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AN OPERATIONAL MODEL OF INTERDEPENDENT WATER AND POWER DISTRIBUTION INFRASTRUCTURE SYSTEMS

by

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September 2018

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We model the interdependent operation of potable water distribution and electric power distribution infrastructure systems as a mixed simulation-optimization problem. Our goal is to capture the key attributes and essential interdependencies of these systems with enough fidelity to represent real infrastructure physics, measure how networks perform in various scenarios, and present new insights on infrastructure interdependencies. We develop a novel model that links together engineering models for water and power networks. We focus on systems at the scale of a military installation or a small island territory, and we study interdependent water-power system behavior across a series of emergency scenarios that interrupt normal operations.

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List of Acronyms and Abbreviations

AC-OPF Alternating Current Optimal Power Flow

AD Attacker-Defender

AD/DAD Attacker-Defender/Defender-Attacker-Defender

DAD Defender-Attacker-Defender

DC-OPF Direct Current Optimal Power Flow

DDF Demand Driven Flow

DHS U.S. Department of Homeland Security

DoD U.S. Department of Defense

DOE U.S. Department of Energy

EDN Electric Distribution Network

EPA U.S. Environmental Protection Agency

GUI graphical user interface

IWPN Island Water-Power Network

LANL Los Alamos National Laboratory

NPS Naval Postgraduate School

NTESS National Technology and Engineering Technology Solutions of Sandia National Labs

OPF Optimal Power Flow

PDD Pressure Driven Demand

RO Reverse Osmosis

SCADA Supervisory Control and Data Acquisition

TWPN Toy Water-Power Network

USN U.S. Navy

USVI U.S. Virgin Islands

WAPA Water and Power Authority

WDN Water Distribution Network

WNTR Water Network Tool for Resilience

Executive Summary

This thesis studies the interdependent operation of two lifeline infrastructure systems: electricity distribution and potable water distribution. These two systems are fundamental to the health and welfare of the population and during times of crisis, they need to be restored rapidly. They are also frequently dependent on one another, making system operation and restoration activities more complex. Water pumps and water filtration systems run on electric power, which impose varying demands on the electrical distribution system. Electric power generation typically requires water for system cooling (e.g., gas turbine generators) and for emergency operations (e.g., fire suppression) imposing varying demands on the water system. Distribution components may also be geographically co-located, which makes them susceptible to mutual failure events, such as flooding. These and other water-power interdependencies make it so water emergencies can also cause power emergencies, and vice versa. Thus, where interdependencies exist, the joint operation of water and electrical distribution systems must be considered when planning for future emergencies

The goal of this work is to represent the key attributes and essential interdependencies of a Water Distribution Network (WDN) and Electric Distribution Network (EDN) with enough fidelity to represent real infrastructure physics, measure how networks perform in various scenarios, and present new insights on infrastructure interdependencies. We achieve these goals by developing an interdependent model that links engineering models for water and power networks together and by studying a representative interdependent water-power system across a series of emergency scenarios that interrupt normal operations.

More specifically, we integrate hydraulic and topological perspectives on WDNs and execute our WDN models in extended period simulations based on pressure-driven demand to investigate emergency situations where customers lose water pressure and access. We link this water model to an EDN 3-phase alternating current (AC) power flow model designed to minimize the unsatisfied demand of electricity customers. By including switching and adherence to 3-phase AC physics, we capture realistic electric power flow across a network and operational decisions for how the network responds to disruptions. Water and power systems are linked by considering varying water demands on the power system and co-location of water and power assets. The resulting water-power model is one-of-a-kind in the

literature and advances a new perspective on operator decisions for both water and power network operators during emergency events.

We analyze several emergency scenarios to exemplify a range of common concerns for water and power system operators. Two simple networks are constructed to test water-power emergency scenarios: one “simple” another one “realistic” (i.e., at the scale of a military installation or a small island territory). Results for each water-power system reveal a number of important insights for interdependent infrastructure systems modeling and analysis.

