ANALYZING WATER/WASTEWATER INFRASTRUCTURE INTERDEPENDENCIES

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ABSTRACT

This paper describes four general categories of infrastructure interdependencies (physical, cyber, geographic, and logical) as they apply to the water/wastewater infrastructure, and provides an overview of one of the analytic approaches and tools used by Argonne National Laboratory to evaluate interdependencies. Also discussed are the dimensions of infrastructure interdependency that create spatial, temporal, and system representation complexities that make analyzing the water/wastewater infrastructure particularly challenging. An analytical model developed to incorporate the impacts of interdependencies on infrastructure repair times is briefly addressed.

KEYWORDS

CI^3, infrastructure, interdependency, outage, repair time, water, wastewater

INTRODUCTION

The importance of infrastructure interdependencies was highlighted in 1998 when the President's Commission on Critical Infrastructure Protection recognized that the security, economic prosperity, and social well being of the nation depend on the reliable functioning of our increasingly complex and interdependent infrastructures. These include water supply and wastewater systems, energy systems (electric power, oil, natural gas), telecommunications, transportation (road, rail, air, water), banking and finance, and emergency and government services. The commission also noted that “mutual dependence and interconnectedness made possible by the information and communications infrastructure lead to the possibility that our infrastructures may be vulnerable in ways they never have been before." Failure to understand how disruptions to one infrastructure could cascade to others, exacerbate response and recovery efforts, or result in common cause failures leaves planners, operators, and emergency response personnel unprepared to deal effectively with the impacts of such disruptions.

Understanding, analyzing, and sustaining the robustness and resilience of the water/wastewater and other interdependent infrastructures requires new modeling and simulation approaches and tools to assess the technical, economic, and national security implications of technology and policy decisions designed to ensure their reliability and security. Figure 1 identifies the critical infrastructures and illustrates the interdependencies among them.

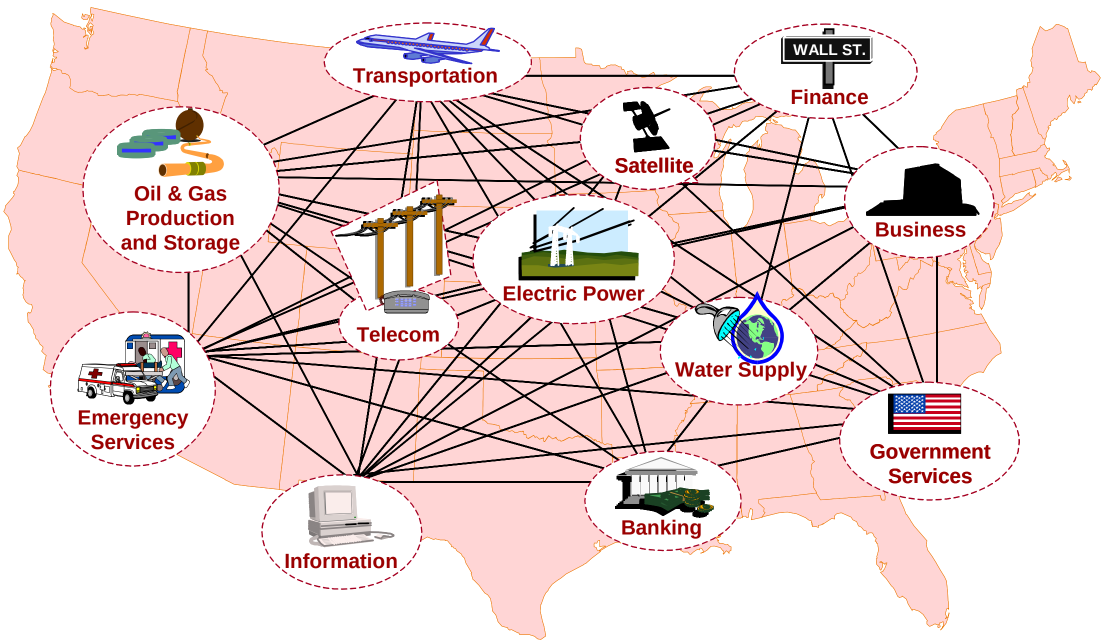

Figure 1: Interdependent critical infrastructures

TYPES OF INTERDEPENDENCIES

Historically, interdependencies have been considered to be either physical or geographic. An example of a physical interdependence is that the water supply infrastructure depends on electric power to operate its pumps while, at the same time, the electric power infrastructure must have water to make steam and cool its equipment. Geographic interdependencies arise when infrastructure components, e.g., water pipelines, transmission lines, gas pipelines, and telecommunications cables, share common corridors thus increasing the vulnerabilities to and consequences from local hazards or sabotage.

