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Identifying and Understanding the Infrastructure Interdependencies in Water Systems

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The water infrastructure system is a complex collection of interconnected infrastructures. Its performance and functioning depends on the performance of its interdependent infrastructures. The interrelationship between these infrastructures gives rise to bi-directional relationships and a host of potential failure scenarios. Modeling the associated complex adaptive system requires to start with analyzing the infrastructures on which the water system depends. While the water infrastructure cannot be made invulnerable to a myriad of stresses and potential failures, understanding the interdependencies can aid in developing computer models that can assist decision makers to test various 'what if' scenarios. In this paper we review and analyze the infrastructure interdependencies associated with water systems. Recent water infrastructure interdependency failures that drew the attention of the national media are highlighted. Existing software that model infrastructure interdependencies in other systems and ideas on how they can be applied to water infrastructure interdependencies are presented.

1. Introduction

While the infrastructure systems in any society provide the foundations for development and prosperity, the infrastructures that fall under the umbrella of civil engineering, i.e., water and transportation systems are lifelines for smooth functioning of day to day activities. Maintaining the integrity of these and other infrastructure systems at all times is essential for the society to have a strong economy. In the past, infrastructure systems were self-contained and operated independently of each other. In today's world, the infrastructures are increasingly interconnected by various degrees of complexity. While these interconnections ease their operations, they also bring about increased complexity for analyzing the infrastructures. The importance of analyzing these interdependencies has been stressed by the Presidents Commission on Critical Infrastructure protection (PCCIP, 1997) which defined an infrastructure as "*a network of independent, mostly private owned, man made systems and processes that function collaboratively and synergistically to produce and distribute a continuous flow of essential goods and services"* (Rinaldi et al. 2001).

The Oklahoma City bombing in 1995 and the 1996 report on Information Warfare

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served as an impetus for the US Federal Government to create the President's Commission on Critical Infrastructure Protection. The commission, made up of representatives from the American Government, industry and academia, was tasked to formulate strategies to protect critical infrastructure from physical and cyber threats. The PCCIP conducted a 15-month study culminating in recommendations reflected in Presidential Decision Directive 63 (PDD-63). PDD-63, issued in 1998, by President Clinton pointed out the importance of critical infrastructures and their associated interdependencies to the economy and outlined a federal framework for critical infrastructure protection. The commission identified eight critical infrastructures, namely power systems, transportation, water systems, government systems, telecommunications, banking and finance and emergency services. The commission noted that “incapacity or destruction of them will have a debilitating impact on the defense and economic security of the country”. Furthermore, the interconnected nature between these critical infrastructures magnifies the consequences of service disruptions. Disturbances originating locally, or in one sector/system, are more likely than ever before to cascade regionally and affect multiple sectors of the economy. As the interdependency of these infrastructure systems increases, their behavior tends to become more complex. Modeling this complex adaptive system requires a good understanding of their interactions and dependencies. In this work we analyze, within the American context, the infrastructure interdependencies associated with water systems. Water systems include water supply, treatment, and distribution components. Although the focus is on America, the ideas presented are relevant to water systems globally.

The integrity of the water systems depends on (a) power infrastructure for operating pumps, valves, and other mechanical components, as well as to power computer, and telecommunications systems; (b) on transportation infrastructure for transporting the required chemicals, personnel and equipment to the treatment plants; (c) on storage infrastructure for storing these chemicals and (d) on telecommunication infrastructure for handling SCADA (supervisor control and data acquisition) related communications as well as conventional forms of communication such as voice, fax and e-mail. Disruptions in any of these infrastructures can affect the water system to various degrees. While water infrastructure interdependency failures do commonly occur, a few high profile failures in the last few years have refocused concern on the infrastructure interactions. These concerns have provided the driving force for investigators to better understand and quantify the interactions within water systems. In addition, the bi-directional interconnection between these infrastructures introduces new and unknown ‘what if’ scenarios coupled with some risks. These interdependencies prevent us from treating water systems as closed system, where a closed system is defined as one which can be analyzed in isolation of other systems. On the other hand, as the discussion in the rest of the paper illustrates, analyzing the complex water infrastructure system requires using an "adaptive system of systems" approach, similar to the approach taken by others in studying power infrastructure systems and interdependencies.

