Water Utility Security: Multiple Hazards and Multiple Barriers

Neil S. Grigg

April 12, 2002

Abstract

In recent years, the nation has learned much from natural disasters about risk to infrastructure systems, and now it faces new threats from malevolent attacks and other human–caused sources. The paper provides a comprehensive report on the experience base with water utility disasters and offers guidance for risk management and analysis. It is based on a AWWA Research Foundation project that included a background study, industry interviews, and a workshop. Methods for risk analysis are in limited use by utilities because of a lack of data and lack of training and priority within utilities. Theories have advanced, but need to be validated and developed further. Other infrastructure systems have characteristics that are similar to water supply and water utility experience with risk can strengthen them. Risk management in utilities is more complex and far–reaching than current methods handle. For natural hazards, a great deal is known about threats, but less about vulnerability and consequences. Human–caused threats need more assessment across–the–board. Improvements in planning, management, design, construction, and operations are required. In spite of the experience base, a great deal of additional research is required. By adopting smart strategies utilities can improve security. They have some tools, but require more comprehensive approaches and better tools, which can be used effectively by their workforces. The "multiple hazards" and "multiple barriers" approach also applies to other infrastructure services, which have similar features. Work is needed to understand system vulnerabilities and protective strategies for them as well.

Introduction

In recent years, the nation has learned much from natural disasters about risk to infrastructure systems. Now, the attacks on the World Trade Towers have shown that malevolent attacks must be anticipated, along with natural and other human–caused threats. Infrastructure risk managers now greater experience to go along with theories of risk management.

This paper provides a comprehensive report on the experience base with water utility disasters and offers guidance for the process of risk management and analysis. It is based on a project supported by the AWWA Research Foundation that included a background study, industry interviews, and a workshop involving disaster survivors and experts (Grigg, 2002).

The project showed that available methods for risk analysis are in limited use by utilities because of a lack of data on threats and vulnerabilities and lack of training and priority within utilities. Theories have advanced, but need to be validated with experience and developed further so they can be more widely used.

Other infrastructure systems, especially electric power, wastewater, and natural gas, have characteristics that are similar to water supply. The water utility experience base with risk can be used to strengthen them as well, thus helping to protect the nation's critical infrastructure.

As a result of research, we know much about natural hazards, particularly earthquakes and floods. Other natural hazards also can have significant effects, but not as major as earthquakes and floods. Utilities believe that threats from natural or unintentional causes of contamination are manageable, but human–caused threats need more attention and weapons of mass destruction remain a low–probability but high–consequence concern. Much more knowledge about human–caused threats is needed.

After September 11, there has been much attention to water utility security. While all components involve risk, distribution systems are seen as particularly vulnerable. Methods for risk analysis against human–caused threats involve the same steps as for natural hazards, with differences being in the nature of threats and protective systems. Considering security and disaster preparedness together will be more effective than separating the two programs and contribute to integrating risk management.

The project showed that much more knowledge is needed about planning for security and survival of disasters. Each step and process requires more development, better data, and a plan for dissemination and training. This starts with the mechanics of risk analysis, and extends to threat analysis, vulnerability analysis, scenario development, assessment of consequences, identifying critical components, and estimating effects on systems and components under uncertainty. Cross–sector tools are needed to identify mitigation, protection, and preparedness options, evaluate the options, and display system data at appropriate levels of detail to facilitate decisions.

Operational aspects of protection also need attention, for example, realistic and cost–effective early detection methods are needed for distribution systems, as well as water sources.

Successful risk management must fit within a culture of strong commitment to security and disaster preparedness. Defining roles of elected officials and staff is a high priority, and human resource and staff policies are critical. Organizational communication is especially important in an all–hazard approach to emergency preparedness. Relationships with other units, expressed in mutual aid pacts, should be established before events occur. Engineering programs such as seismic improvement and flood mitigation are also critical components in preparedness and design of robust systems.

In the next section, risk management as a process is reviewed. Then, threats to utilities are summarized, including both natural hazards and human–caused threats. Experiences of water utilities with these threats are presented, leading to conclusions about lessons learned about water utility risk management.

Review of risk management

Risk management is a broad and evolving field. Kloman (2000) explained how different sectors such as finance, insurance, safety, and emergency managers use different risk language and "remain encapsulated within ... specialty bubbles." Fragmentation of the field hinders transfer of experience from one field to another.

Water utility experiences show that risk– and performance–based methods are needed to plan and design more resilient and reliable systems. Risk analysis for infrastructure and water systems was recently summarized by Ezell and others (2000a, 2000b). It has interesting methods, but they are in limited use by water utilities. Moreover, while limited applications of current methods are feasible, risk has many facets, and is more complex and far–reaching than current methods handle.

Risk to water utilities covers many threats. One way to classify risk to a utility is by security, natural disaster, and business risks (including health and safety). Figure 1 presents an enterprise view of risk management in a utility.

Figure 1

It is generally agreed that risk is the "combination of the probability of an event and its consequence (ISO)." Some writers present this by a conceptual equation, but risk has too many facets to be expressed this way quantitatively.

Risk = (probability of event) * (consequence of event)

There are many versions of the risk management process, but they feature common steps. (Kolluru, 1996; Levitt, 1997; Kaplan, 1997; Haimes, 1998; Ezell, Farr, and Wiese, 2000a; ISO, 2000). Risk management can be considered as risk identification, analysis, reduction and treatment, using ISO terminology. Steps are:

Risk identification and analysis

- **Hazard assessment**: Determine what can go wrong and why, identify and estimate likelihood of hazards and threats
- **Consequences**: Study consequences of each out–of–course event on victims, potential losses and impacts to health, property, life, property)
- **Vulnerability analysis**: Analyze vulnerabilities

Risk reduction and treatment

- **Emergency preparedness**: Establish mechanisms to counterbalance risks
- **Mitigation/protection**: Reduce levels of risk to as low as reasonably practicable
- **Respond and recover**: Respond to events, recover, learn from disasters and unforeseen events and improve resilience

Clearly, a simple protocol for risk management will benefit practitioners. The following description is offered as a framework for risk management in water utilities, to include the closely–related terms security, safety, and reliability.

