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WATER INFRASTRUCTURE INTERDEPENDENCIES: A COMPLEX ADAPTIVE SYSTEM

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The objective of this work is to investigate key questions regarding infrastructure interdependencies related to water systems. Water systems depend on a number of infrastructures like power, transportation, and communications for their daily operations. This bidirectional, interconnected nature poses new unknowns and risks for maintaining the integrity of the water system. Maintaining the integrity of the water system requires analyzing these related infrastructures, from a systems point of view. In this work, we review the salient features of these interdependencies and present the ability of agent based modeling paradigms for modeling the water infrastructure interdependencies.

INTRODUCTION

The infrastructures that fall under the umbrella of civil engineering (viz., water, transportation) provide the backbone for any country's economy and society (Little, 2003). Maintaining the quality of these infrastructures and ensuring that they serve their design purpose is vital. System failures, originating locally in one infrastructure system, can spread to multiple sectors of the economy and society (ASCE, 2003). The interconnectedness between infrastructure systems brings about increased complexity in analyzing their behavior.

In today's world, the operation of water infrastructure is interrelated and dependent on various other infrastructures, institutions, policies and social behavior. Given the interdependencies, water systems cannot reasonably be treated as a closed system, where a "closed" system is defined as a system that can be analyzed in isolation, independent of other systems. As systems in general and water systems in particular become interdependent on one another, predicting their combined behavior becomes more complex. Understanding how systems are linked can aid in designing better integrated systems that have the capacity to absorb failure of other systems upon which they are dependent, and still remain functional (North, 2001) .

The performance of water systems depends on power, transportation, storage and telecommunication infrastructures. Other nonphysical interdependencies, termed human interdependencies, include regulatory, legal, financial, marketplace and social constraints. Currently, gaps exist in our capability to analyze and understand the full interconnectedness of the water infrastructure. With respect to water systems, this limits our ability to plan for optimal performance and respond to sub system breakdowns. Although the benefits of ad hoc development of algorithms has been demonstrated, a rigorous process for deriving emergent algorithms from infrastructure interdependencies is essential for protecting and optimally using and managing infrastructure systems. Such algorithms can be invaluable tools for engineers, planners, consumers and decision makers.

While models to predict the behavior of individual components of water systems (e.g. KYPIPE, Stimela etc.) are well developed, not much work has been reported for predicting the interaction of these individual components with other infrastructures. Computer models are an obvious choice for simulating the interactions among infrastructure elements. Agent based modeling (ABM) tools are becoming popular for modeling these interactions (Macal and Sallach, 2000). In ABM, interactions are modeled individually by computer programs called agents, which are decision making entities. A model based on ABM methodology can assist decision makers in testing the survivability of the water system for different "what if" failure scenarios.

Rinaldi et al. (2001) formulated a general framework for analyzing infrastructure interdependencies. They took into account six infrastructure interdependencies: infrastructure environment, coupling, response behavior, failure types, infrastructure characteristics, and state of operation. Their framework identifies infrastructure systems as Complex Adaptive Systems (CAS) and provides details for developing agent-based simulations (ABS) of complex systems. Macal and North (2002) and North (2000) used ABS for modeling the interaction between power and gas infrastructures. Other ABS models, to model electrical infrastructure include the works of Bunn and Oliveira (2000), Petrov and Sheblé (2000), and Veselka, et al. (2002). Farrell et al. (2002) stressed the need for protecting power systems again disasters and the ability to provide service should they be subjected to a disaster.

This paper presents a broad overview of the water system and its interdependencies. This is followed by a discussion of the ability of agent based modeling tools for modeling water systems as complex adaptive systems.

OVERVIEW OF THE WATER INFRASTRUCTURE SYSTEM

Man made water systems typically comprise of four major subsystems, namely storage, water treatment, distribution and wastewater treatment subsystems (Water Resources Engineering Inc., 1968). Storage systems are facilities such as reservoirs, dams and tanks which impound or collect raw or treated water for eventual use. These systems can act as buffers to system demand. Water demands typically fluctuate throughout the day and through seasons. During periods of low demand, the storage systems store excess water and make it available during periods of high demand. The advantage offered by such systems is that the overall system can be operated at a relatively steady rate and processes do not have to be oversized to deliver peak flows. Instead, they can rely on storage capacity for excess flows during peak demand conditions.