Research into infrastructure interdependencies is fast gaining momentum in large due to the tragic events that occurred on September 11, 2001. Although the investigators are not aware of any work focusing on water infrastructure interdependencies, related work that focuses on civil and power infrastructures are presented here. The content of this paper is built on the ideas originally suggested by Rinaldi et al. (2001) in which the power infrastructure interdependencies and their analysis as a complex adaptive system were first detailed. Macal and North (2002) analyzed the interaction between power and gas infrastructures. Together with some of their other publications (North 2000, North 2001, Macal and Sallach 2000), the interdependencies between these two infrastructures and the reasoning behind modeling them as a complex adaptive system has been well detailed. Heller (2001) and Little (2003) presented different issues relating to making civil infrastructures more resilient and reliable. Basler et al. (2001) conducted exploratory study of vulnerabilities of interdependent infrastructures, as a consequence of inter-linkages through information infrastructure, with particular attention on infrastructures in Switzerland. Liu et al. (2000) presented a conceptual design for protecting power infrastructure systems. Zimmerman and Sparrow (1996) outlined the necessity of integrated research between infrastructure related technological fields and social and service side fields, to obtain a better understanding of the effects of economic, political and social interactions on the performance of infrastructure. Farrell et al. (2002) stressed the need for protecting power systems again disasters and the ability of such systems to provide service should they be subjected to a disaster.

The outline of this paper is as follows. In section two, an overview of the water infrastructure system is presented. The physical and cyber interdependencies are analyzed in section three. Infrastructure failures are discussed in section four and recent interdependency failures in the United States of America that drew the attention of national media are presented in section five. In section six, potential modeling approaches that can be used for modeling infrastructure interdependencies are discussed.

2. Overview of the Water Infrastructure System

Water infrastructure systems broadly consists of (a) surface and ground water sources (b) channels and pipes that convey untreated water (c) water treatment plants (d) water distribution systems which convey treated water (e) storage tanks, that store treated water and (f) wastewater collection, treatment and disposal systems. In the United States of America, the water system comprises more than 76,000 dams and reservoirs, thousands of miles of pipes and aqueducts, 54,000 public drinking water facilities and about 16,000 publicly owned wastewater treatment facilities (ASCE 2003, NRC 2002).

The water system can be visualized as four subsystems: water storage, water treatment, water use and wastewater treatment, as shown in Figure 1. The functionalities associated with these subsystems are:

(a) Water storage subsystems comprise of dams, reservoirs, tanks and other facilities, man-made or natural, used to store water for eventual use. This subsystem includes tanks that store treated water.

(b) Water treatment subsystems consist of facilities necessary to treat raw water. Treatment involves adding and/or removing substances from water so as to protect the health of the consumers.

(c) Water use subsystem which consists of the water users as well as the network of pipes, valves and hydrants, water meters, and backflow preventers which deliver water to the end-user. The system is responsible for conveyance, as well as the regulation and operation of water for all.

(d) Wastewater treatment subsystems consist of facilities designed to treat used water to a quality at which it would have a minimum harmful impact when reintroduced into the environment (Water Resources Engineering 1968).

