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UNDERSTANDING THE IMPLICATIONS OF CRITICAL INFRASTRUCTURE INTERDEPENDENCIES FOR WATER

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Abstract: Direct terror attacks on water infrastructure will have implications not only for water or wastewater systems but also for other interdependent systems (e.g. fire protection and other emergency services, manufacturing, and food production). At the same time, attacks on other infrastructures (e.g. power production, chemicals production, transportation, and communications) may have an impact that would impair or debilitate the operation of water and wastewater systems. Although broad system interdependencies are covered earlier in the Handbook, this article will discuss the water-specific interdependencies and what infrastructure managers can do to understand, quantify, and hence plan for the implications of infrastructure failures beyond their direct control.

Keywords: water; interdependencies; critical infrastructure; natural hazards; security; energy; telecommunications; transportation

Water systems are dependent on and interdependent with many other infrastructures. This is an outcome of functional necessities, spatial proximity to other infrastructures, and economies of scale that have arisen over time. These relationships are growing with the size of the population, generally increased demand for water resources [[1], p. 10] particularly for public supplies [[2], p. 39], population distribution that has promoted the transmission of water over long distances, the geographic concentration of water-related infrastructure components, and changes in technology for water control and delivery.

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systems. This article begins by introducing the concept of dependence and interdependence, characteristics of water systems (covering water supply and wastewater treatment) essential to understanding the nature and impact of these relationships, and the relevance of this area of inquiry for security policy, including the allocation of resources for risk management and needs of emergency response. Finally, existing research organized by the major infrastructure sectors to which water is interrelated, how interdependencies can be measured, and recommendations for future research directions are discussed.

Dependence and interdependence as they pertain to infrastructure are usually considered distinct concepts. Rinaldi et al. ([3], p. 14) define dependency as a relationship between two infrastructures in a single direction, that is, one infrastructure influences the state of another, whereas interdependency is bidirectional (and implicitly multidirectional) with two (and implicitly more) infrastructures influencing each other. Spatial and functional concentration is a key element associated with interdependence.

Although interdependencies are often beneficial, they may also be disadvantageous if they potentially increase the vulnerability of water systems and the systems that depend on water to threats posed by natural hazards and terrorism. Disruptions in systems upon which water is dependent, whether from natural hazards, terrorism, or accidents, necessarily magnify the effects on water systems. Security strategies now emphasize an all-hazards approach encompassing natural hazards, terrorism, and other intentional attacks given that outcomes or consequences of these different events are often similar. Natural hazards that often drive infrastructure disruptions have been increasing, with the annual rise in federally declared major US disasters estimated at 2.7% per year from 1953 to 2005 ([4], p. 382). Similarly, terrorist attacks disrupting the interdependent infrastructure can magnify the consequences. Although terrorist attacks directly on water infrastructure (as distinct from vandalism or acts of sabotage) are rare in the United States, the threat for water is real enough to prompt the US government to include it in the list of critical infrastructures slated for protection under federal homeland security programs. In the United States, water systems have been compromised in a manner analogous to a terrorist attack, and internationally, terrorist attacks on water have been quite prevalent ([5], p. 528).

Interdependencies between the water sector and many other kinds of infrastructure and especially those that comprise emergency services have been identified as a critical element of federal security policy, including resource allocation for risk management. Interdependencies are a centerpiece of the National Infrastructure Protection Plan (NIPP), and are a component of assessing risk to the water sector. For energy and water interdependencies alone, the House and Senate Subcommittees on Energy and Water Development Appropriations requested “a report on energy and water interdependencies, focusing on threats to national energy production that might result from limited water supplies” ([6], p. 9). The US Department of Homeland Security (DHS) issued sector-specific plans (SSPs) to implement the NIPP with input from other agencies. The water sector is one of 17 critical infrastructure sectors to which the plan applies. The water SSP is the longest of the SSPs issued by the US DHS [7]. The water SSP defines dependency and interdependencies in the following way: “Reliance on another asset or sector for the functioning of certain assets is called a dependency; if two assets depend on one another, they are called interdependent” ([7], p. 50). Interdependencies between the communications sector and the water sector are included as an important element in the Communications SSP [8]. The water sector is mentioned in and regulated by over a dozen security and environmental laws combined and addressed in a half dozen federal directives and executive orders [7].
1 WATER SYSTEM COMPONENTS AND INTERDEPENDENCY

Water usage patterns provide a context for understanding water infrastructure and its relationship with other sectors. Figures 1 and 2 show the distribution of water use for total water and freshwater, respectively, in the United States (not including return flows, i.e. water consumption).

