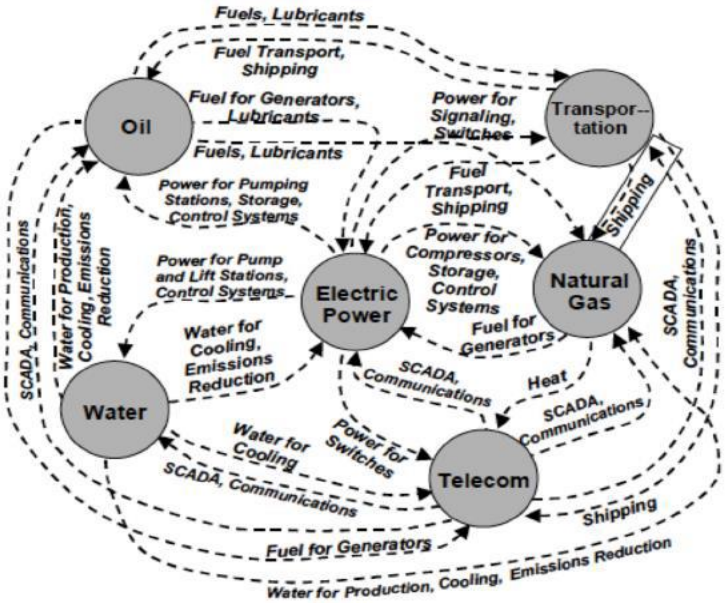

Figure 1 Schematic of Cross-sector Interdependencies

# KEY INTERDEPENDENCIES FOR THE WATER SECTOR

## Overview

The water sector relies upon and/or is relied upon by several sectors discussed below.

### *Energy*

The water sector's reliance upon energy is common knowledge, with the term "water-energy nexus" a beacon of the frequent hyperbole surrounding the connection. An often-cited factoid claims that nearly 20 percent of California's energy is used for water. The factoid turns out to be both false and misleading; the truth is that an estimated 20 percent of *electricity use* is connected to water, and the lion's share of that usage is by end-users and is not for water supply or treatment.[viii] Other uses dominate: for example, personal vehicles account for 17%[ix] of total energy usage in the US, a share that dwarfs the few percent used to treat and supply water.

Hyperbole aside, the water sector is strongly dependent upon energy for essential treatment and pumping operations. Like many utilities, EBMUD's treatment process relies upon electricity, and EBMUD can serve only about half of its 1.3 million customers by gravity, relying upon electrical power to pump water to the remainder.

Beyond the role of grid power for water treatment plants and pumps, fuel energy is needed to power a utility's emergency generators and fleet vehicles and for the workforce to be able to report to their jobs. California is particularly vulnerable to fuel disruption because its fuel mixture is non-standard – it must refine all of its own gasoline and cannot import refined gasoline from other states. Minor hiccups such as refinery fires have demonstrated the state's vulnerability to fuel shortages. The state as a whole has an average of about a ten-day supply of refined gasoline, less than a third of the national average inventory level.[x] Those modest reserves of refined gasoline may prove difficult to access since local fuel stations as a rule do not have backup power (only Florida and Louisiana among the 50 states require backup power at service stations[xi]).

The energy sector is also strongly dependent upon the water sector; in EBMUD's service area, two oil refineries with an average water demand of about 12MGD account or about 7% of EBMUD's system-wide usage. A disruption of those refineries would be very serious since five Bay Area refineries comprise about 40% of the refining capacity for the entire state of California[xii].

Given the strong interdependence of water and energy, this particular interdependency is studied in more detail later.

### *Communications*

Communication systems are essential for supervisory control and data acquisition (SCADA), computer networks, and voice networks. This dependency has been magnified in recent years by several trends:

- Increased reliance on control systems for daily operations
- Increased reliance on cloud computing and hence on the network
- Increased reliance on long, just-in-time supply chains

Further, a trend toward increased reliance on commercial providers has in many cases increased day-to-day functionality and efficiency but has also introduced a new set of risks. Some utilities that in the past used their own analog radio network have transitioned to regional radio services such as P25 or outsourced aspects of communications using leased lines, commercial cellular or internet connections. This trend is pervasive, applying even to extremely sensitive and critical operations such as the US military, which by many estimates relies upon commercial providers for over 80% of its satellite communications[xiii].

That transition to commercial or regional communications can provide various benefits such as better areal coverage, encryption and selectivity at low cost. However, that transition increases exposure to common-cause failures (since multiple sectors may be affected by the same communications failure) and to acts of malice. For example, the P25 radio system is subject to jamming[xiv], by which a bad actor could cripple regional communications across multiple sectors. Vulnerability to denial of service and attacks are not unique to P25 but rather likely apply more broadly to other trunked radio systems.[xv] Despite these vulnerabilities, adoption of digital trunked radio systems continues as evidenced by the growing list of agencies using trunked radio systems[xvi] and driven by the mentioned advantages.