However, the proliferation of information technology (IT), the increased use of automated monitoring and control systems (e.g., Supervisory Control And Data Acquisition (SCADA) systems), and the reliance on the open marketplace for purchasing and selling of infrastructure commodities and services have linked infrastructures in new and complex ways and have created new vulnerabilities. The dependence of the new energy marketplace on the internet and other e-commerce systems, and the complicated links to financial markets, highlight the breadth of cyber and logical interdependencies.

Therefore, four basic categories of interdependencies are described in this paper: *physical*, where the output of one infrastructure is used by another; *cyber*, where an infrastructure depends on information transmitted through the information and communications infrastructure; *geographic*, where two or more infrastructures are co-located, such as in a common utility corridor, and can be affected by a local event; and *logical*, where the state of an infrastructure depends on the state of another infrastructure in a way that is not physical, cyber, or geographic (e.g., linkages through financial markets). Such linkages vary in scale and complexity and must be appropriately considered in analyzing infrastructure vulnerabilities and response actions.

WATER SYSTEM INTERDEPENDENCIES

Water and wastewater systems have unique interdependencies with other infrastructures that must be considered when conducting vulnerability assessments, developing response and recovery plans, and in addressing other issues of security and protection. Figure 2 illustrates some of the dependencies of the water and wastewater infrastructures with the transportation, natural gas, petroleum liquids, telecommunications, and electric power infrastructures. Similar figures could be made showing the dependence of these other infrastructures on the water and wastewater infrastructures.