The type, extent, and impact of dependencies and interdependencies associated with water and other infrastructure vary depending on the water component and the type of technology used for each. Technologies for the provision of water and size of facilities are likely to dramatically alter the way in which other infrastructures are used to provide services for water infrastructure; for example, the Electric Power Research Institute (EPRI) [[9], p. 3–5] estimates that unit electricity consumption for surface water treatment and wastewater treatment declines with the size of plant and for a given plant size, the variation in energy consumption for wastewater treatment can vary depending on the type of technology by one and a half to three times. The water-supply sector consists of a very complex system of interconnected resources, facilities, and services. Water sources exist both above and below ground. Large transmission systems, called aqueducts, primarily bring surface water supplies to the points of consumption connecting to the holding or storage reservoirs and extensive distribution lines. O’Rourke [[10], p. 23] identifies water distribution lines as a type of “lifeline system” interdependent with other infrastructure lifelines noting that during the 2001 World Trade Center (WTC) catastrophe, water line breakages affected other infrastructure lifelines, flooding transit arteries and fiber-optic lines [[10], p. 24; [11]]. Underground water resources, accounting for about one-third of the US public water supply [2], serve both large systems and individual users relying on
CRITICAL INFRASTRUCTURE INTERDEPENDENCIES FOR WATER


wells usually associated with electricity-driven pumps for supply. Water storage represents another set of infrastructure facilities that interface with and are usually connected with the transmission and distribution systems.

Attributes of a couple of the key components—water and wastewater treatment plants and dams—are highlighted here because of their special significance for interdependencies and their consequences.

1.1 Water and Wastewater Treatment Plants

Water-supply plants are extensively distributed or localized throughout the US water supplies or community water supplies, defined under the Safe Drinking Water Act as serving 25 persons or more or having 15 service connections, as of 2004 numbered approximately 161,201 ([7], p. 16) and serve 84% of the US population ([7], p. 1). In spite of the extensive geographic coverage of community water-supply facilities in the United States, they are concentrated, reflecting the fact that 45% of the US population is served by only 6.8% of the water-supply facilities ([5], p. 531). Wastewater utilities, regulated under the Clean Water Act, are far more concentrated than water systems, given their generally larger size and urban orientation, and the number of wastewater facilities is about one-tenth the number of water supplies. There are 16,255 regulated publicly owned treatment works ([7], p. 19), serving 75% of the US population ([7], p. 1). The relatively greater degree of concentration of wastewater facilities is not accounted for by the lower percentage of people served, and has to do with economies of scale in treatment technology. The degree of concentration is even greater in both the sectors when one considers that relatively few of these utilities serve the bulk of the population.
These characteristics do not take into account private bottled water providers, organized and regulated differently, and is beyond the scope of this article.

1.2 Dams

Dams are another area where interdependencies can occur, since the provision of water (excluding individual water systems) usually begins with the use of dams, and the operation and control of dams depends on many other infrastructures. The National Inventory of Dams (NID) records close to 80,000 dams in the United States. The spatial distribution of dams is potentially significant for interdependencies and the vulnerabilities they may pose. At the state level, the number of dams and to a greater extent capacity (total maximum capacity) is highly concentrated: about half of all dams is located in only eight states, and about half of the total maximum dam capacity is located in only five states. The results of an initial analysis of the distribution of the number of dams and total maximum dam capacity as distributed by state in the United States are shown in Figures 3 and 4 [12]. People’s dependency on storage of water by dams can in a gross way be portrayed in terms of where dams are located relative to population. The location of dams relative to population and population density is portrayed in Figure 5, indicating a modest relationship with a low, even though not significant, correlation. Numerous activities depend on the water supply that dams provide, reflecting the purpose that these dams serve (Fig. 6). Many dams serve multiple purposes. Analysis of data on the number of dams by primary purpose from the NID indicates that the following activities are dependent upon dams: recreation (33.4%), flood protection including storm water management (15.5%), and fire protection including stock and small pond farms (13.6%). In addition, 9.3% of the dams are used for water supply (as the primary purpose).