Communication providers rely directly upon the energy sector and thus indirectly upon the water sector. The energy sector in turn relies heavily upon the communication sector – and like the water sector, its dependence has grown greatly in recent years with the mass migration from private communication systems to commercial networks.[xvii] Thus, the trio of communications, water and energy are tightly interconnected interdependent systems.

### *Food*

Water providers rely upon food to the degree they rely upon a workforce including employees, contractors and vendors. A 2006 study[xviii,xix] indicated that on average 41% of water-sector employees are critical to operations; thus it seems reasonable that food stockpiles would be based on sustaining at least that fraction of the total workforce after a disaster.

### *Chemicals*

While it’s common to have significant inventory of certain chemicals on hand, particularly disinfectants, the water treatment process relies upon regular chemical deliveries. The chemical industry in turn relies upon water.  Chemical manufacturing in EBMUD’s service area accounts for about 0.5 MGD, or about half of one percent of the total system demand. While that water demand is small compared to the energy sector, it’s highly inelastic and quality-sensitive. Even minor disruptions in water quantity or quality can have large effects.

### *Transportation*

Transportation networks are vital for a retail water service provider to facilitate day-to-day operations and maintenance. This dependency can increase substantially in a post-disaster setting that increases the need for field response, e.g. to elevated levels of main breaks. Transportation networks in the Bay Area are quite vulnerable to direct disruption by an earthquake or other disaster[xx], and are also vulnerable to cascading failure due to strong reliance upon the energy sector (e.g. for traffic signals and electrically powered rail).

### *Medical*

Water providers rely on the medical sector to the extent that the medical infrastructures sustain a healthy workforce, a reliance that should not be underestimated: A 2013 study[xxi] by the Mayo Clinic found that approximately 70 percent of Americans take at least one prescription medication, up from 44 percent in 1999. The dependence upon medical services may increase substantially following a disaster.

Medical providers rely heavily upon water for potable consumption, cooling, dialysis and other functions, as well as energy for all essential functions. Given the surge in demand for medical services following many disasters, medical sector dependencies are discussed in more detail later.

## STATE OF CURRENT KNOWLEDGE AND BELIEF

Current knowledge and belief about inter-sector dependencies and cascading effects can be revealed in at least five ways:

1. By published advice. For example, water utility customers may be advised by the water agency or other authority to plan on outages lasting up to a certain period of time.
2. By regulation. For example, facilities (hospitals, water treatment plants, etc.) may be required to store fuel and water to sustain a certain number of days or hours.
3. By stated intent. For example, a water utility's emergency plan that calls for storing 48 hours' worth of fuel reveals a key assumption about the contemplated duration of a power outage.
4. By experience. For example, Hurricane Sandy revealed some inter-sector dependencies which, while obvious to some prior to the event, became indisputable to all after the event.
5. By action. Action is perhaps the truest statement of belief. For example, if a utility invests in the ability to provide essential functions entirely off-grid, it's revealing an assumption about the grid's reliability and resilience.

### Selected Dependencies

For purposes of this paper, "current knowledge" was explored for the following specific dependencies:

- Dependencies of water providers upon several sectors: energy, communications, food, chemicals, transportation and medical.
- Dependency of the medical sector upon water.

These sets of dependencies were chosen because they have received enough attention to permit characterization of the state of current knowledge. Current knowledge and-or assumptions regarding specific relevant dependencies are discussed below, one sector at a time.

### *Energy*

Stand-by power for water utilities is addressed in Section 2.6 of the widely adopted "10 States Standard". One interpretation[xxii] has expressed that the goal is to have either standby power *or* water storage at treatment and pumping locations to meet average-day flows plus fire flow for a period of at least eight hours.

The American Water Works Association (AWWA) has a clear policy statement[xxiii] calling for utilities to examine and mitigate the impact of electrical outages of "72 hours or longer", but the policy statement has no force of law.

Some jurisdictions clearly go well beyond the meager "10 States Standard" of eight hours. For example, New Jersey's standards, adopted in the aftermath of Hurricane Sandy, state "although power failures can vary in duration from a matter of minutes to multiple days, maintaining continuity of operations is required regardless of the duration of the outage."[xxiv] The New Jersey standard seems to envision that substantial pre-incident warning may be available, e.g., it advises stockpiling fuel in anticipation of a storm's imminent arrival. Thus, while the standard sets a high bar, it's not clear that it's realistic for zero-warning incidents like earthquakes or terror attacks.