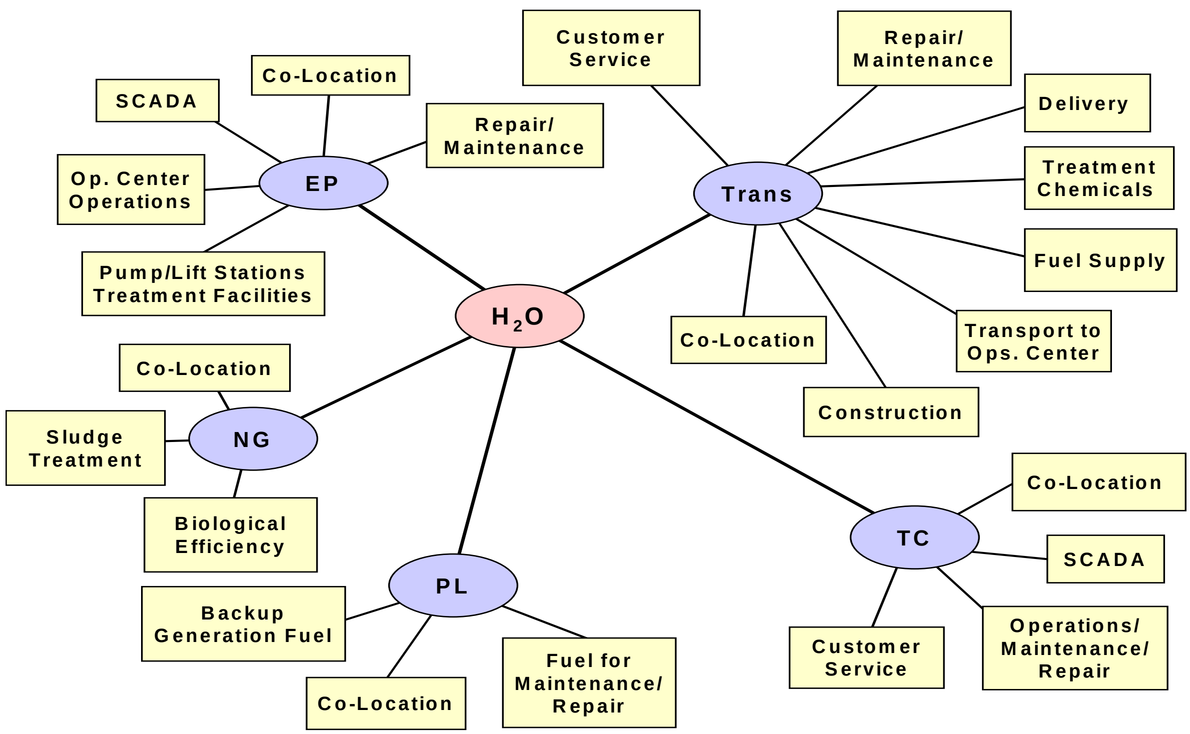

Figure 2: Water and wastewater interdependencies

DIMENSIONS OF INFRASTRUCTURE INTERDEPENDENCIES

By definition, infrastructure interdependencies transcend individual sectors and generally transcend individual companies. Further, they vary in scale and complexity, ranging from local linkages (e.g., municipal water supply systems and local emergency services), to regional ones (e.g., electric power coordinating councils), to national ones (e.g., interstate natural gas and transportation systems), to international ones (e.g., telecommunications, banking, and financial systems). These scale and complexity differences create a variety of spatial, temporal, and system representation complexities that are not well understood or readily analyzed.

Such gaps in understanding and analytic capability are apparent in the context of analyzing multiple contingency events involving interdependent infrastructures. As indicated in the above figures, each linkage in the water/wastewater infrastructure has important, and potentially different, spatial, temporal, and system characteristics.

Several major dimensions for describing infrastructure interdependencies have been identified. These dimensions are briefly discussed below.

Type of Failure

Three types of failures can affect interdependent infrastructures. A cascading failure is a disruption in which one infrastructure causes a disruption in a second. An escalating failure is a disruption in one infrastructure that exacerbates an independent disruption of a second infrastructure (e.g., the time for restoration of a failure of a water pipeline increases because the transportation infrastructure has a failure that prevents parts or repair workers from reaching the failed pipeline). A common cause failure is a disruption of two or more infrastructures at the same time as the result of a common cause (e.g., natural disaster).

Infrastructure Characteristics

Among the characteristics that can influence the impacts of interdependencies are the organizational structures of the interconnected infrastructures. Other such characteristics include the operational relationships and the relative spatial makeups of the infrastructures. There is potentially a temporal component to these characteristics as well.

State of Operation

The state of operation of an infrastructure (ranging from normal operation to various levels of stress, disruption, or repair and restoration) must be considered. For example, hourly, daily, weekly, and seasonal variations in load, outages, maintenance schedules, reserve capacity, weather, and other operational factors may change the character and importance of interdependencies. An understanding is necessary both of backup systems or other mitigation mechanisms that reduce interdependence problems, and of the change in interdependencies as a function of outage duration and frequency.

Types of Interdependence

In addition to the four types of interdependencies discussed earlier, the degree to which infrastructures are linked also influences their vulnerabilities and response requirements. Some linkages are loose and thus relatively flexible, such as the linkage between a water treatment facility that maintains a large inventory of chlorine and the transportation infrastructure that delivers the chlorine. Short-term disruptions of the transportation system may not affect water treatment. Other linkages are tight, leaving little or no flexibility for the system to respond to changing conditions. For example, electric-powered pumps would be immediately affected by a loss of electric power.

Infrastructure Environment

Information technologies (IT), deregulation, and multiple business mergers are forces that have dramatically affected the economic and business aspects of the infrastructure environment. IT provided business with a powerful tool to increase operational efficiency, but subsequently led to the proliferation of cyber interdependencies (and the introduction of new vulnerabilities). The move toward deregulation and/or privatization of some infrastructures resulted in the shedding of excess capacity that had served as a shock absorber against system failures. Mergers further eliminated redundancy and overhead in infrastructure operations. These forces have combined to create an environment in which infrastructures are much more interdependent, have little or no cushion in case of failures, and have few if any alternative sources of service.

Additional environmental factors influencing infrastructure interdependencies include government investment decisions, legal and regulatory issues and changes, and public health and safety concerns. Decisions in these areas have, in some cases, had very strong impacts in how infrastructures operate and interact with each other.

Coupling and Response Behavior

This dimension describes the interdependencies in terms of their rigidity (i.e., are they fixed, inflexible relationships or can they be adapted to different circumstances) and their complexity (e.g., does one infrastructure completely shut down with a partial loss of another).