Water utilities require secure and reliable systems. A secure system is safe from danger, harm or risk of loss and will be reliable, with high probability of performing to standards for a specified interval in the face of threats. To plan for secure and reliable systems in the face of threats, managers consider risk, or the probability of events and their consequences. Their risk management programs include risk identification, analysis, reduction and treatment. Risk analysis includes vulnerability assessment and reliability analysis considers how systems perform under unusual loading. Risk and reliability also measure security and safety. Low risk means high security and safety. Reliability is a function of risk in that high risk causes high probability of failure in the environment considered, hence high risk and low reliability go together.

Threats to water utilities

As discussed, threats to water utilities include natural hazards, human–caused threats, and business risks. Tables 1 and 2 list major categories of natural and human–caused threats, along with consequences that have occurred. Table 3 lists business risks, but the paper does not discuss them further.

Table 1. Natural hazards and consequences to water utilities

Hazard	Examples of consequences
Earthquake	Pipe breaks, loss of power, structure collapse
Flooding— river, flash, coastal, dam break	Loss of treatment plant, contamination of distribution system
Wind—hurricanes, tornados	Flood-induced problems, also structure damage, loss of power
Waterborne disease—Cryptosporidium, Giardia, E. coli, Legionella	Sickness, death, loss of public confidence
Drought and dust	Water shortages, water quality problems, financial problems
Severe weather—cold, heat, snow, ice, lightning	Frozen pipes, outages and leaks, high water use, stolen water, SCADA problems
Fire—forest, brush, firestorm	Dramatic increases in water demands
Mudflow, landslide, sedimentation	Loss of surface water facilities, washout of crossings
Volcano and ashfall	Loss of facilities to lava flow, contamination by ash

Natural hazards have been studied extensively, and information is available at the web page of the University of Colorado Natural Hazards Research and Applications Information Center, among other places.

Human–caused threats involve inherent uncertainties. Their classification is not as clear as for natural hazards. Based on project findings, a classification with four categories is proposed (Table 2).

Table 2. Human–caused threats and consequences to water utilities

Threat	Examples of consequences
Attacks: terrorism, vandalism, sabotage, arson, cyber attacks	Consequences range from harmless to loss of key facilities to mass terror
Accidents: transportation, construction, industrial, nuclear power, hazardous-material releases, fires	Contamination of sources, loss of key facilities, loss of structures, breakage and outage
Failures: breaks, system failures, power or computer system failure	Loss of system capacity and functionality, loss of controls, loss of public confidence
Psychological threats: hoaxes, misinformation, incitement of panic	Panic, loss of public confidence

Human–caused threats need further research, especially those that involve malevolent intent.

Other threats include issues of concern to all businesses, such as health and safety. These risk categories can be classified along insurance lines, property and casualty, liability, etc. Table 3 lists some of the categories, but these are not discussed further in the paper.

Table 3. Risk categories to utility business processes

Threat	Examples of consequences
Employee health and safety	Public image, HR problems, impaired utility operation
Reputation and loss of public confidence	Political problems, impacts on organization and employees
Employee misconduct and grievances	Poor morale, impaired utility operation, negative press
Financial problems	Threats to solvency, higher rates, loss of public confidence, lack of funds
Property losses	Threats to financial base
General liability	Financial losses
Regulatory problems	Financial problems, negative press, loss of public confidence

The consequences can be aligned with utility organizational units and summarized as:

- Infrastructure: frozen pipes, pipe breaks, loss of system capacity and functionality, structure collapse, washout of crossings, loss of supplies, loss of key facilities
- Operations: stolen water, dramatic increases in water demands, contamination of source water and/or distribution system, loss of power and controls, SCADA problems, outages and leaks, loss of treatment plant, employee and organizational problems, poor morale, impaired utility operation, sabotage.

- Resources: water shortages
- Health: Contamination of sources, water quality problems, sickness, deaths, many deaths
- Finances: losses, financial problems, lack of funds, higher rates, threats to solvency
- Public confidence: negative press, loss of confidence, political problems, panic, mass terror

An all–hazard approach anticipates a range of threats. Fortunately, a strategy to protect against one hazard may also protect against others. For example, emergency response forces can respond to a range of events.

The threat matrix to each utility will be somewhat different, depending on the context. Figure 2 presents a generalized approach that resulted from queries to experts at the workshop.

Figure 2

Utility experiences and knowledge in natural and human–caused hazards

Surviving disasters project and workshop

The goals of the AWWARF project were to review reports of utility disasters, interview utilities, and bring together survivors and experts to identify lessons learned. Background studies included both the natural hazards and utility fields. The workshop occurred on October 11–12, 2001, when some 50 experts gathered to exchange lessons learned from recent disasters and security incidents. The experience base of these experts included management of major disasters and programs, and knowledge of many disasters around the world.

The experts compiled lessons learned and recommendations to help water utilities prepare for future disasters. Uppermost in their minds were potential security events that include bioterrorism, cyber attacks, and chemical warfare against water systems. Workshop proceedings are summarized in the final report (Grigg, 2002).

Events discussed included earthquakes such as the 1994 Northridge and the 1995 Kobe events, which caused great damage to water systems and critical facilities. Flood events such as the 1993 and 1997 Midwestern floods inundated water treatment plants and left communities without water service for weeks. More recently, Hurricane Floyd, which hit in 1999, knocked out water service in towns such as Portsmouth, Virginia and Rocky Mount, North Carolina.