Water treatment systems treat raw water to standards necessary for the end-user. Water quality standards for residential, public and commercial use are similar, while standards required for industrial use depend on the type of industry. In the case of the former, water treatment tries to ensure that the water is safe for drinking. Treatment involves adding or removing substances from water so as to protect the health of customers. Within industries, the water quality requirements vary significantly depending on the type of use: cooling, processing, power generation, sanitary services, fire protection, general uses (including washing and air conditioning).

Water distribution systems are made up of pipes, canals, pump stations, control devices and other appurtenances which convey water to users. The size and layout of distribution systems are dictated by topology, demand and end-use. Residential, industrial, agricultural and emergency service facilities, all have different flow and pressure requirements.

Wastewater treatment systems are comprised of facilities that treat effluent to a quality at which it can be reintroduced to the environment with minimal environmental impact. These systems are also increasingly being used to produce reclaimed (recycled) water.

INFRASTRUCTURE INTERDEPENDENCIES IN THE WATER SYSTEM

Water related infrastructure interdependencies can be broadly categorized into three general categories, namely physical, cyber, and human (nonphysical) interdependencies.

Physical Interdependencies

Physical interdependencies can be defined as interdependencies where the output or component facilities of one infrastructure system are used by another system. Power and transportation are two principal interdependencies, for water systems, within this category.

(a) *Power Infrastructure*

Modern water infrastructure systems are highly dependent on power, mainly in the form of electricity, for their continued operation. Pumps, ventilation systems, treatment processes, operation and maintenance and controls all require electricity. Most of the electricity needs of water systems in the United States of America (USA) are supplied by electric utilities, with a small fraction being generated onsite, mainly in wastewater treatment plants. Energy accounts for up to fifty percent of operational costs for water treatment systems (HDR Eng., 2001). Groundwater pumping and pumping for conveyance, when flow by gravity is not practical, are also high-energy consuming processes.

The interdependency between water and power infrastructure systems is bidirectional; power infrastructure systems are highly reliant on water systems also. Generation of power by hydroelectric means depends on impoundment of water using dams and conversion of its energy to electricity. In addition, thermoelectric plants require water for steam generation and for condenser and reactor cooling. A study conducted by the USGS, in 1995 (Solley et al., 1998), established that twenty-eight gallons of water are needed for each kilowatt hour of electricity generated. The same study concluded that power generation accounted for thirty nine percent of fresh water usage in the USA.

(b) *Transportation Infrastructure*

Treatment plants need various chemicals for their daily operation. Various factors limit the amount of chemicals that can be stored on site. Transportation infrastructure is needed to supply these chemicals. To get a better grasp of the transportation needs, one could look at chlorine requirements for water treatment. Chlorine is widely used for disinfection (chlorination). A treatment plant operating at a capacity of 30 million gallons per day (mgd) requires approximately 2 tons of chlorine per week (HDR Eng., 2001). Most water treatment facilities have storage for a month's worth of supply. Chlorine is supplied in a liquefied form (compressed gas under pressure) in various sizes: ranging from cylinders (100-150 pounds) to containers (1 ton).

Water treatment residuals are formed as a by-product of treatment. 175-300 pounds of residuals are produced on average per million gallons of treated water (HDR Eng., 2001). Most water-treatment residuals are low in organics, nutrients and metal content; nontoxic and nonpathogenic making them suitable for a number of reuse applications, including land application. Residuals are usually trucked out of treatment facilities, for reuse or for landfill disposal. The size of the treatment facility, location and treatment method, all play a role in determining the mode of transport. The most frequent mode of transport is by truck or rail, or by barges for plants located along navigable waterways.

Cyber Interdependencies

Cyber interdependencies can be defined as interdependencies between infrastructures using data transfer protocols or communications. With the advent of control systems, especially in the form of supervisory control and data acquisition (SCADA) systems, the relevancy and importance of this interdependency to water systems is increasing. SCADA systems are well established and have a long history in other industries such as power generation and petroleum refinement. Water infrastructure systems are beginning to integrate more of their operations with SCADA. Older system did not permit real time monitoring of operational data such as reservoir levels, pressure levels, chemical concentrations etc. SCADA systems allow the operator to remotely view and control virtually all components of the water system. Flows and pressures throughout the systems can be monitored by meters and transducers equipped with electronic input/output interfaces; valves equipped with actuators can be remotely throttled. Increased cyber interdependencies are a direct product of advances and lowering in prices of communications, controls, and computer hardware and software (Munshi, 2003).