![Image of dam distribution map]

**FIGURE 3** Number of dams by state in the United States, 2006. (Source: mapped from The Stanford National Program on Dam Performance Database as of 2007 By Sara A. Clark, Graduate Research Assistant, NYU-Wagner, Institute for Civil Infrastructure Systems.)
CRITICAL INFRASTRUCTURE INTERDEPENDENCIES FOR WATER

2 TYPES OF INTERDEPENDENCY

Conceptual literature in the infrastructure interdependency area emphasizes functional and geographic interdependencies as major types of interdependency, though other typologies have expanded or refined the number of categories [3, 13].

2.1 Geographic Interdependencies: Co-location

Physical interconnections often called utility bundling or utilidors [14] are enhanced in utility distribution systems by economies of co-location. Transportation is one infrastructure that has important physical linkages to water distribution systems. The water supply for the city of Paris, France, uses bridges to link water from the Left Bank to the Right Bank. A town in New Jersey shares wastewater treatment services with a town in Pennsylvania which involves transporting wastewater across a bridge. During a drought period, New York City constructed a temporary water-supply line, which traveled across the George Washington Bridge to supply water to New Jersey if required. Spatial linkages between water distribution systems and electric power and telecommunication lines are also common. Although these interdependencies provide many advantages and innovations, the proximity of water distribution lines to other infrastructures potentially magnifies vulnerabilities to disruption.

Large cities routinely experience water distribution disruptions, and causes vary. In New York City, environmental factors are a major factor contributing to the average
FIGURE 5 Relationship of number of dams to state population and state population density in the United States, 2006. (Source: graphed from the national inventory of dams as of fall 2006 by Sara A. Clark, Graduate Research Assistant, NYU-Wagner, Institute for Civil Infrastructure Systems.)

of 500–600 water main breakages annually. Water main breakages can disrupt other infrastructure and vice versa. Ways that water disruptions affect other infrastructures include undermining or washing out of street surfaces by water releases, shorting out of electrical lines, and undermining support of gas lines. Ways that water disruptions are caused by other infrastructures include proximity to roads and transit systems [15], vibration, weakening of lines from the undermining of soil support due to construction, being hit by construction equipment, and electrical conductance created by proximity to electrical lines and voltages from trains. An analysis of about 100 cases of multiple infrastructure failures involving water main and other infrastructure breakages found that water main breakages are more commonly initiators of outages in other nearby infrastructures, such as gas main breaks and roadway washouts, than vice versa, but these findings are sensitive to the types of cases in the database [16].
2.2 Functional Interdependencies by Infrastructure Sector

2.2.1 The Energy Sector: Water and Energy Interdependencies

Water for energy production. As shown in Figures 1 and 2, 48% of total water usage and 39% of freshwater withdrawals in the United States in 2000 were accounted for by thermoelectric power [[12], p. 35], though when consumption is considered, most of that water is returned and thermoelectric power production in 1995 accounted for 3.3% of consumption [6]. The U.S. Department of Energy (DOE) notes that “of the 132 billion gallons per day of freshwater withdrawn for thermoelectric power plants in 1995, all but about 3.3 billion gallons per day (3%) was returned to the source. While this water was returned at a higher temperature and with other changes in water quality, it was available for further use” [[6], p. 17]. Thermoelectric generating plants using open-loop cooling in turn produce 31% of US energy generation [[6], p. 18].