Uppermost in participants' minds were potential security events that include bioterrorism, cyber attacks, and chemical warfare. They reported that water systems are secure against most attacks, but continued vigilance and preparation are needed. While it will never be possible to protect every aspect of water systems, greater security is being provided for reservoirs, treatment plants, and distribution systems.

Experiences with natural hazards

The water utility experience base with floods and earthquakes is extensive, and most categories of consequences have been identified and studied. Wind is a common hazard, but most significant utility damage due to wind was from wind–induced flooding. Water utilities have experience with drought, but it was not discussed in this project. See (Grigg and Vlachos, 1993) for a summary of drought experiences. Waterborne disease is a special category of threat to water utilities. Other natural disasters such as extreme weather and lightning threaten utilities also, but not as significantly as earthquake, flood, and waterborne disease.

Water utility experiences with earthquakes are well–reported. Earthquake experiences beginning with the Loma Prieta event are given in Table 4.

Table 4. Recent water utility earthquake experiences and information sources

Earthquake	**Experiences**
Loma Prieta, CA. 17 Oct 1989.	Loma Prieta has been extensively reported. It caused 62 deaths and $7.1 billion in damage. There were electric power interruptions and extensive water main damage. Key reports: overall report (Earthquake Engineering Research Institute, 1989); mutual aid and California's Water Agency Response Network (WARN) system, (Riordan, 1995); seismic improvement by EBMUD, (Diemer, 1998).
Northridge, CA. 17 Jan 1994.	More reports than Loma Prieta. Northridge caused 58 deaths and $30 billion damages including aqueduct, tanks, and pipelines. Key studies: structures, lifelines, and fire protection, (Todd and others, 1994); lifelines and post-earthquake response (Schiff, 1995); MWD EOC and patrol success (Young and Means, 1995); LADWP success in service restoration (McReynolds and Simmons, 1995); communication (Tanaka, 1995).
Kobe, Japan. 17 Jan 1995.	Over 5000 deaths, mostly in vulnerable wooden houses, and $100 billion in damages with main breaks, damage to pumps and treatment plants. Key reports: overall (Earthquake Engineering Research Institute, 1995); Northridge and Kobe comparisons (ASCE, 1996 and Ballantyne, 1998).
Turkey (August 17, 1999) and Taiwan (September 21, 1999)	Both sites near vulnerable areas and lessons focus on building codes (Eidinger, 2001). Turkey event killed at least 16,000 and was largest since 1939. Direct damage estimated at $25-40B with great damage to building stock. Water systems performed fairly well. Pipes crossing faults were damaged. Taiwan event killed more than 2300. Dam across a

	fault sustained serious damage, releasing 2.3 MM^3 of water.
Peru, 2001	Caused landslides and other damage, and had serious impacts on local water systems (Eidinger, 2001).
India, 2001	Caused many deaths and severe impacts on local water systems (Eidinger, 2001).
Northwest US, 2001	Damages small. Roads and buildings damaged but Olympia's water supply had few problems. Power out for few hours, and high turbidity and cracks in small supply lines. The ground continued to settle and cracked small lines (DeCillo, 2001).

Actually, flooding is the most destructive and costly natural disaster faced by the United States, but it does not have the area–wide effect on utilities of earthquakes. In the United States, knowledge about floods is substantial, but infrastructure system survival has not received as much attention as floodplain regulation. The most dramatic recent effects of flood on water utilities have been loss of treatment plants.

Table 5 provides a summary of water utility impacts by flood beginning with the 1993 Midwestern flooding.

Table 5. Recent water utility flood experience and information sources

1993 Midwestern Flood.	Caused more than $15B in damage and contaminated water at 250 drinking water treatment plants in Missouri, Kansas, Illinois, and Iowa. (Reid, 1994; Horsley, Carlson, McCarthy, and Gupta, 1994). Des Moines, Iowa lost treatment plant (McMullen, 1994) as shown in AWWA's videotape on emergency management. Lessons learned valuable in response, communications, and media relations.
1994 Georgia floods.	Flooding cut water to more than 300,000 people. In Macon, 150,000 people were without potable water for three weeks (Kusel, 1997; Reid, 1995).
1995-96 Oregon flooding.	Portland Water Bureau practiced emergency operations for one event after another, learning many lessons (Humphrey, 1996; Elliott, 1996; Jutila, 1996).
1994 Texas flooding	October 1994 flooding impacted water and wastewater services in Houston (Jeng and Rogers (1995).
1997 Midwestern flooding	Cities in Upper Midwest had interrupted services. (Thornley, 1997). Grand Forks, ND lost system during 1997 Red River flood, with 90% of city evacuated (Sletten and Vein, 2001). Lessons include alternative water supplies, standby power, record archives, regional and local response teams, state and

	federal contacts, need for daily notes, communication with regulators, safety issues, employee work schedules, and keeping a current plan.
1999 Floyd flooding.	Disaster states were NC, NJ, PA, VA, NY. Elizabethtown NJ closed main water plant for five days (Flood Waters Recede, 1999). Noah (2000) described problems and mitigation programs. Rocky Mount, North Carolina lost treatment plant and had other facilities out of service (Van Hoose, 2001). Utility staff performed heroic tasks to bring plant back after flood waters receded. Lessons are taking care of staff, outside resources, and mutual aid program. Documentation of relief was crucial. Logical mitigation is to elevate facilities. Portsmouth, VA also reported treatment plant out of service.