Human Interdependencies

Water infrastructure operate within an intricate network comprised of internal stakeholders (i.e., employees) and external stakeholderssuch as consumers, the general public, private enterprises and governmental agencies. The interdependent relationships developed between them comprise organization-environment relationships. Government and market institutions play an important role in regulation of water infrastructure systems. In addition to the various public and private organizations, individual stakeholders also have an important influence on operation of water systems both directly and indirectly.

In the past water, as a resource, was not regulated and in general was readily available for basic needs such as drinking, food production and sanitation. As demand for water has increased, with increased population growth and increase in overall water consumption, policies, rules and laws regarding water resources have been instituted. Water management policies are predominantly a combination of government and market policies. The combination and importance of each varies from country to country. Government regulations aim to achieve the following:

- Assure that the basic needs of the population, especially low income people, are met
- Serve to limit monopolization of the water sector by large players
- Assure quality standards are met
- Ensure that environmental impacts are minimized
- Promote water development in disadvantaged regions

Markets treat water as a commodity. Water is supplied to customers within the framework instituted by government policy. Market forces serve to regulate prices at which suppliers sell and consumers buy water. Customer's perception of water quality and willingness to pay also serve to regulate the market.

Water policy plays an important role in regulating water usage and the cost of water to customers. Increased water usage necessitates development of new sources, which in general are of marginal quality or located at further distances from their point of use. The cost of water from such new sources can be excessive and not affordable to consumers. Water sector policies arise to redistribute the cost of development equitably among all users such that a single group or sector does not bear the brunt of the costs. In addition taxes and increased water prices, or water rationing can act as incentives for conservation of water, more efficient use of water and reuse of water. Environmental regulations penalizing polluters, or standards, controlling increased salinity (a by-product of inefficient irrigation) are further examples of how water systems are regulated.

AGENT BASED APPROACH FOR MODELING WATER SYSTEM

Analyzing the water system requires using a complex adaptive approach. Complex adaptive systems are defined as systems which evolve and self-organize as a result of interactions between the individual subunits or building blocks of the system. Whereas the behavior of the individual components is simple, the emergent behavior that arises as a result of the interactions can be complex, and cannot be deduced from an understanding of the behavior of the units in isolation. Complex adaptive systems have been valuable in explaining various emergent phenomena which are not centrally controlled. Examples of complex adaptive system studies in other fields are shown on Table 1.

Models to simulate individual components of water systems have been well developed. Models have been developed for all water infrastructure subsystems. Notable examples being EPANet (http://www.epa.gov/ORD/NRMRL/wswrd/epanet.html) and KYPipe (www.kypipe.com) for distribution

Table 1. Complex Adaptive System Studies (Schuster, 2001)

Chemical networks	Kauffman (1993)
Communication networks	Albert, Jeong and Barabasi (2000)
Ecological networks	Sigmund (1993)
Economic networks	Arthur, Durlauf and Lane (1997)
Power infrastructures	Rinaldi, Peerenboom and Kelly (2001)
Social networks	Frank (1998)
Transportation networks	Narguney (2000)

system modeling, Stimela (http://www.stimela.nl/) and Water!Pro (http://www.chemsw.com/11068.htm) for water and wastewater treatment modeling and HEC (http://www.hec.usace.army.mil) 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. Furthermore, the various models were developed at different scales with different parameters and different underlying assumptions; never with the intent of being combined. As such, they do not lend to being coupled. New approaches such as complex adaptive analysis offer better frameworks for understanding infrastructure system interdependencies (Little, 2003).

A new programming paradigm, called Agent Based Modeling (ABM), has been developed in recent years to simulate complex adaptive systems. Traditional modeling involved defining rules for how an entire system would interact. In ABM, rules are given to the each of the individual agents. The rules dictate how the agent behave and interact. Such models simulate the patterns that emerge out of the individual behavior and interactions. Agent based modeling tools have the potential to be valuable tools in modeling infrastructure interactions (North, 2001).