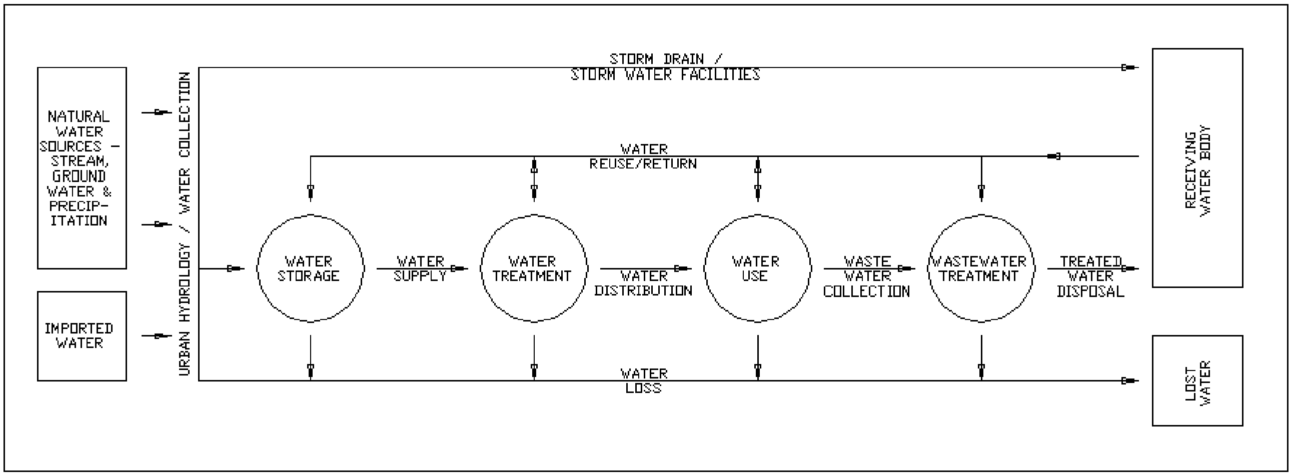

FIGURE 1: Overview of the water infrastructure system. (Water treatment and water use subsystems have storage components in them)

3. Water Infrastructure Interdependencies

Figure 2 illustrates the water related infrastructure interdependencies. These can be broadly categorized in two general categories as: (a) Physical (i.e., the output of one infrastructure system is used by the water system) and (b) Cyber (i.e., infrastructures using data transfer protocols)

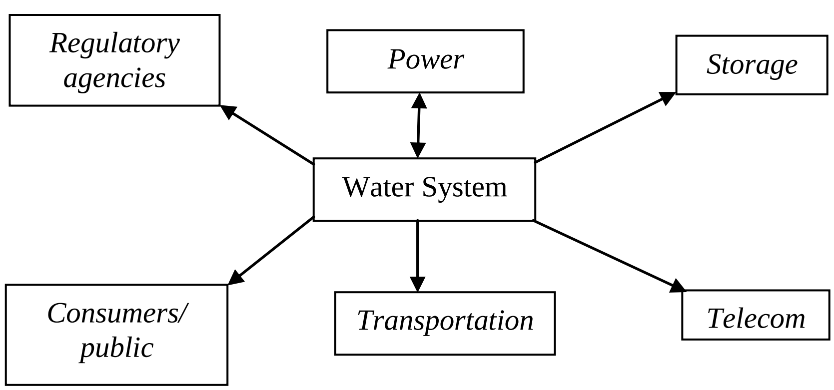

FIGURE 2: Interdependencies between water systems, other infrastructures and key stake holders

3.1. Physical Interdependencies

3.1.1. Power infrastructure

Virtually all components of the modern water infrastructure need power to operate. Electric power is needed for pumping, operation and maintenance, controls and for individual unit treatment processes. Velocity pumps and positive-displacement pumps are the two categories of pumps that are commonly used in water supply operations. Velocity pumps, which include centrifugal and vertical turbine pumps, are used for most distribution system applications. Positive-displacement pumps, which include rotary and reciprocating pumps, are most commonly used in water treatment plants for chemical metering and pumping sludge. The vast majority of electricity used by water infrastructure systems is obtained from the electric utilities with a small fraction being generated onsite (mainly in waste water treatment plants). Vice versa, the water usage by electric utilities is also high. According to studies done by the United States Geological Survey (USGS), in 1995, 39% of all the total fresh water volume used by the country was used by the process of power generation (Solley et al. 1998). Water is used in thermoelectric plants for steam generation and for condenser and reactor cooling. The study indicated that on an average twenty eight gallons of water are needed for each kilowatt-hour of electricity generated. Energy costs are a major portion of the operating costs of water systems and can account for up to 50% of all operational costs. Typical energy consumption, for municipal water treatment plants, range from 447 to 495 kWh per million liters (ML) [1693 to 1875 kWh per million gallon (Mgal)] of treated water. Figure 3 shows the relative distribution of energy for a 19 million liters per day (ML/day) [5 MG/day] treatment facility (HDR Engg., 2001).