Industry practice can also provide some insight into beliefs. For example, EBMUD has 375 facilities that require electrical power to perform their essential functions. This number includes 7 supply reservoirs, 2 regulators, 122 pumping plants, 28 rate control stations, 7 treatment locations and 185 treated-water reservoirs. Only 12 of the 375 locations (about 3%), including the 7 treatment locations and 5 critical pumping plants have permanently installed backup power. The rationale for the other 98% of facilities is that treated-water storage is never less than 24 hours, i.e., a "max day"[1], and is often substantially more. For the few locations with backup power, the average fuel supply is approximately 24 hours based on average, not peak, loads.

In summary, stated industry standards, and actual practice, involve various assumptions ranging from as little as 8 hours to 72 hours or more without power. It's worth examining the degree to which these standards are reasonable and prudent, based on two measures:

- actual power outage durations based on experience
- projected power outage durations based on modeling, analysis or extrapolation of experience

Neither of these measures is straightforward, since we have not agreed on, among other things, the probability of exceedance that would be acceptable, i.e., what risk we're willing to assume of running out of water based on lack of power or storage. Regional power outages in the United States have lasted two or more days, and some of them have been even larger than "regional" such as the 2003 Northeast blackout that lasted over two days and affected about 10 million people. Despite some perceptions that the 2003 outage was a fluke, or that weaknesses it exposed were flukes, the overall risk of power outage has not abated since 2003 but rather continues to rise.[xxv] Several well-documented large outages were actually near misses, i.e., they

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[1] Storage criterion historically was 1.5 times Max Day Demand (MDD), with operating range of 70-100, leaving about 1 MDD as minimum. In 2003, EBMUD revised the criterion to 1.0 times MDD based on water quality concerns and the new standard is resulting in a gradual decrease in storage as EBMUD rehabilitates its reservoirs.

could have easily been either larger in extent or duration but for luck; a good example is the 12-hour Pacific Southwest outage of September 8, 2011 that affected about 3 million people.

While many of the power outages comprising the statistical baseline were caused by severe weather, some are "sunny day" failures, i.e., they occurred in the absence of a major disaster such as an earthquake, solar storm, act of malice, etc. Seen in this light, it's clear that if regional-scale power outages lasting a few days may readily occur absent a disaster, we ought to assume that much longer outages might occur post-disaster since the extent of damage might be greater and restoration would be hampered by interdependencies. Overall, given that actual power outages in excess of 48 hours have actually occurred, criteria such as the 8-hour "10 States Standard" should be regarded with skepticism. It is notable that the 2003 blackout discussed above actually affected the geographic area governed by the "10 States Standards". Direct experience of affected utilities, such as in Cleveland, Ohio, one the "10 States," showed conclusively that regional outages far longer than 8 hours may occur[xxvi].

Anecdotal information supports the idea that the duration of a power outage might be extended by circumstances of a simultaneous disaster (as opposed to "sunny day" failures). After the 1994 6.7M Northridge earthquake, about 300,000 people still lacked power a week later; the number would have been far larger but for urgent (and effective) restoration efforts that shrank the extent of the power outage from an initial 2,000,000 people to about 1.2M by 8 hours after the earthquake and to 680,000 within twelve hours. The gas supply was disrupted for up to 12 days.[xxvii]

Various attempts have been made to quantitatively model energy system outages following particular scenario disasters[xxviii]. The modeling challenge is quite significant. It seems easier to estimate the likely extent of a power outage than to estimate restoration time, given the multiplicity of factors contributing to restoration times such as which components are damaged, whether spare parts are available, extent of damage to other sectors, etc.

A final reference point might be drawn from the assumptions of other sectors about their energy supply reliability. In California, the Hospital Facilities Seismic Safety Act passed in the immediate aftermath of the 1994 Northridge quake requires that hospitals be prepared for 72 hours without energy or water (although the standard is not mandatory until 2030). Federal accreditation standards for hospitals require 96 hours but with an exception, which is that a hospital can achieve accreditation with less than 96 hours of energy by planning to close as needed.

In summary, while there is a wide range of assumptions in play regarding the duration of power outage that ought to be anticipated, some of the assumptions are more reasonable than others. The preponderance of industry guidance, as validated by our limited experience, seems to validate an assumption of 72 hours or more without power.

## *Communications*

The primary risk factor for a communication system outage is often thought to be loss of power, although other credible causes of outage exist such as acts of malice. For example, a hacker could disrupt communications such as trunked digital radio or internet communications, or a saboteur could physically destroy critical network links or nodes.

Code provisions and other standards describe standby power for communications and other important functions. For example, the National Electric Code (NEC) 701 requires standby power be enabled within 60 seconds for important "legally required" systems, which is far less demanding than the 10 second standard for "essential emergency" systems. That standby power must be sufficient for at least two hours per NEC 701.11(B)(2); it need not include truly independent power and thus can be met by an auxiliary power service rather than battery or generator power.