Agent-Based Modeling (ABM) is a computer-driven tool used to study the intricate dynamics of real world systems in which complicated system behaviors emerge from relatively simple individual behaviors and interactions. ABM relies on the power of computers to explore the associated dynamics that are out of the reach for other modeling approaches. In ABM, systems are modeled as a collection of autonomous decision-making entities called "agents". Each agent makes decisions based on a set of rules. Agents may represent either a single entity (e.g. a person) or a collective group (such as a utility or institution).

There are different platforms available for developing agent based systems. These platforms provide a set of libraries for creating, running, displaying and collecting data from an agent based simulation. Table 2 summarizes some of these platforms, detailing the development language and web address (URL), where additional information regarding the platform can be found and in many cases, the platform itself, downloaded.

One of the important aspects of ABM is its ability to capture emergent phenomena (behaviors or occurrences that come about during the course of a simulation resulting from the interactions of individual entities). Emergent phenomenon are difficult to predict and can be counter-intuitive. Therefore, predetermining the output of such phenomena can enhance the decision making processes. Another attribute of agent-based modeling is its flexibility. Models can be modified and enhanced with ease. For example, additional agents can easily be added to a model if necessary. In addition, the complexity of agents (their behavior, ability to learn and evolve, and rules of interactions), can be modified.

Table 2. ABM Computing Platforms

Name	Development Language	URL
AScape	Java	http://www.brook.edu/es/dynamics/models/ascape
JADE	Java	http://sharon.cselt.it/projects/jade/
MadKit	Java	www.madkit.org/
MAML	Objective C	http://www.syslab.ceu.hu/maml
NetLogo	StarLogo	http://ccl.northwestern.edu/cm/netlogo/
RePast	Java	http://repast.sf.net
StarLogo	StarLogo	http://www.media.mit.edu/starlogo/
Swarm	Objective C & Java	http://www.swarm.org

ABM models utilize repetitive interactions between agents to evaluate the end system. Agent-based models offer unique advantages for studying different types of complex systems. ABM gives the decision makers the ability to run different "what if" scenarios in controlled environments. ABM tools can facilitate in testing the survivability of the water system by analyzing its response to different "what if" scenarios. It can thus provide design guidance to system design and management personnel. It includes analysis of how susceptible the water systems are to changes or failure in other systems, and suggestions for improving the design of systems based on this analysis. The end results can aid the decision makers in formulating the appropriate strategies aimed at ensuring continued system performance even during service disruptions.

There are no central rules governing how the various infrastructures interact. On the other hand, each infrastructure system acts in a decentralized manner and could be appropriately simulated as an agent. Each agent could be endowed with individual objective, mode-of-operation, operational framework and patterns. Using such models, valuable insight into infrastructure system reactions to system disruptions, financial fluctuations, availability of commodities, policy changes etc., can be simulated.

Models developed to understand the above mentioned interactions could 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 and (e) reliability of different contingency formulations aimed at addressing different "what if" conditions (Heller, 2001; Zimmerman and Sparrow, 1996).

CONCLUSIONS

While the infrastructures in any society provide the foundation for development and prosperity, the infrastructures that fall under the umbrella of civil engineering, i.e., transportation and water systems, are lifelines for smooth functioning of day to day activities. Maintaining the integrity of these and other infrastructures at all times is essential for the society/nation to have a strong economy (Little, 2003). In the past, infrastructure systems were more self-contained and operated independently of each other. In today's world, the infrastructures are increasingly interconnected by various degrees of complexity. While this interconnection does ease their operation, it also brings about increased complexity for analyzing the infrastructures.

Modern water systems have evolved into systems that are highly dependent on other infrastructure systems. The dependency is bidirectional, in that not only do the water systems depend on other infrastructure systems, but other infrastructure systems also depend on water systems to a certain degree. As a consequence water systems cannot be considered in isolation but have to be studied holistically, as components of overall infrastructure systems. Water infrastructure systems have the characteristics of complex adaptive systems in that they are highly dependent on other infrastructures which behave according to certain rules, and vice versa other infrastructures also depend on them.

Developing models that can represent interactions between infrastructures can assist decision makers 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 of not only various physical-numerical constraints but also of financial, legal, regulatory and marketplace constraints. Such complex adaptive relationships cannot be adequately represented by existing models. Agent based modeling algorithms, on the other hand, have the capacity to simulate such relationships.

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