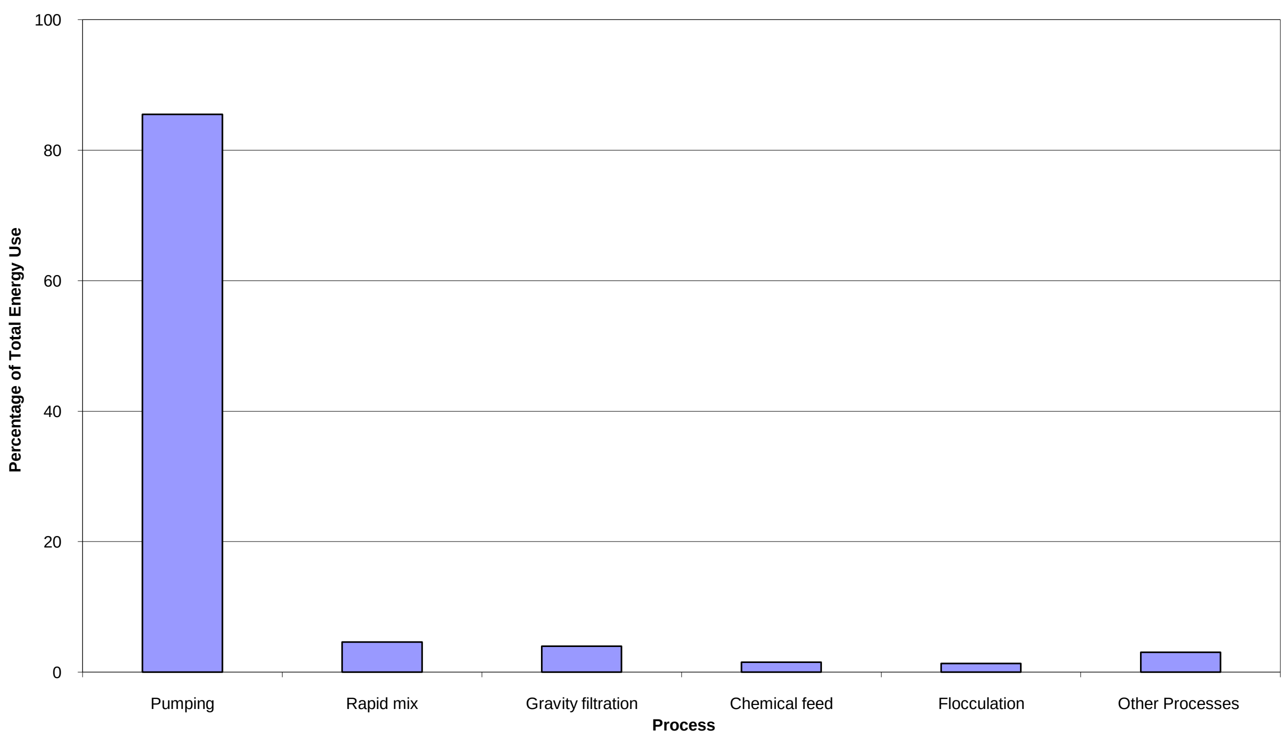

FIGURE 3: Distribution of Energy by Process in a 19 ML/day [5 Mgal/day] water treatment plant (HDR Engg., 2001)

3.1.2. Transportation Infrastructure

Water treatment plants rely on a variety of hazardous chemicals for their daily operation. Chemicals have to be replenished on a continual basis. These chemicals are primarily supplied via the existing transportation infrastructure. A number of factors limit the amount of chemicals that can be stored on site, thus warranting their transportation on a regular basis. Solid byproducts that are formed as a result of the treatment processes also need to be transported out of the treatment plants for disposal or reuse.

To aid this discussion, we quantify the amount of chlorine required for performing chlorination, which is one of the common water treatment processes. In America, chlorine is typically supplied in a liquefied from (compressed gas under pressure) in various sizes: ranging from cylinders (45-68 kg [100-150lb]) to containers (908kg [1 ton]). A treatment plant operating at a maximum day flow of 141 ML/day [30 Mgal/day] requires approximately 908 kg [1 ton] of chlorine for every 3 days. Transporting and storing the chemicals safely, is critical in ensuring that the system continues to operate safely. Most facilities provide in house storage for a month.

Delivery of chemicals is via existing transportation infrastructure. The most frequent mode of transport of chemicals is by truck or rail, or by barges for plants located along navigable waterways. The size of the treatment facility, location and treatment method all play a role in determining the mode of transport.

A by-product of producing treated water is water treatment plant residuals. The residuals are mainly obtained as sludge in various forms (viz. pre sedimentation, chemical clarification, lime softening, etc.) from sedimentation basins and carbon slurries. The sludge is formed when alum or other coagulants are added to the raw water where they bind with suspended particles and settle out as sludge. Overall, most water-treatment residuals are low in organics, nutrients and metal content; in addition they are non-toxic and non-pathogenic. They are suitable for a number of reuse applications including land application. On average 80-136 kg [175-300 lb] of residuals are produced per 3.8 ML [1 Mgal] of treated water (HDR Engg. 2001). A large majority of treatment plants truck residuals out for reuse or for landfill disposal.