However, few if any communication systems used by water providers are legally required to have either "essential emergency" or "standby" power. Based on the experience of Hurricane Katrina, the Federal Communications Commission (FCC) had proposed in 2007 that cellular providers be required to provide 8-24 hours of backup power[xxix] or comply with one of various proposed exemptions. The rule was withdrawn after industry opposition[xxx] pointed out the challenges in providing backup power in often extremely space-constrained sites. In the meantime, a commission set up by the FCC to study the issue has recommended a far higher bar of a minimum 48-72 hours of backup power.[xxxi] This recommendation by the FCC meshes with recommendations of other agencies, e.g. the former CEO of United Kingdom Radio Communications Agency calls for a 72-hour standard.[xxxii]

From the viewpoint of a water service provider, a key question is whether we can safely assume that the communications sector has fully mitigated its known cross-sector vulnerabilities – in which case we can assume zero downtime of communication – or not, in which case we may be exposed to some or all of their underlying vulnerabilities. Clearly the failure of an 8-hour power rule stands in stark contrast to the 72-hour standard based on expert opinion, and signals that we ought to plan for major disruption of communications during any power outage exceeding a few hours. Moreover, since power is required to run all modern communication systems, many backup communication systems will suffer common-cause failures at the same time as the primary communication systems fail. Thus, prudent planning would assume that many or most communications may be down for the same duration as power, i.e. one should plan for 72 hours or more.

## *Food*

The water sector depends upon the food sector to the extent the workforce supporting the water sector needs to eat. Current beliefs about the food dependency can be inferred from guidance given to that workforce and guidance given to the population at large.

The Red Cross in some of its publications suggests *everybody* have *at least* three days' worth of food and other necessities. By contrast, the Federal Emergency Management Agency (FEMA) in its 2004 Publication 477[xxxiii] (A5055) suggests preparing for a *two week* interruption in food, water and electricity. The Centers for Disease Control (CDC) bridges these two values by suggesting three days as a bare minimum and recommends a two-week assumption "if possible".

It's reasonable that water utilities, as critical infrastructure providers, would base their own readiness on the upper end of the spectrum, given that caloric intake reduction strategies available to the population at large are not viable for workers who are vital to response and recovery efforts.

The medical sector has regulations that reveal its assumptions regarding food and water reliability. State law (CA Title 22 Section 70277) requires a seven-day supply of non-perishable staples and two days of perishables. A 2013 guidance document[xxxiv] by the California Hospital Association makes it clear that it's prudent to plan for potentially more, not less, than the baseline number of mouths to feed.

In short, it's generally acknowledged that the food supply may be disrupted for up to two weeks, with three days being the minimum responsible planning criterion. As mentioned earlier, in the absence of contrary evidence a utility might assume that 41% of their workforce is critical to operations, and thus may be able to rationalize keeping food for only that subset of the total workforce.

### *Chemicals*

The "10 States Standard" among others calls for minimum 30-day inventories of all chemicals[xxxv]. Because sodium hypochlorite degrades with time, it's not common to greatly exceed a 30-day supply of that vital chemical.

### *Transportation*

Transportation impacts of a major Bay Area earthquake have been recently studied.[xxxvi] In general, it is expected that a major earthquake will cause severe regional transportation impacts including direct damage, loss of service due to power outages, and loss of service due to debris blockage[xxxvii]. This expectation is generally validated by experience in the Bay Area and worldwide. Even the relatively modest 1989 Loma Prieta earthquake caused damage to the transportation network that caused significant regional impact for several weeks, and took years to fully repair. A larger event is likely to cripple primary commuting links for months.

Unlike the dependencies of other sectors, which were characterized by anticipated outage durations, the transportation dependency cannot be well characterized by a single number because even in the worst case, the entire transportation network is not likely to be down. Rather, the network will be degraded, effectively increasing the time and cost associated with moving various people and goods. This increase leads to reduced workforce productivity and higher lead times for delivery of materials, supplies and equipment, both of which *could* in theory be factored into recovery and response plans.

### *Medical*

It's generally accepted that various disasters will pose increased need for various medical services or supplies.  For example, earthquakes are expected to cause a surge in trauma cases by the event itself and possibly by the response efforts. Given that hospitals will be facing their own set of issues, discussed below, it's important that utilities have first aid capability for reasonably foreseeable minor injuries. However there appears to be no quantitative standard for first aid capability.