The experience base with other natural disasters is also substantial, but damages have not been as dramatic as for earthquakes and floods (other than hurricane–induced flooding). Hurricanes and tornados also damage structures directly. Drought is a significant creeping hazard. Extreme cold, with snow and ice, causes loss of power and can cut water supplies. Pipelines freeze and break, and even routine cold weather increases pipe breaks in old systems. Heat causes dramatic increases in water use, and vandals may turn on hydrants illegally. Fire creates large, sudden demands for water, and sediment problems after a forest fire can affect supply sources. Lightning can disrupt power and communications. Examples of these are summarized in (Grigg, 2002). Waterborne disease is a hazard that deserves separate discussion, which occurs next.

Public health

Disasters can cause disease outbreaks, and disease outbreaks can be disasters. Cryptosporidium, Giardia, E. coli, and Legionella have been of concern in recent years, but are not the only threats. Risk assessment for public health deals with health effects of various contaminants, including toxic or pathogenic agents, which can be either natural or human–caused threats (US Environmental Protection Agency, 2000; AWWA, 1999).

Environmental epidemiology, or “use of epidemiologic methods to assess health effects of environmental contaminants,” is the field to study public health effects of water disasters (Craun, Calderon, and Frost, 1996). "The Public Health Consequences of Disasters" explains water–related epidemiology from natural disasters and accidents (Noji, 1997). An AWWA committee evaluated risks of bacteria, viruses, protozoa, and algae. Pathogen monitoring remains controversial (Allen, Clancy, and Rice, 2000). Poor data keeps water agencies from using monitoring for public health decision making (Clancy and Hansen, 1999). More research is needed (AWWA Microbiological Contaminants Research Committee, 2000 a and b). Engineers and microbiologists should work together on public health disasters.

Conclusions from reports and the workshop point to little public health hazard on the source side. The treatment barrier is effective, but the distribution side is more vulnerable. Realistic and cost effective detection methods are needed and treatment systems need better tuning. Attention to early warning monitoring and chlorine in distribution systems is considered inadequate. According to participants in a 1999 workshop on early warning monitoring, serious threats are spills of oil and industrial products; insecticides and herbicides; and pathogens from untreated sewage. Few intentional threats have occurred, and hoaxes are more likely. Main lines of defense are seen to be redundant treatment and distribution and denial of access. Maintenance of chlorine and increasing it in times of danger is important (Brosnan, 1999).

Table 6 lists recent water utility outbreaks that received attention and references to others. Starting with this table, the reader can locate a large body of reports on disease outbreaks.

Table 6. Recent water utility outbreak experiences

Survey of 35 outbreaks	These reports review and comment on 35 outbreaks (Craun et al, 1998; Solo–Gabriele and Neumeister, 1996)
Milwaukee, WI Cryptosporidium	Illness in 400,000 persons and a number of deaths. Water supply from Lake Michigan. Before outbreak there were severe spring storms. May have been rise in particulates in plant and oocysts passed through plant (Fox and Lytle, 1996).
Las Vegas, NV	Outbreak came in system with no apparent deficiencies (Roefer, Monscvitz and Rexing, 1996).
Sydney, Australia	Author’s opinion that reliance on poor quality monitoring data created water quality crisis when, no threats to public health existed (Clancy, 2000).
Walkerton, Ontario	E coli incident led to seven deaths and over 2000 sick, half the population. Flood waters over cattle grazing lands and alleged utility problems suggested (AWWA Mainstream, 2000; Mossman, 2000, Everhart, 2000).

Human–caused threats including terrorism

Human–caused threats and protective measures can be classified into four groups: attacks, accidents, failures, and psychological threats. Uncertainty from them is hard to assess and major threats such as bio–terrorism also induce fear among water users.

Attacks involve use of varying degrees of violence, force, deception, terror, intimidation, or technological means to unlawfully threaten or harm a water system: Terrorism, vandalism, sabotage, and cyber attacks are examples. Motivations range from ignorant but semi–benign pranksters to malevolent terrorists, intent on using weapons of mass destruction.

The basic protection against attacks or threats of attack is the security system. Training resources are increasing. AWWA's latest emergency planning manual includes a guidebook on security to explain emergency planning methods for security (Burns, Cooper, Dobbins, Edwards, and Lampe, 2001). This includes hazard assessment, vulnerability assessment, mitigation, response planning, and crisis communications. Key words in security are "detect, delay, and respond."

The experience base shows a number of minor incidents of attacks or threats of attacks, and prospects of major chemical or biological attacks against potable water systems. Vandalism and sabotage have been reported, ranging from teenagers writing on water tanks to break–ins at treatment plants. Cyber attacks have been detected, and utilities are concerned about vulnerability of SCADA systems.

So far, no major act of bio–terrorism or chemical contamination has been detected, but the threat of direct attacks against water utilities is not new. During World War II, for example, Nazi Germany landed a sabotage team in the US with a mission to attack a drinking water system. The mission failed, but water supply attacks were recognized as a way to alarm the public about their vulnerability. Hoaxes can still have that effect, and might undermine public confidence in their water supplies.

War and civil disturbances can lead to attacks or sudden changes in demand. The conflict in former Yugoslavia, for example, showed residents of Sarajevo without water for long periods. During the Gulf War, Jordan experienced a sudden 40% increase in population.