3.1.3. Storage Infrastructure

Treatment plants rely on a variety of chemicals for operation. A number of factors limit the amount of chemicals that can be stored on site. The storage life of a chemical, the duration for which it will retain its full potency, limits the amount of chemicals that can be purchased and stored on-site. It doesn't make sense to purchase chemicals in quantities that wouldn't be used up within their lifetime. Adequate storage capacity and cost of storage within the facility have to be economically feasible. Health and safety code requirements dictate the amount of and form of chemicals that can be safely stored at location, without necessitating further expensive safety measures and check-guards. Chemicals have to be stored in quantities that meet safety requirements and such that they don't pose any threat, such as not posing an explosive hazard etc. Safety becomes more of an issue as the amount of chemical in storage increase. Health and safety codes also become more stringent and cost of compliance increases with increases in the amount of chemicals stored. Lastly, the amount of chemicals stored has to be at a volume in which ease of operation is maintained. For the reasons described above, storage of chemicals onsite in treatment plants has it limits and delivery of chemicals on a regular basis is necessary to stock chemicals needed for daily operations.

3.2. Cyber Interdependencies

Cyber dependencies include the reliance on telecommunications for operating supervisory control and data acquisition (SCADA) systems that control water flow and monitor quality throughout the water system. In the past, real time operational data of the reservoir levels, pressure levels, chemical concentrations etc. were not available. Advances in communications, controls, and computer hardware and software are bringing better control and management to operators of water infrastructure systems in the form of SCADA. SCADA systems are well established and have a long history in other industries such as power generation and petroleum refinement. Building upon the success that other infrastructures had with SCADA systems, water infrastructure systems are now integrating more of their operations with SCADA.

A typical SCADA system consists of a central control unit (CCU) and remote terminal units (RTU). Remote terminal units monitor and acquire data at vital locations, such as pumps, reservoirs, metering locations etc., and relay the information to the central control unit. Information is relayed via existing communication lines such as phone lines, radio or microwave. The central control unit gathers data and is able to have a system-wide understanding of how the water system network is working. Modern systems not only allow the operator to view how the entire system is working from one location, but also allow the operator to remotely control various components of the systems such as control valves. Figure 4 illustrates a simplified water SCADA system.