Disasters other than earthquakes may pose more significant medical needs; for example a pandemic would prompt personal protective equipment (PPE) in the form of gloves and masks or respirators.  Regulatory guidance for a pandemic calls for a stockpile of PPE sufficient for each critical infrastructure worker to have two sets of PPE (gloves, masks) per work shift for 120 work shifts[xxxviii]. Recalling that about 41% of water sector workers are deemed critical, and assuming non-critical workers either stayed home or were denied PPE, a utility with 2,000 employees needs a stockpile of about 200,000 sets of PPE. The rationale behind the stockpile is the assumption that one will not be able to obtain PPE after the onset of a pandemic from vendors, hospitals or government; this assumption is validated by government guidance as well as by shortages experienced in the past for even minor events.[xxxix]

### *Medical Sector Dependence on Water*

As mentioned earlier, the medical sector has regulations governing planning for food, water and energy. In California, regulations call for a minimum of 72 hours, but those regulations don't come into full effect until 2030. At the federal level, the Joint Commission, an organization that certifies hospitals, in 2009 called for a 96-hour standard, but provided a major way to achieve compliance without meeting the standard: closing the facility when the water ran out.[xl]

Also as mentioned above, the water sector and various governmental and non-profit groups advise all sectors to be prepared for water outages. Specifics vary:

- Red Cross says "at least" 3 days
- FEMA advises 14 days[xli]
- CDC advises 3-14 days
- USGS advises "at least" 3-5 days[xlii]
- EBMUD advises all of its customers to be ready for 3-7 days of service interruption and acknowledges that for some scenarios and some customers the outage may be greater

In summary, it's generally acknowledged that all sectors, including medical, should be prepared for water outages of 3-14 days. The medical community has access to sector-specific guidance documents by AWWA, CDC[xliii] and others[xliv]. Actual experience of the medical sector includes several anecdotes of multi-day outages, with very few exceeding 14 days, so the 3-14 day guideline is not unreasonable.

## Summary of current knowledge about cross-sector interdependencies

The best available current knowledge is that various sectors should be prepared for interruptions in services from other sectors, as follows:

- 3-day interruption in electrical power on a regional scale, longer interruptions on local scales
- 3-day suspension of fuel, with longer periods of very limited supply
- 3-day interruption in communications
- 30-day interruption in chemical delivery
- 3-14 day interruption in water delivery
- 3-14 day interruption in food availability
- Variable, possibly major impacts to transportation, some lasting for months or years

As stated earlier, the information cited above is not the result of new sophisticated modeling, but rather a synthesis of readily available and generally accepted standards among regulators and industry experts, informed by actual experience. The next section explores the degree to which this "common knowledge" about cross-sector dependencies is reflected in practice.

## APPLICATION OF KNOWLEDGE TO ACTION

### Water Sector Dependencies

Information about water sector readiness is largely anecdotal. For this paper, five major urban water utilities in the western US were questioned, with the understanding that information cited would not be connected with individual utilities. Additionally, recent published accounts of utility experiences during natural disasters were consulted.

The survey results suggest there may be a gap between current knowledge of cross-sector dependencies and actions to mitigate them. The following summarizes the cross-sector dependencies of the five utilities surveyed, with any significant variances among the utilities noted. Some utilities provided information in select areas only so in some cases the sample size is smaller than five.

#### *Energy*

Accounting for storage of treated water, the utilities can generally withstand a power outage of 24-72 hours under average demand and supply conditions before the first customer runs out of water. The wide range cited is owing to some variation among the utilities, as well as some fundamental uncertainty, and variation in standby water storage across a large network. The range is fairly representative since none of the utilities strives for more than 72 hours of uninterrupted service, nor does any strive for less than 24 hours – except one utility that has no formal goal.

Should a power outage exceed 72 hours, serious problems might develop:

- Most of the utilities have permanent standby generators at a small fraction of the total electricity-reliant locations such as treatment plants and pumping plants, and limited mobile generators sufficient for a fraction of the remainder.
- Those permanent generators have fuel on-hand ranging from about 24 hours' worth to as much as 72 hours.
- Fuel stockpiles for major equipment and vehicles are likewise sufficient for about 24-72 hours of normal usage, most of the time. Usage for many types of equipment would likely spike after an earthquake in order to deal with assessment and repair of damage. One utility shares fuel storage with other agencies that could assert higher priority, and thus has no assurance of even 24 hours of storage for use by the water system.
- No utility earmarks fuel for emergency use by employees, despite the common assumption that a major disaster could find employees unable to purchase fuel and mass transit severely disrupted. At least one utility's emergency plan advises employees to pre-install on their smartphones Gas Buddy software, an application which reports fuel prices based on location. This measure would be irrelevant should a disaster render smartphones useless and gas unavailable in any case.
- Stockpile of flashlights and batteries is sufficient for a few percent of the workforce for a few hours of use.

Overall, fuel stockpiling practices assume that fuel delivery from either commercial or in-house sources would be readily available within 24-72 hours of a crisis – an assumption that could be in doubt if the transportation network is degraded, local refineries are offline, and power outages of regional or larger scope are occurring.

The major factor contributing to good overall resilience for most of the utilities is that a significant amount of treated water is kept in storage, which mitigates risks of many kinds even beyond power outages. To the extent these large reserves would be considered "oversized" today, they are legacies of an earlier era when more storage was considered better. As awareness of disinfection byproducts has grown and regulations have evolved, the tendency is for treated-water storage to shrink rather than grow, and for storage-derived resilience to likewise shrink.