MODELING OF INFRASTRUCTURE INTERDEPENDENCIES

The "science" of infrastructure interdependencies is relatively new and current modeling and simulation tools are only beginning to address the issues noted above. Many models and computer simulations exist for aspects of individual infrastructures (e.g., load flow and stability programs for electric power networks, connectivity and hydraulic analyses for pipeline systems, traffic management models for transportation networks), but simulation frameworks that allow the coupling of multiple, interdependent infrastructures are only beginning to emerge.

One of the fundamental questions addressed by interdependency analyses is the time required to restore service to key infrastructure components that have been lost or degraded. Such losses adversely affect the deliverability of a commodity and/or the performance of other infrastructures that depend on that component for their respective operations.

Argonne National Laboratory has developed a software tool called the Critical Infrastructure Interdependencies Integrator (CI^3) to estimate (through Monte Carlo simulation) the time and/or cost to restore a given infrastructure component, a specific infrastructure system, or an interdependent set of infrastructures to an operational state. The “point and click” format allows users to create a representative model of recovery and restoration activities, and to set up and run a simulation. Graphical and tabular results assist analysts to better quantify the impact of infrastructure disruptions. CI^3 also provides a framework for incorporating uncertainty into the analysis of critical infrastructures.

Typically, the impacts of an infrastructure disruption will vary as a function of the outage duration. Furthermore, the impacts generally do not scale linearly, e.g., the impacts of a two-day outage may not be simply twice those of a one-day outage. Similarly, the outage duration cannot be predicted with certainty, but rather the outage duration can be represented as a probability distribution. CI^3 was developed to address outage times while also considering escalating failures in other infrastructures. CI^3 estimates the amount of time needed for restoration activities for a given infrastructure component, a specific infrastructure system, or an interdependent set of infrastructures.

The estimate outage times assist in determining appropriate mitigation measures. For example, if no impacts will result from a failure of four hours or less, and the decision maker is highly confident that the infrastructure can be restored within that time, then no mitigation action may be justified.

Better information on outage times can assist infrastructure operators in determining their vulnerability to infrastructure failures. Decision makers can better decide on potential mitigation measures such as redundant infrastructure connections or alternative fuel sources. Infrastructure operators can better understand bottlenecks in the restoration process and take action to potentially lessen outage times. Bottlenecks such as staff and spare part placement can be optimized throughout their service territory. Finally, other critical infrastructures can better understand their risks of failure resulting a failure of an interdependent infrastructure and implement appropriate mitigation measures.

Sample output shown in Figure 3 compares the cumulative probability for outage times with the critical outage time, i.e., the outage duration at which the consequences of failure become very significant. Other CI[3] output includes probability distributions. This output can be used in planning mitigation options, response actions, and other means of dealing with vulnerabilities and consequences in the water/wastewater infrastructure.

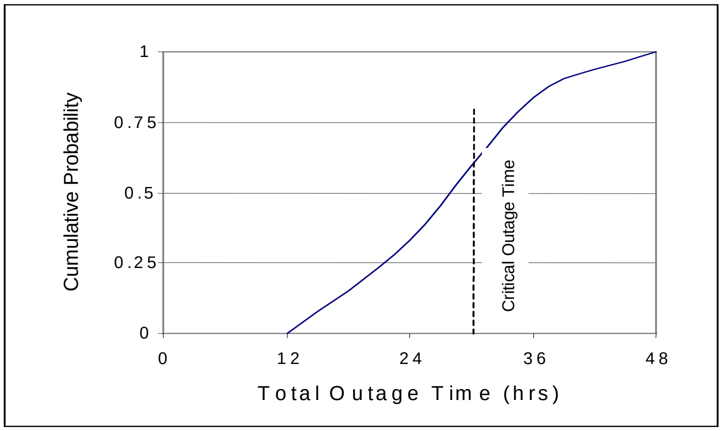

Figure 3: Cumulative Probability Distribution for Outage Time

INTERDEPENDENCIES ANALYSES NEXT STEPS

The CI[3] model provides an initial framework for recognizing interdependencies and incorporating uncertainty into the analysis of critical infrastructures. As critical infrastructures become more tightly coupled, the likelihood increases that infrastructure failures will cascade and escalate in complex ways.

Additional research is needed in applying uncertainty techniques to better understand the infrastructure component restoration processes and linkages with other infrastructures. Analyzing and quantifying the various dimensions of the linkages among infrastructures is at the core of evaluating interdependencies and additional work on both the understanding and modeling of these dimensions is needed.

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