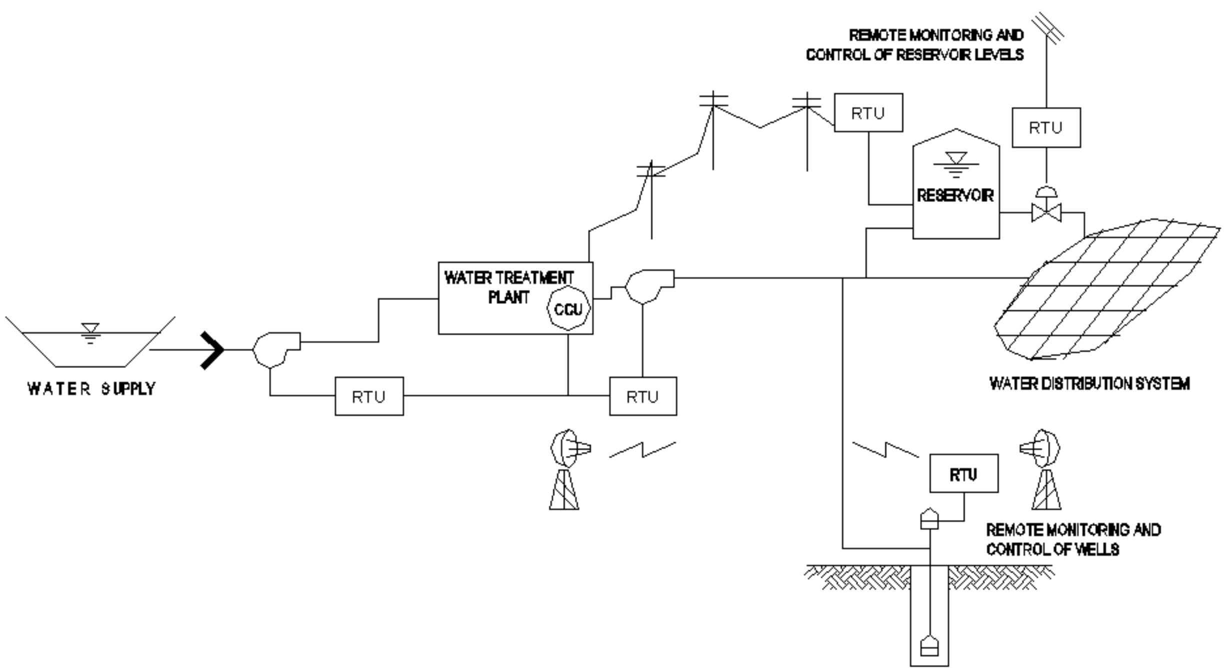

FIGURE 4: Schematic of simplified SCADA system (CCU = Central Control Unit, RTU = Remote Control Unit)

A safe and reliable communication network is essential to the proper functioning and maintenance of water infrastructure systems be it either a system adapted with the latest in instrumentation, controls and technology or a traditional system depending on phones or radios for communication with operators at location. With the increase in use of SCADA, reliability of the telecommunication networks cannot be overemphasized. SCADA systems are vulnerable to intentional breaches, defined as "acts by an unauthorized party to read, alter, insert or substitute data" (Munshi 2003). SCADA systems introduce a new dimension of vulnerability to the water systems

4. Infrastructure failures

Failures affecting the water interdependent infrastructures can be classified into two categories: (a) Cascading and (b) Common Cause.

4.1. Cascading Failure

A failure is termed as cascading if its disruption causes a disruption on its dependent infrastructures. This is a standard cause for major failures among infrastructure systems that are interconnected. Since each infrastructure has a bi-directional relationship with other infrastructures, any breakdown can generate cascading affects of varying degrees across other infrastructures. For example, while absence of water can affect power plants, absence of power can in-turn affect the performance of water systems. The increasing complexity and interconnectedness among the above discussed components pose new challenges for reliably managing and operating the water systems.

4.2. Common Cause Failure

A disruption of two or more interrelated infrastructures at the same time can result in a common cause failure (CCF) (e.g., natural or man made disaster). CCF failures can also result from inadequate maintenance practices, improper design criteria, human errors related to procedural problems and equipment failure. Preventing a CCF is essential for ensuring the reliability of the water system, as they have the potential for leading to a systems failure for highly redundant systems.

5. Recent Water Related Infrastructure Interdependencies Failures in the United States of America

The widespread blackout, which began August 14, 2003 and shut down electrical power in several states in the northeastern United States affected the water supply system in many cities (AWWA 2003). While hard hit with water disruptions were Detroit (MI) and Cleveland (OH) other smaller cities and towns in the region were affected to a lesser degree. In Cleveland, about 75% of the city's 1.5 million residents were completely out of water or had reduced water pressure for about half a day. In Detroit, the water pressure in its whole system was lost when the pumps stopped (Warikoo 2003). In New York, by the time power was restored, 1.9 billion liters [490 Mgal] of raw sewage had spilled into surrounding waterways — 548 million liters [145 Mgal] from the city's largest pumping station, on the Lower East Side — posing health and environmental hazards.

The underground train derailment and fire in Baltimore, Maryland that occurred in the summer of 2001 is an example of failure which can be classified as a combination of cascading and common cause failures. On July 18 a freight train carrying chemicals derailed and caught fire in the Howard Street Tunnel. The rail fire led to the break of a 1-meter [40-inch] diameter water main located on top of the rail tunnel. The water main break resulted in a gush of water into downtown streets and created a 2.4 by 1.8 meter [8 by 6 feet] hole in the middle of a major intersection. Water services were disrupted to a number of downtown businesses. The University of Maryland Medical Center saw a temporary loss in water pressure and cloudy water as did numerous residences in the vicinity of the accident. Water services were restored within a day through backup distribution loops and bypasses within the distribution network. Down town-traffic, already heavy, was further jammed by road closures due to the flooding. The water main break knocked out electricity in the immediate vicinity (Calvert and Scarcella 2001).