Assessing accident risk is difficult because there are so many possibilities. Accidents involve unintentional actions against utilities, but still might cause major damage or harm. Examples include a nuclear power plant accident that led to radioactive contamination, a construction accident that disabled a reservoir, major pipeline, or treatment plant, or a transportation incident such as an oil spill that contaminated source water. If you assess vulnerability to intentional attack, it may cover unintentional attacks. Structure fires might be the result, rather than the means, of a human–caused threat. They might occur from an attack, a natural disaster, an accident, or a failure, and are listed as a threat to identify that they constitute a major concern for water utilities. A structure fire can disable water systems at just the time they are needed to fight fire, and it can call for large quantities of water for fire–fighting. Structure fires or arson–caused wildfire, as opposed to their cousins, wildfires

Failures include breaks, system failures, power or computer system failure. They are human–caused threats in the sense that the failure occurs due to less–than–intended performance of a component or a system. The system manager will not ordinarily know the risk of failure because there are so many components in a water system, but techniques to predict failure rates and identify likely failures are improving.

Conclusions and lessons learned

Risk management in utilities is more complex and far–reaching than current methods handle. In particular, more comprehensive approaches are needed. Risk– and performance–based methods are needed to plan and design more resilient and reliable systems but they are in limited use by water utilities. Protective strategies must be comprehensive to anticipate a range of threats and measures. This approach should involve "multiple hazards" and "multiple barriers."

For natural hazards, a great deal is known about threats, but less about vulnerability and consequences. For example, utilities usually know if they are at risk for earthquake or flood damages, but how much at risk is hard to determine. Public health threats from natural hazards are of some concern, but utilities face uncertainty about intentional threats and hoaxes. Weapons of mass destruction remain a low–probability but high–consequence threat to water utilities.

Human–caused threats need more assessment across–the–board. Security systems are the defense against attacks. Assessing accident risk is difficult because there are so many possibilities. Failure risks involve uncertainty because there are so many components in water systems, but techniques to predict failures are improving. Psychological threats are not a major concern, but should be monitored by utilities, as in any business.

Analysis of threats and consequences leads to help in identifying vulnerabilities. A table was presented to identify consequences to infrastructure, operations, resources, health, finances, and public confidence. This classification lends itself to appointing "risk owners" in utilities, to be responsible for risk management in these categories.

Preparing and leading the organization for disaster survival requires commitment from a champion in the organization. Without leadership, lack of commitment, token efforts, and complacency may result. Managers must see the need and create the plan. Employees must cooperate and partners must be involved. Mobilizing organizations and keeping attention on preparedness requires actions such as drills, recognizing excellence, and overcoming the "token pat on the head" syndrome.

Defining emergency roles of elected officials and staff is a high priority. Ordinary flow charts do not help much with unstructured decision scenarios. Procedures for emergency operations should be kept close to normal operations, and scenarios should be scripted to aid in preparation.

Regardless of the extent of mitigation, an all–hazard approach to emergency preparedness is required. A clear line of command and use of an incident command system is required for emergencies. An effective Operations Center is required. For example, MWD was able to get their EOC up within 40 minutes for the Northridge earthquake, having been prepared by the 1971 San Fernando event. Also, their reconnaissance patrols completed damage inspection work in 5 hours and the decision to buy heavy machining equipment paid off in reestablishing systems (Young and Means, 1995). LADWP also had had extensive experience in earthquakes and restored service to 99% of customers within 5 days after the Northridge event (McReynolds and Simmons, 1995).

Effective human resource policies are critical to disaster preparedness. Constant training and preparation to become a "learning organization" and maintain a lessons–learned database are required to reverse loss of institutional memory. Employees require attention during disasters to attend to their families and basic needs. Trauma, stimulus overload, stress, and ripple effects of disasters after a disaster are common, and units require recovery.

Post–disaster reports emphasize organizational communication (Tanaka, 1995). This requires effective internal and external communication and to build good relationships internally and with other organizations that typically don't interact, including with regulators. All units should participate in drills, and utilities should cooperate with partners. Committees, staff meetings, clarification of roles, cross-communication, and project-oriented units help the unit to communicate. Media relations are critical during an emergency. During disasters archives must be protected, and daily notes of the event should be kept. Mutual aid pacts should be established before events occur. California's Water Agency Response Network (WARN) system and experiences of NC during Hurricane Floyd show this.

Seismic improvement is one design and construction measure to prepare for disasters. For example, EBMUD initiated seismic improvement work after Loma Prieta (Miller, 2001). Numerous other lessons have been learned, such as about failures of welded steel joints in earthquakes, need for alternative water supplies and standby power, and need for unit–wide attention to mitigation measures.

In spite of the experience base, a great deal of additional research is required. A few key issues include:

- For decision support, system complexity demands better methods to display system data at appropriate level of detail to facilitate planning and decisions.
- Planners need better data about threats and more effective techniques for threat analysis.
- As utilities face many threats of an uncertain nature, tools to estimate system vulnerabilities and effects under uncertainty are needed.
- To plan protective systems, a method to estimate and present system capability under disaster scenarios is needed.
- A better method to isolate and display critical components and systems is needed.
- In operations, treatment systems need better tuning and distribution system vulnerability requires more research. Early warning monitoring systems need more work.
- Mutlti–disciplinary evaluation tools from engineering, economics, finance, law, political science, and behavioral fields are needed to select the best options.

By adopting a smart strategy utilities can improve security. They have some of the tools, but require a more comprehensive approaches and better tools, which can be used effectively by their workforces.

The “multiple hazards” and “multiple barriers” approach to improving security also applies to other infrastructure services, which have similar features to water systems. Work is needed to understand system vulnerabilities and protective strategies for them as well.

Acknowledgements

The paper resulted from AWWARF Project 2696, Surviving Disasters: Learning from Experience. Appreciation goes to the cooperating utilities and workshop participants. Special thanks to Kevin Gertig, Director of Water Supply and Treatment Fort Collins Utilities, Marilyn Miller, Director of Engineering and Construction, East Bay Municipal Utility District, John Porco, Senior Emergency Management Consultant Engineer, Michael Baker Jr. Inc. and Peter S. Puglionesi, Technical Director, Duke Engineering & Services Inc.Jacob Hautaloma, Professor of Psychology at Colorado State University and Steve Price, Camp Dresser & McKee, Inc., Denver, and Charles R. Scawthorn, ABS Consulting, all of whom helped greatly during the workshop.