Energy for water production and wastewater treatment. The dependency of water on electric power has been underscored by a number of very large power outages that threatened water services or actually did bring water production and wastewater treatment to a halt. Electric power outages in California in 2001 nearly stopped major water pumps [[3], p. 11; [17]]. The August 2003 US and Canada electric power outage stopped wastewater pumps in New York City resulting in untreated water discharges to New York waterways. The same outage disrupted water-supply plants in major cities such as Cleveland and Detroit, and it took those two cities over two times as long to restore their water systems as relative to the amount of time it took to restore electricity (see Section 3). Electric power outages have been increasing at the rate of 7.2% in the United States between 1990 and 2004 [18]. Weather-related events have been dominating other conditions as causes of electric power outages, contributing to an increasing overall outage duration rate of 14% between 1990 and 2004 in the United States and higher rates since the late 1990s [19]. Both these trends are likely to affect water systems. Although water production and movement (for both treatment and supply) account for a small portion of energy produced in the United States, estimated at 4% across all functions [[6], p. 25; [9], pp. 1–2], from the perspective of the individual water company, energy figures prominently in water production, accounting for an estimated 80% of the costs for processing...
and distribution of municipal water supplies [9], pp. 1–2]. The estimated electricity consumption for fresh water supply in 2000 provided by public water-supply agencies was 30.6 billion kWh per year, and this was estimated to increase up to 45.7 billion kWh per year by 2050, an increase of about 50%, largely driven by population growth [9, p. A-3]. In the water production process, most of the energy is used for pumping and treatment. For example, the East Bay Municipal Utilities District, a water company that provides both water supply and wastewater treatment, uses half of its energy for pumping and treatment (Fig. 7). Its use of energy to acquire raw water is lowered by the fact that it obtains its water resources via gravity.

The transportation of water itself is dependent upon energy in most cases unless transport occurs via gravity. Although no comprehensive information exists on changes in the acquisition of water, it is often cited that water is being accessed from longer and longer distances to meet water needs, especially for urban areas, which will inevitably involve increases in the use of electricity.

2.2.2 The Transportation Sector: Water, the Chemical Industry, and Transportation

The reliance of the water industry on transportation for the provision of chemicals to treat water is a potential vulnerability point, and has contributed to changes in the choice of chemicals. The viability of providing water services by centralized water utilities to dense urban areas is dependent on quality controls, which, in turn, is dependent on chemicals, in particular, chlorine gas for disinfection. Potential attacks on chlorine storage tanks and transport vehicles and accidents involving the transport of chlorine by truck or rail have underscored this as a distinct vulnerability. The water industry performs conversions from chlorine gas to the less vulnerable sodium hypochlorite and ultraviolet disinfection, and this conversion has been estimated to be $647,000 to $13.1 million per plant at about two dozen selected larger plants [20]. An analysis of the conversion cost data reveals a moderate but positive correlation between the cost of conversion and plant size as shown in Figure 8 [12].
2.2.3 Water, Communications, and Information Technology  In the water sector, communication and information technologies increasingly control water quality, distribution, and customer interfaces. Information technologies are not only linked to water systems but also provide connections between water and other systems. The dependency of water on communications and information technology is identified in the Communications SSP [[8], p. 41]. The effect of disruptions of computerized control systems, such as supervisory control and data acquisition (SCADA), on water systems is noteworthy. For example, in 2001, a hacker disabled the SCADA system operating the wastewater treatment system, Queensland, Australia, causing extensive discharge of sewage [[21], p. 9].

Information technology, particularly as used in water applications, has been revolutionized by nanotechnology enabling detection of water chemicals to achieve extraordinary sensitivity. Wireless communication technologies further revolutionized water measurement. In the mid twentieth century, water-supply and wastewater quality standards were largely based on qualitative measures of chemical and biological material, for example, appearance, and by the late twentieth century quantitative standards gradually emerged, for example, expressed in parts per thousand and parts per million. In the twenty-first century those measures often went into the parts per trillion levels. These increasingly more stringent standards were made possible by newer detection technologies [[22], p. 80]. As a result of the increase in the quantification of and limits of detection for water quality measures, the water industry has become more dependent on information technologies that are usually very specialized [22, 23]. In 2006, American Society of Civil Engineers (ASCE) and American Water Works Association (AWWA) draft guidelines for water utility security outlined an extensive set of criteria for sensor-based detection, which reflect the greater use of, and hence dependency upon information technologies for water infrastructure [[24], Section 9].
3 MEASURING FUNCTIONAL INTERDEPENDENCY