A third example of interdependency failures occurred during the California power crisis in early 2001 (Behr and Booth 2001). During this period the demand for power exceeded the available supply, thus stressing the western grid and resulting in rolling power blackouts. This affected the power distribution, which in turn disrupted the water supply at all levels thus idling key industries. The increased power costs also increased the operational costs of the water utilities. The Metropolitan Water District saw its total power costs during this period for operation of its 390 km [242 mile] long Colorado river aqueduct, which provides about 25% of water to Southern California go up by 106.2 million dollars (Metropolitan Water District 2002). Cities such as Los Angeles, Las Vegas, Boston, New York and San Francisco are primarily served by aqueducts which carry water across long distances. Since water is pumped along certain reaches in these aqueducts, either the unavailability of power or higher power costs, will impact the local water supplies and their rates.

6. Modeling Tools and Challenges

Existing models used in the water industry are highly developed and can reasonably represent water systems when treated in isolation. However, they are ill-suited for studying infrastructure interdependencies. Models developed to understand the above mentioned interactions should shed more light on (a) the degree of interdependency and vulnerability of the water systems (b) the adequacy of the water system to withstand any interdependency failures (c) look ahead tools that can predict the breakdown in the water distribution system and system response recovery times and (d) economic losses/affects of water system breakdown (e) reliability of different contingency formulations aimed at addressing different 'what if' conditions.

Accurate models of the individual components of water systems are well developed. Models have been developed for all water infrastructure subsystems. Notable examples being EPANet and KYPipe for distribution system modeling, Stimela and Water!Pro for water and wastewater treatment modeling and HEC for hydrologic modeling. Models at a larger scale, representing the various components of water systems and at an even larger scale representing the infrastructure systems are lacking. The numerical modeling techniques used in simulating the individual components are not adept at simulating interactions between the systems. The short-coming arises in that interactions between infrastructures are not based solely on physical-numerical constraints but also on financial, legal, regulatory and market-place constraints (North 2001).

New modeling techniques such as Complex Adaptive System (CAS) models and Agent Based Models (ABM) are better suited to simulate infrastructure interactions (North 2000). These models allow us to define the various agents and how they behave to different stimuli. Within these modeling frameworks the various infrastructure systems can be represented as agents, each with their individual objective, mode-of operation, operational framework and patterns.

As an example, one could look at the how water utilities and power utilities are operated independently of each other but depend on each others output, viz. water and electricity, for their operation. Both systems are managed and operated with the objective of providing an optimal level of service and at the same time maximizing financial gains. With the realization that generating capacity is not sufficient to sustain full usage by all during peak periods, electrical utilities in California have introduced various rate structures, called “Time of Use” (TOU). TOU rate structures charge varying rates at different times of the day. Rates during peak hours, when demand is highest, generally between the hours of 8am to 6pm are higher than rates during off-peak hours. The electric utilities objective is to minimize usage during peak-hours, so as not to overload the system, by charging a premium for peak-hour use.

From the water utilities perspective, largest demands for water are generally during the day, corresponding to when electric charges are the highest. Water utilities have had to modify their operational patterns so as to modify their power usage during peak-hours and at the same time satisfy water demands. Pump schedules have to be modified so as to pump to reservoirs during off-peak hours in sufficient quantity so as to be able to satisfy demand during peak-hours with minimal pump operation (i.e. electricity usage). From a strictly hydraulic point-of view this mode of operation might not be the optimal way to run a system. However, this is one such instance where other factors, economical in this case, overshadow physical (hydraulic) constraints in determining the mode of operation of a system. Existing numerical models in themselves are not able to properly simulate the reaction of systems to various external factors, CAS models and ABM on the other hand are more appropriate for studying such scenarios.

7. Existing Models for Simulating Infrastructure Interactions

Although the authors are not aware of models that can simulate water infrastructure interdependencies, models developed for other infrastructures are discussed herein. Work done by Michael J. North and others, at Argonne National Laboratory’s (ANL) Decision and Information Sciences Division’s Center for Complex Adaptive Agent Systems Simulation (DIS CAS2), in developing an integrated model of the electric power and natural gas markets provides a useful example and guide on how to study infrastructure interdependencies from a complex adaptive systems, agent based modelling perspective (http://www.dis.anl.gov). This section will describe the model developed by ANL its capabilities and how it could be imported to model water infrastructure system interdependencies and serve as a valuable reference for development of a model.