References

Allen, Martin J., Jennifer L Clancy, and Eugene W. Rice. 2000. The Plain Hard Truth about Pathogen Monitoring. Journal AWWA. 92(9)64-76. September.

American Water Works Association. 1999. AWWA Microbiological Contaminants Research Committee. Committee Report: Emerging Pathogens–Viruses, Protozoa, and Algal Toxins. Journal AWWA. 91(9)110-121.

American Water Works Association. 1999. AWWA Microbiological Contaminants Research Committee. Committee Report: Emerging Pathogens–Viruses, Protozoa, and Algal Toxins. Journal AWWA. 91(9)110

American Water Works Association. 2000. Mainstream. Walkerton Coroner’s Office Investigating Deaths. 44(7)1,3.

Ballantyne, Donald. 1998. Proceedings of the 7th U.S. - Japan Workshop on Earthquake Disaster Prevention for Lifeline Systems. Seattle, Wash., EQE International.

Brosnan, Thomas, editor. 1999. Early Warning Monitoring to Detect Hazardous Events in Water Supplies. International Life Sciences Institute, Risk Science Institute Workshop Report, Washington DC, December.

Burns, Nicholas L., Cooper, Christine A., Dobbins, David A., Edwards, Jessica C., and Lampe, Les K. 2001. Security Analysis and Response for Water Utilities. American Water Works Association. Denver.

Chung, Riley. 1996. The January 17, 1995 Hyogoken-Nanbu (Kobe) Earthquake: Performance of Structures, Lifelines, and Fire Protection Systems. Washington, D.C., U.S. Dept. of Commerce, National Institute of Standards and Technology.

Clancy, Jennifer L. 2000. Sidney's 1998 Water Quality Crisis. Journal AWWA. 92(3)55-66. March.

Craun, Gunther F., Rebecca L. Calderon, and Floyd J. Frost,. 1996. An Introduction to Epidemiology. Journal AWWA. 88(9)54-65. September.

Craun, Gunther F., Stephen A. Hubbs, Floyd Frost, Rebecca L. Calderon, and Steve H. Via. 1998. Waterborne Outbreaks of Cryptosporidiosis. Journal AWWA. 90(9)81-91. September.

DeCillo, 2001. Olympia's Earthquake Experiences. Workshop on Surviving Disasters: Learning from Experience. Colorado State University, October, 2001.

Diemer, Dennis M. 1998. Anti–Seismic Measures on Water Supply in California. In International Water Services Association and Japan Water Works Association. 1998. IWSA International Workshop, Water & Earthquake '98 Tokyo, November 15–18, 1998. pp 1-21

Earthquake Engineering Research Institute. Loma Prieta Earthquake, October 17, 1989--Preliminary Reconnaissance Report. 1989. El Cerrito, Calif., Earthquake Engineering Research Institute.

Earthquake Engineering Research Institute. The Hyogo-Ken Nanbu Earthquake, January 17, 1995: Preliminary Reconnaissance Report. 1995. Oakland, Calif., Earthquake Engineering Research Institute.

Eidinger, 2001. Performance of water systems in earthquakes; vulnerability assessments, Workshop on Surviving Disasters: Learning from Experience. Colorado State University, October, 2001.

Elliott, William M. 1996. Emergency Operations in the City of Portland, Oregon During the Great Flood of 1996. Proceedings Distribution System Symposium. September 8-11, 1996. Portland, OR

Everhart, Joyce. 2000. Fatal Lack of Training Revealed in Walterton Tragedy. Public Works Online, www.publicworks.com, 12-29-00

Ezell, Barry C., Farr, John V., and Wiese, Ian. 2000a. "Infrastructure risk analysis model." J. Infrastructure Sys., ASCE, 6(3)114-117.

Ezell, Barry C., Farr, John V., and Wiese, Ian. 2000b. "Infrastructure risk analysis of municipal water distribution systems." J. Infrastructure Sys., ASCE, 6(3)118-122.

Fox, Kim R. And Darren A. Lytle. 1996. Milwaukee's Crypto Outbreak: Investigation and Recommendations. Journal AWWA. 88(9)87-94. September.

Grigg, Neil S. 2002. Surviving Disasters: Learning from Experience. AWWARF Report.

Grigg, Neil S. and Evan C. Vlachos, Drought and Water-Supply Management: Roles and Responsibilities (1993): 119(5), Journal of Water Resources Planning and Management, American Society of Civil Engineers, September/October.

Haimes, Y.Y. 1998. Risk modeling, assessment, and management. Wiley, New York.

Haimes, Yacov Y.; Matalas, Nicolas C.; Lambert, James H.; Jackson, Bronwyn A., and

Fellows, James F. R. "Reducing Vulnerability of Water Supply Systems To Attack." Journal of Infrastructure Systems. (December 1998): 164-177.

Horsley, Michael B., Carlson, David J.,McCarthy, Daniel W. and Gupta, Don P. 1994, Design Lessons From the Flood of '93. 1994 Annual Conference Proceedings; American Water Works Association.

Humphrey, Todd A. 1996. White Knuckle Operations During Multiple Weather Related Emergencies. Proceedings Distribution System Symposium. Portland, OR.

ISO. 2001. Draft ISO Guide 73, ISO, Geneva, prepared by the ISO Technical Management Board Working Group on risk management terminology

Jutila, Dale L.. 1996. Perils of the Clackamas Rivers. Proceedings Distribution System Symposium. Portland, OR. September 8-11, 1996

Kaplan, S. 1997. "The words of risk analysis." Risk Analysis. 17(4).