### *Communications*

The utilities generally have multiple communication pathways intended to provide a measure of reliability through redundancy. For example, it's common to have some limited satellite voice and-or data communications as a fallback should the primary system go offline.

In general, however, despite significant effort by all of the utilities surveyed, communications remain something of an Achilles heel. The challenges faced by the utilities include:

- All of the utilities have over time become increasingly reliant on IT and various forms of electronic communication for virtually every aspect of work.
- Reliance on commercial providers in particular has increased over the past 20 years for cellular, internet and SCADA communications. At least one utility abandoned its analog radio system in favor of commercial providers; while this move improved areal coverage and day-to-day reliability, it makes the utility more vulnerable to a common-cause failure such as a regional power loss or cyber-attack on vendor systems.
- As mentioned earlier, commercial providers are fairly resilient for short-term power outages but their ability to withstand multi-day power outages is highly questionable.
- Events that cause no direct damage to telecommunications and power systems can still result in crippling levels of overload to those systems. This has been demonstrated by small earthquakes in the Bay Area as well as the Boston marathon bombing, to name just two examples.
- There is little or no systematic deployment of solar backup communications gear. EBMUD for example has solar power for communications at only a handful of locations; the vast majority of battery backup for communications is only good for a few hours.
- There is little or no systematic deployment of backup batteries or hand-cranked equipment for communications. As many people have experienced firsthand, power consumption of cell phones tends to increase as network service degrades, so the need for a recharging station for handhelds may peak shortly after the onset of a crisis.
- At least one utility reports that a fallback communications plan based on ham radios had atrophied based in part on a conservative legal opinion that planned use of ham radio by an organization might be illegal since ham radios are for amateurs.

In summary, the measures taken thus far by most utilities will likely be insufficient to fully mitigate the impacts of a major disaster on communication networks.

### *Food (and Drinking Water)*

Not all utilities have a formal goal for emergency food. Most of the utilities with a goal reported that the goal is to stockpile about three days of emergency food and drinking water. The limitations of the plans include:

- As discussed, three days is the bare minimum, and is far less than the two weeks advised by FEMA.
- While some utilities all employees in the headcount for emergency food and water, some considered a relatively small percentage of the total workforce, in some cases far less than the industry-average 41% comprising “critical” workers.
- Some utilities reported that food readiness goals are not formally adopted within the utility, nor universally followed – essentially, each work unit handles its own readiness in an ad hoc manner.
- A major crisis will result in around-the-clock operations, two to three shifts per day, with each shift requiring up to three meals, so the burn rate of the food may be far larger than planned.

In short, stockpiling of food and drink is very uneven: while some utilities both strive for and actually have approximately three days’ worth of food, others fall short in various ways, ranging from vague or missing goals to optimistic staffing and operational assumptions. And as mentioned, the three-day goal, even if it were being met, lies at the extreme low end of accepted guidelines for the general population and is thus very questionable for a critical infrastructure provider.

### *Transportation*

Anticipated transportation impacts could include higher costs and greater lag times for movement of people and goods following a disaster. One measure of whether these impacts are accounted for by a water utility would be whether response and recovery plans have assumed post-disaster time and cost multipliers greater than 1.0.

The short answer appears to be no. The surveyed utilities have instead taken measures such as spare parts inventories and prearranged vendor contracts. While those measures are unquestionably prudent, it’s not clear that they are sufficient to mitigate a widespread disruption of transportation. Local-area vendors themselves will be affected by any large-scale disaster, and may be unable to respond. Even if vendors can respond on a limited basis, equipment lead times for many electrical and mechanical items may be exceptionally large, given that some equipment such as transformers and large valves has lead times of several months or a full year even *without* supply chain disruption.

It is likely that major damage to the transportation sector will impact not only equipment lead times but virtually every aspect of work, starting with the basic ability of workers to report for duty and obtain basic necessities. Fuel shortages will tend to create cascading impacts, particularly since none of the utilities stockpile fuel for employee use. In an environment of critical fuel shortages and possibly major transit disruptions, utilities will be hoping that employees either possess their own reserves of fuel sufficient to commute to and from work through debris-laden and possibly damaged roadways, or else can purchase fuel somehow.

### *Medical*

One utility reported that very rudimentary first aid kits are kept in the workplace but they contain nothing for major trauma and, owing to liability concerns, contain only very limited medication. Employees are advised in internal documents to keep an unspecified quantity of any needed prescription medication on hand. Of course some prescription medication requires refrigeration that may not be covered by backup power.