The Spot Market Agent Research Tool Versions 2.0 Plus Natural Gas (SMART II+) is the latest in a line of models developed by the DIS CAS2 division of ANL to study infrastructure interdependencies as complex adaptive systems using agent based modeling techniques. The SMART II+ model simulates the actions and decision processes of the electrical power generators and suppliers, natural gas suppliers and transmission companies and independent power traders. The electric power marketing and transmission infrastructure, the natural gas marketing and distributing infrastructure and natural gas-fired electrical generators are represented as agents in the model. Also included represented are the interconnection between the various systems.

Within the United States of America, use of natural gas as fuel for generation of electrical power has been rapidly growing. Factors contributing to this include:

i. The favorable capital construction costs and shorter construction times in developing natural gas fired electrical generators when compeered to electrical generators powered by other fuel sources (i.e. coal, nuclear, solar etc.)

ii. Flexibility of operation of natural gas-fired generating units which can be started up or shut down in response to short-term fluctuations in electric load demand at a minimal cost when compared to electrical generators powered by other fuel sources

iii. Readily available natural gas supply

The growth in use of natural gas for power generation has lead to an increased interdependency between the electrical power and natural gas infrastructures systems and markets.

The SMART II+ model includes elements which capture the following:

i. Electric power marketing and transmission infrastructure

ii. Natural gas marketing and transmission infrastructure.

iii. Natural gas-fired electrical generators which form the core of the interdependencies between the two infrastructure systems. The generators use fuel from the natural gas system and generate electricity for the power system.

iv. Transmission and distribution systems for both infrastructures.

v. Ability to represent economic factors, including investment capital, demand growth, new generation capacity and bankruptcy of noncompetitive entities.

vi. Ability to disable components to simulate system failures.

Using the SMART II+ model researchers at ANL have been able to better understand interdependencies between the electric power and natural gas markets. Preliminary results they obtained from the model indicate:

i. Natural gas fired generators are highly competitive in comparison to generators powered by other fuel sources leading them to increase their market share in power generation.

ii. As the market share of natural gas fired generators increases, the interdependencies between the two infrastructures systems and markets increase significantly.

iii. During periods of service disruptions, prices for both commodities rise sharply since both infrastructure systems compete for the same natural resource – natural gas.

iv. Metrics generated from the model, which help better understand the systems and interdependencies, include:

a. Unserved Energy (UE): the energy demand that was not met by the market.

b. Gas-fired Electrical Generator Market Share (MS): a measurement of the electric generation capacity provided by gas-fired generators and important indicator of the interdependencies between the natural gas and electrical power systems.

Many of the factors represented in the SMART II+ model are analogous to features present in infrastructure interdependencies between water and power utilities. The problem of optimizing water supply, to react to changing rate structures, as described in Section 6, can be addressed by developing a water-power infrastructures interdependency model with features similar to the SMART II+ model. The SMART II+ model serves as a valuable starting point and shows the potential of ABM models in addressing infrastructure interdependencies.

8. Conclusions

The importance of water systems cannot be overemphasized. A clean and dependable source of water is a fundamental necessity for all people and one which is taken for granted. Events in the recent past have brought about an awareness of the interdependency between infrastructures and realization of our limited knowledge on how such systems work under stress. Modern water systems have evolved into systems that are highly dependent on other infrastructure systems. In certain instances the dependency is bi-directional, in that not only do the water systems depend on other infrastructure systems, but other infrastructure systems also depend on water systems to a degree or other. As a consequence, water systems cannot only be considered in isolation but have to be studied from a larger viewpoint, as components of overall infrastructure systems.

In this work, infrastructure interdependencies associated with water systems are analyzed. The interdependencies primarily result from the dependence of water systems on power, transportation, telecommunication and storage infrastructure (defined as physical storage facilities for materials needed for water treatment as well as the by-products of the treatment process). Failure of water system has a potential of generating cascading affects across multiple infrastructure components. A few recent water infrastructure interdependency failures have been highlighted.

Developing models that can aid decision makers in testing different 'what if' scenarios can assist the utilities and local governments in the planning process. The relationship between various infrastructures cannot be described by a set of equations. The relationship that arises between systems is the consequence not only of various physical-numerical constraints but also of financial, legal, regulatory and market-place constraints. Such relationships cannot be adequately represented by existing models. Agent based modeling algorithms on the other-hand appears to be promising tools for modeling such relationships.

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