Kloman, Felix. 2000. Integrated Risk Management: Understanding the New Mantra. Reactions. April 2000. No vol no. pp. 22-23

Kolluru, Rao V. 1996. Risk Assessment and Management, A Unified Approach, in Kolluru, Rao, Steven Bartell, Robin Pitblado, and Scott Stricoff. 1996. Risk Management Handbook for Environmental, Health, and Safety Professionals. McGraw–Hill, New York.

Kusel, Marty. 1997. Out Front: New Plant to Meet Demands of Future. AWWA Mainstream. Vol 2. Page 12.

Levitt, Alan M. 1997. Disaster Planning and Recovery: A Guide for Facility Professionals. New York: John Wiley & Sons.

McMullen, L.D. 1994. Surviving the Flood: Teamwork Pays Off in Des Moines. Journal American Water Works Association. (86(1):68-72.

McReynolds, Larry and Robert L. Simmons. 1995. LA's Rehearsal for the Big One. Journal AWWA. 87(5)65-70. May.

Miller, Marilyn. 2001. Seismic Upgrades And Planning For Post–Earthquake Water Service: Level Of Service Planning. Workshop on Surviving Disasters: Learning from Experience. Colorado State University, October, 2001.

Mossman, Matt. 2000. Water Official to Testify Today in Fatal Canadian E. coli Case. Denver Post. December 18. Page 12A.

Noji, Eric K. The Public Health Consequences of Disasters. 1997. New York, N.Y., Oxford University Press.

Reid, Joe. 1994. Overcoming Flood: How Midwestern Utilities Managed Disaster. Journal AWWA. 86(1)58-67. January.

Riordan, Raymond A. 1995. Mutual Aid and Emergency Response for Water Utilities. Journal AWWA. 87(5)52-58. May.

Roefer, Peggy A. , J. T. Monscvitz and David J. Rexing. The Las Vegas Cryptosporidiosis Outbreak. 1996. An Introduction to Epidemiology. Journal AWWA.

88(9)95-106. September.

Schiff, Anshel J. Northridge Earthquake: Lifeline Performance and Post-Earthquake Response. 1995. New York, American Society of Civil Engineers, Technical Council on Lifeline Earthquake Engineering.

Sletten, Hazel and Vein, Charles. 2001. Grand Forks Flood Experience. Workshop on Surviving Disasters: Learning from Experience. Colorado State University, October, 2001.

Solo–Gabriele, Helena and Shondra Neumeister. 1996. US Outbreaks of Cryptosporidiosis. Journal AWWA. 99(9)76-86. September.

Tanaka, Sandra. 1995. Shaken into Action. Journal AWWA. 87(5)71-75. May.

Thornley, Stew. 1997. Minnesota Operators Respond to Flooding. Opflow. Volume 11. Page 1, 4-5.

Todd, Diana and others. 1994 Northridge Earthquake: Performance of Structures, Lifelines, and Fire Protection Systems. 1994. Washington, D.C., U.S. Dept. of Commerce, Technology Administration, National Institute of Standards and Technology.

US Environmental Protection Agency. www.epa.gov. accessed December 15, 2000.

Van Hoose, Jay. 2001. Rocky Mount NC—Standardized Emergency Mutual Aid Response. Workshop on Surviving Disasters: Learning from Experience. Colorado State University, October, 2001.

Young, Michael B. and Edward G. Means. 1995. Earthquake Lessons Pay Off in Southern California. Journal AWWA. 87(5)59-64. May.