When attention was first drawn to the importance and centrality of infrastructure interdependence, it was at a more conceptual and scenario-based level. Over the past decade or more, quantified measures of interdependence have emerged, potentially providing inputs for some of the modeling efforts underway in the area of infrastructure interdependencies. For example, Zimmerman and Restrepo [25], p. 223 applied the ratio of the amount of time it took for electric power to be restored and the time it took for water services to be restored after the August 2003 blackout, finding that the restoration time for the Cleveland water supply and Detroit system was at least two times three, respectively, as long as the time it took for electric power to be restored in those cities, assuming an average electricity outage of 24h. Dependency on electricity-driven pumps (rather than reliance on gravity systems) accounted for most of the delay in these areas. In other cases, backup power enables water systems to be restored more quickly than relying on the restoration of the general electric power systems [25], p. 226.

4 GLOBAL CONSIDERATIONS

Considerable attention has been paid to the dependence of population growth and economic development on resource capacity, and water and the infrastructure that supports it is a key component of the resource base. A concept capturing the resource capacity and usage relationship is the “ecological footprint”, defined as utilization of resources by a population or economy relative to the availability or production of that resource [26]. The footprint or imbalance cited by the World Wildlife Fund (WWF) is that the use of resources globally by 2006 has exceeded the ability to regenerate those resources by approximately 25% and the footprint has increased more than three times what it was in 1961 [26], p. 1. Globally, water withdrawal per capita and the ratio of withdrawals to resources (water stress) vary dramatically from country to country. Globally, the correlation between water stress and the ecological footprint (defined at the country level) is positive at 0.4 and statistically significant; however, if the four countries (in the Middle East and Africa) with extreme values of water stress are eliminated, the correlation between these two factors approaches zero [12]. The ecological footprint appears unrelated to water consumption, however, it seems to be qualified by two factors that are likely to influence water consumption: a country’s income and availability of water. With respect to income, the WWF [26], Table 2], for example, notes that high-income countries withdraw almost double the amount of water per capita (957,000 m$^3$ per year) than middle- or low-income communities do (552,000 and 550,000 m$^3$ per year, respectively). However, “water stress” is the same in high- and low-income countries (10% of total resources), whereas it is half of that (5% of total resources) in middle-income countries.

5 RESEARCH DIRECTIONS

Water systems depend upon other infrastructures, in particular, electric power, information technologies, and transportation, and indications are that this dependency is likely to increase with technological changes in water production and delivery. Other infrastructures in turn require water to function. These relationships imply that a disruption
in water systems or the infrastructures upon which water is interdependent creates a far
more complex system of impacts than is typically portrayed by a direct or single disrup-
tion of one infrastructure, and in some cases can magnify the costs to human life, health,
and welfare. Thus, a deeper understanding of the ramifications of these interdependencies
and their consequences should disruptions occur is needed. A means to quantify these
interdependencies and their consequences is a necessary prerequisite to comparing the
nature and magnitude of consequences across different types of interdependencies.

Vulnerabilities from interdependencies exist on top of vulnerabilities posed by any
condition or performance problems that water infrastructure may experience. Water and
wastewater infrastructures nationwide were rated D−, the lowest grade given to any
infrastructure area, by the ASCE in its 2005 infrastructure scorecard on the basis of con-
dition alone from noncatastrophic sources [27]. Research is needed on how such ratings
and other assessments can incorporate interdependencies and the natural hazard and ter-
rorism context. This will ultimately affect the performance and viability of infrastructures
dependent on water.

Global perspectives on water usage are important in addressing a new set of dimen-
sions about dependency and interdependency that impact infrastructure and the people
who depend on these systems. Water usage is a key component of the global resource
base. An understanding of how patterns of water usage by different kinds of infra-
structures influences resource capacity as measured by such concepts as the ecological
footprint is critical to linking security with sustainability.

Interdependencies among infrastructures have a special significance in times of emer-
gencies, since emergency response is heavily dependent upon infrastructure. In fact, it
is likely that the impact of such interdependencies may become magnified given the
compressed time frame necessary for emergency response.

Thus, the scope of the concept of infrastructure interdependencies is expanding and
undergoing a transformation to adapt to the needs of security. The water sector represents
a key part of that picture.

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**FURTHER READING**


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