Considering PPE needs appropriate to various types of major disasters, the readiness gap for seismic is relatively modest (utilities should have PPE appropriate for facility inspections, for example) but the readiness gap for a pandemic, as one example, is far more significant.
None of the utilities contacted had significant if any stockpiles of pandemic-suitable PPE, a finding that seems to mirror other reports of relatively little detailed operational planning for pandemics[xlv]; for some utilities the inventory of masks and gloves may be little or nothing beyond that might be found in a few first aid kits -- a level that is dwarfed by the thousands of sets that would be recommended for a medium-size utility per regulatory guidelines.

### *Summary of Water Utility Readiness*

The thumbnail sketch outlined above illustrates that the surveyed water utilities have generally taken sound measures to mitigate their dependence on various sectors, but that more could be done:

- Standby fuel storage in some cases falls short of the generally agreed 72-hour standard, based in part on the shaky assumption that fuel deliveries will be available within 24 hours. That shaky assumption is widespread: for example, a 2012 AWWA Journal article[xlvi] acknowledges that “the power may be out for weeks or even months” but in the same paragraph advises 24 hours’ worth of fuel.
- No provision is being made to facilitate the workforce getting to and from work following a disaster when fuel may be very limited and mass transit may be down or disrupted. Fuel inventories are not sized for this need. To the extent that it’s assumed employees could “camp out” at work in lieu of commuting, there is no evidence of other planning consistent with that assumption, e.g., additional stores of food and water, or other plans for employee care.
- Food and drinking water stockpiles run toward the lower end of the 3-14 day standard. In some cases food and water stockpiles may fall short of even the 3-day standard due to optimistic assumptions or failure to set a formal goal.
- The most serious readiness gap is relative to communications, for which typical mitigations consisting of backup systems are all vulnerable to common-cause failures such as loss of power. And while many utilities strive to be ready for direct impacts of extended power outages up to 72 hours, those utilities rely on commercial communication systems that in many cases may only withstand power outages of 8 hours or so.
- It is not clear that water utilities are fully prepared for post-disaster medical needs. Gaps include lack of serious first aid capabilities, and lack of PPE suitable for scenarios such as pandemics.

## Medical Provider Dependency on Water

There are a few sources of information about hospital readiness:

- A 2001 survey of all state hospitals by the State's "OSHPD"
- A 2006 survey[xlvii] of 31 hospitals in the Washington, DC area
- EBMUD's discussions with hospitals within its service area
- Anecdotal information

Generally, the above information sources indicate that while most hospitals acknowledge 96 hours as a reasonable goal, very few hospitals are currently prepared to meet even the 72-hour minimum standard set by the 1994 Hospital Facilities Seismic Safety Act, and none could sustain an outage of greater duration, such as the FEMA-suggested two week duration, without significant service curtailment. Details follow:

- The 2001 State survey showed only 53 hospital buildings out of 2,467 statewide had achieved "NPC5" status, which includes a 72-hour readiness for power, water and wastewater.[xlviii]
- The 2006 survey at first glance seems to contain good news: 26 of 31 hospitals reported water for 2.5 days, only 0.5 days short of the 3-day minimum. But further probing reveals that most of the respondents were reporting on levels of bottled water for drinking, which represents a small fraction of a hospital's needs even under emergency "Code Dry" conditions.
- EBMUD's recent survey of 16 hospitals in its service area was consistent with the 2006 study, in that many responding hospitals generally believed their level of preparedness was higher than it actually is. The statistics indicate the following:

    - Only 6 of the 16 hospitals knew or accurately estimated their baseline water usage
    - 1 of 16 reported having virtually no backup water supply
    - 2 of 16 reported backup water supplies sufficient for just a few hours (3-5 hr, 7.8 hr)
    - 2 of 16 estimated they have 24-48 hours of supply
    - 11 of 16 believe they can function for more than 48 hours -- 96 hours was the single most-cited number – but typical backup supplies are sufficient for a few hours of normal demand, so the validity of this belief would hinge on immediate and drastic demand reduction along with service level cuts.

Overall, there appears to be a gap at many facilities between the acknowledged goal of 96-hour readiness versus actual readiness. Hospitals that need tens of thousands of gallons per day to care for dozens or hundreds of patients are relying on backup storage volumes of a few thousand or even a few hundred gallons. Cited contingency plans include evacuation, diversion (no new patients), no sterilization, no cooling, etc.; some of these contingencies simply don't pencil out, and others fall far short of the societal goal, which is that hospitals remain functional for a *higher*-than-baseline patient load following a zero-warning regional disaster.

For major hospitals, the sheer volume of water required to make up the gap would require several or even dozens of truck deliveries per day, a scenario that is simply not credible in a post-disaster environment where the transportation network may be heavily damaged, communication networks are crippled or down, fuel is likely extremely limited, and any available sources of trucked water are vastly overcommitted.