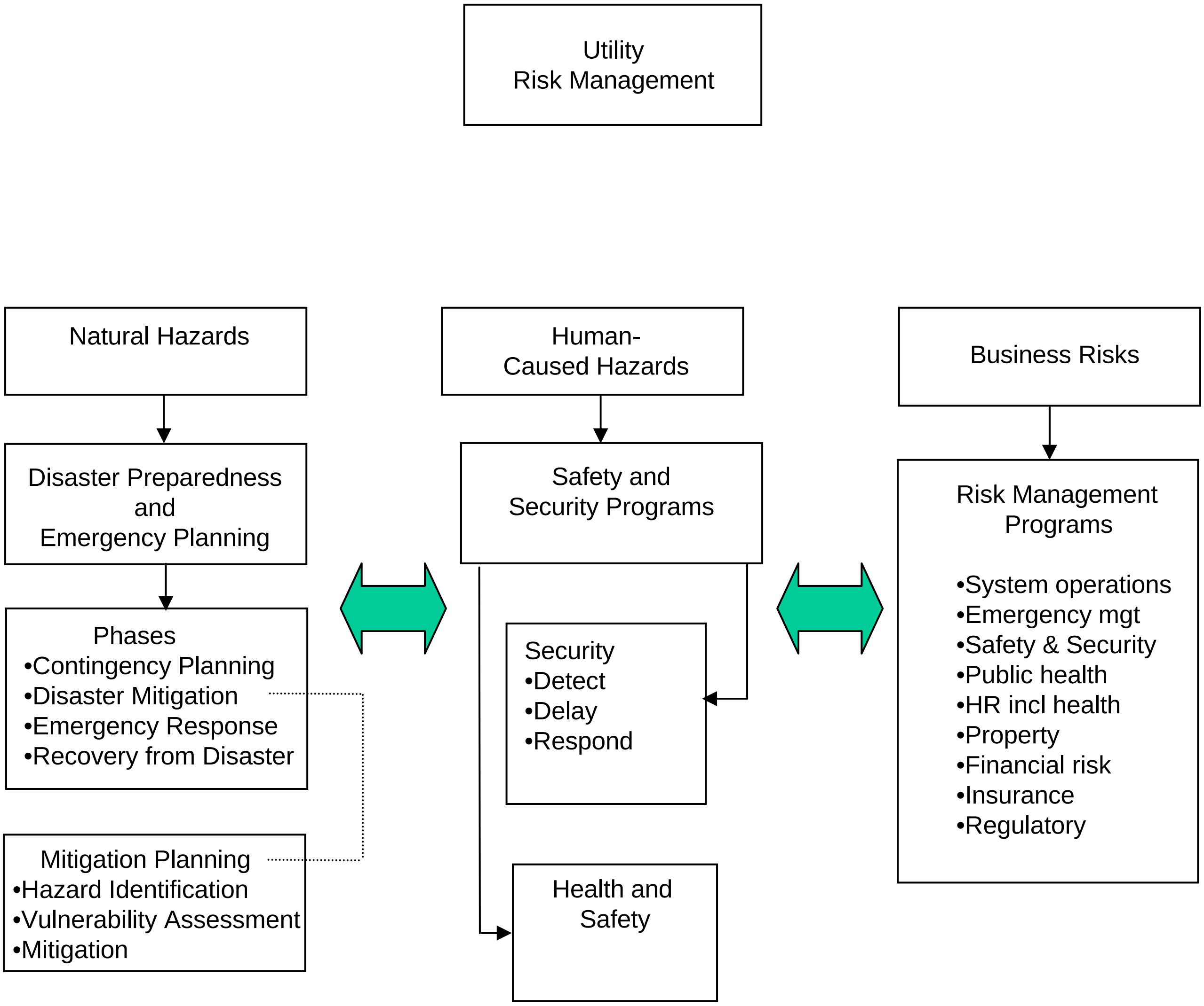

Figure 1. Utility Risk Management Program

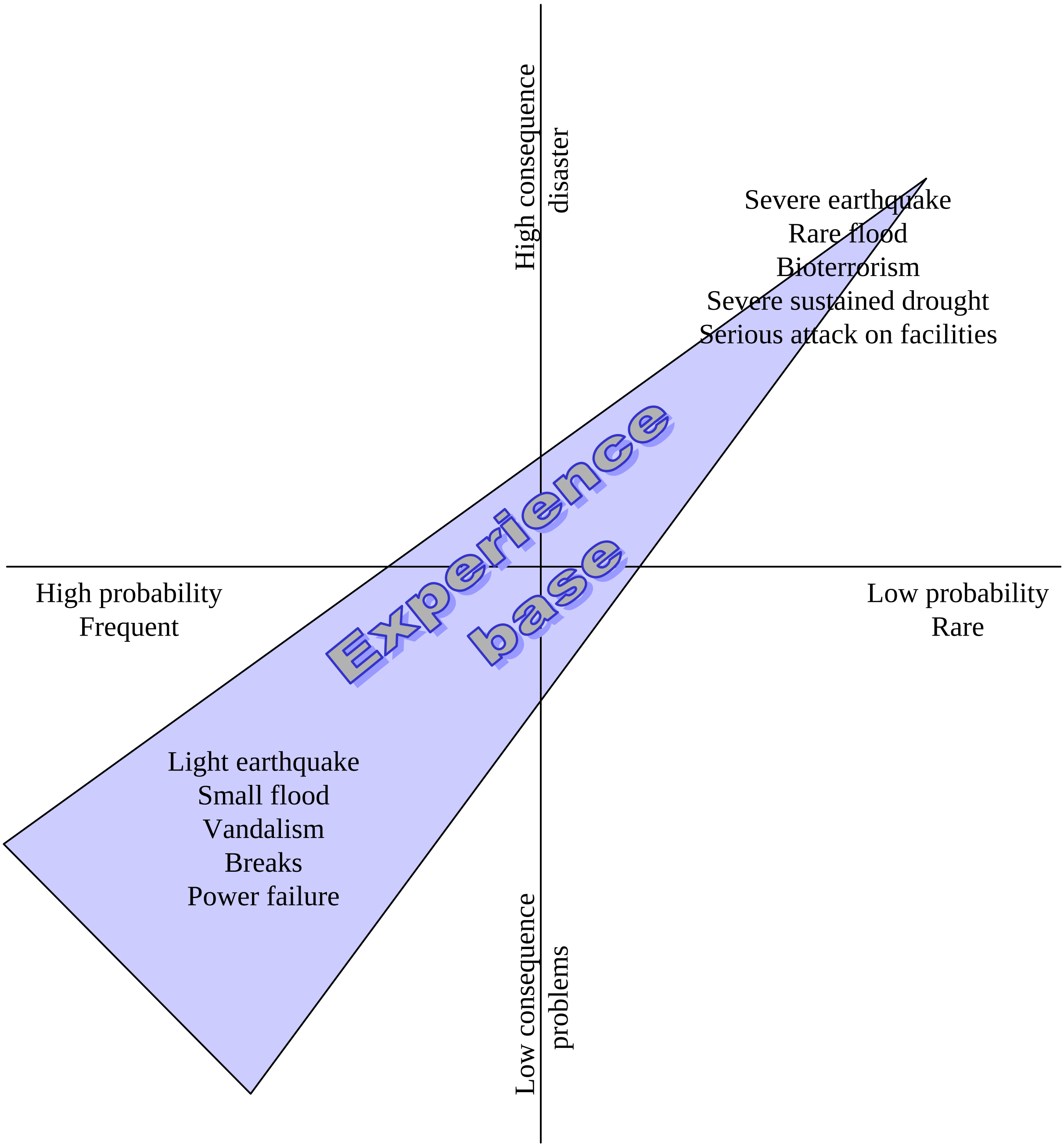

Figure 2. Threat matrix for utilities