## POSSIBLE REASONS FOR THE OBSERVED GAPS

The above discussion indicated that there are some mismatches between our knowledge of interdependencies and our actions. Water utilities generally accept the prudence of planning for major disruptions to food, water, energy and communications lasting 72 hours or more, but actual readiness tends to fall short. Hospitals set a slightly higher bar, 72-96 hours without water or energy, but in practice may be able to tolerate less than 24 hours without severely curtailing services at a time when society may be expecting the most from them.

Resolving the observed gaps between knowledge and action is clearly beyond the scope of this paper, but some possible reasons for the gaps are very briefly considered below:

### Insufficient resources

Lack of resources cannot be the sole or primary reason for the gap, since the "common knowledge" by which we measured the gap was developed by those with knowledge of resource limitations. For example, the water sector consensus that one ought to plan for 3-14 days without water, rather than 30 days without water, incorporates an awareness of limited resources and the need to make prudent compromises when allocating resources.

In a general sense, resource constraints have already been accounted for and we need to look elsewhere for the underlying reasons that common knowledge is not being brought to bear on interdependencies.

### Information about interdependencies too compartmentalized

While those "in the know" believe that, for example, it's prudent to plan for power outages of up to three days, the individuals who need to apply that knowledge (those responsible for designing a facility, for stockpiling fuel, etc.) may be unaware of that "common knowledge". Anecdotally, this reason appears to be a major factor in explaining why facility designs and/or operational practices are not always consistent with their established dependencies.

### Information about interdependencies shared but not universally believed

Even when common knowledge is brought to the attention of an individual who is being asked to take appropriate action, that person may reject the information if there is no legal mandate. As discussed below, incentives or lack thereof may be a factor, but beyond that there may be a fundamental lack of acceptance. It has been observed that what is unfamiliar seems unlikely, and thus not worth planning for.

### Lack of incentive or wrong incentives

Even when interdependencies are known, there may be no legal penalties for ignoring them or economic incentives for heeding them. For example, boosting the reliability of the electric grid beyond that required by law makes no economic sense for an electric power provider whose only loss during a blackout is power revenue. The major societal costs of a power outage are externalized and hence distort economic incentives.

Beyond the obvious disincentive to action posed by present-day costs, there may be other disincentives including a growing pattern of post-disaster government assistance, as measured by increasing numbers of federal “disaster declarations”, and concerns about increased liability that may be created by formalizing goals for higher reliability.

### Cognitive bias

Humans are not skilled at weighing risk posed by low-probability, high-consequence events. Specific biases include a status quo bias, i.e. the perception that things are okay right now (never mind that our experience is a poor gauge of risk for low-frequency events), a herd “groupthink” mentality (most of us are loathe to take action until we see others taking action – even in response to a fire alarm), and a self-aggrandizing bias (“we may have issues, but fortunately we’re better than average”). All of these biases can be amplified by incentives (e.g., annual bonuses) that may reward short-term results. Thus even well-known important risks may be put on the back burner in favor of lower-priority work.

Close calls and disasters should provide a dose of reality that would combat cognitive bias, but sometimes they have the opposite effect. Close calls can lead to a growing sense of invincibility rather than vulnerability (“see, we contained the problem, that’s proof the system works”). And while a rational actor would interpret a surprise (e.g., a power outage of greater extent and duration than expected) as a sign that prior expectations were wrong, a human actor may construe an unexpected event as “worst case” for the sole reason that it’s worse than previously observed or expected. A person may also learn an excessively narrow lesson from experience, and thus for example install backup power at a single facility that lost power in a disaster rather than learning the broader lesson about power vulnerability at all facilities.

### Lack of awareness of one’s own vulnerability

It can be relatively easy to spot gaps in the planning of others. For example a water provider can observe whether a hospital’s plan for water service interruption is realistic or not.

But one’s own vulnerability is not always so easy to spot, especially when it grows gradually. No single year since the first commercial electric power flowed in 1880 is dramatically different than the year before, but the cumulative changes over those years have produced a highly interconnected, interdependent society that may be more vulnerable than commonly appreciated. The virtues enabled by interconnectedness such as reduction in excess capacity, excess inventory and excess redundancy can be hidden sources of vulnerability.

Clearly no single reason discussed above accounts for our general failure to orchestrate common knowledge of cross-sector interdependencies -- likely all of the reasons work in concert. Given the magnitude of the observed gaps between knowledge and action, we ought to pay at least as much attention to improving our application of current knowledge as we do on advanced research into the technical nature of interdependencies.

## CONCLUSIONS

Despite imperfect knowledge, there are broad areas of agreement on reasonable planning assumptions for service interruption of discrete infrastructures following a major disaster. However, there are significant inconsistencies in the dissemination and application of that knowledge to help mitigate the effect of disasters. Reasons for those inconsistencies are many including lack of knowledge, lack of incentive, and bias. Future efforts to “square up” planning assumptions across sectors would result in a higher likelihood of the critical infrastructure collectively meeting society goals after a disaster.

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