First, *the proper treatment of time for water and electric distribution networks is important for ensuring realistic interdependent emergency results.* Water and power operators work on different physical time scales: water flow operates on timescales larger than electricity flow. Time-based modeling assumptions must be made to run a coherent and observable interdependent system. The different operating characteristics for individual systems need to be understood with respect to time and system state, such as matching power consumption (in watts) to water consumption (in liters).

Second, *impacts across interdependent systems exist even when dependencies between individual systems are not strictly bi-directional.* Our water-power models only have physical dependencies from power to water (i.e., water requires electricity to operate pumps) and geographic dependencies from water to power (i.e., water could flood power infrastructure or put out fires). Several emergency excursions show events that create system imbalances across these simple dependencies that may have far-reaching consequences on each system. For example, the loss of power at a critical pump in the water system requires re-dispatch of all other pumps, shifting power demand. This new operational state can cause further electric power imbalances that are difficult to predict from the perspective of a power utility.

Third, *different classes of interdependencies can lead to similar operational outcomes.* Though a pipe break is different than a pump outage, depending on the location of the break, the loss of supplied demands remains the same. This is easily understood for a simple network, but it is not so obvious when the model is extended to larger, more realistic networks. This implies that the impacts of water-power coupling are difficult to discern from studying each system independently. It also implies that the number (more or less) of interdependencies across systems might not dictate the types of emergencies and cascades witnessed.

Finally, *working within the Python computational environment provides an effective way to link models of infrastructure operations.* Due to the structure and simplicity of data input, data modification, and model objects as Python libraries, the water-electric distribution network model developed herein easily scales from smaller, simpler systems to larger, more realistic systems.

Overall, this thesis provides models and analysis with realism and simplicity, making it an ideal foundation for future analysis on even more complex water-power systems.

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CHAPTER 1:
Introduction

The U.S. government defines *critical infrastructure* as "systems and assets, whether physical or virtual, so vital to the United States that the incapacity or destruction of such systems and assets would have a debilitating impact on security, national economic security, national public health or safety, or any combination of those matters." These infrastructures include, but are not limited to, electric power, water, waste water, transportation, and telecommunications. As society grows more complex, so does its dependence on its critical infrastructures. The U.S. Department of Homeland Security (DHS) currently characterizes critical infrastructure as belonging to 16 sectors (U.S. Department of Homeland Security 2018). Because these systems maintain the health and well-being of the populace, it is becoming increasingly important to understand the relationship between societal needs and the design and operation of critical infrastructure.

Like society, critical infrastructure systems are also becoming more complex which may be increasing their brittleness to failure. Two primary drivers influencing the complexity of critical infrastructure systems are their growth in *scale* (i.e., they are getting bigger and are made of more components), and their increasing *interdependence* (i.e., multiple critical infrastructure systems are becoming reliant on each other). Most of the infrastructures in the United States evolved as small, stand-alone systems, but they are now increasingly regional in size and connected together. This is due in part to the rise of the Internet over the last 30 years as a common central nervous system for infrastructure operations and management. But it is also because of the dramatic successes in reliability of infrastructure systems like electric power and telecommunications—these systems rarely fail, making it efficient and convenient to design and deploy other systems and services like water and food that presume their availability. Together, this means critical infrastructure systems are not just "lifelines" for more and more people, but also for more and more infrastructure systems.

The dependencies both within and between individual infrastructure sectors are now so pervasive and difficult to identify that we often discover them only when things fail. In the wake of a service disruption, either deliberate or non-deliberate, it is not uncommon to hear something along the lines of, "We never realized that system X depended on component

Y." Indeed, identifying and understanding the dependencies between critical infrastructure systems is a major challenge for engineers and analysts alike.

This thesis seeks insight about the interdependent operation of two lifeline systems: electricity distribution and potable water distribution. These two systems are fundamental to the health and welfare of the population, and during times of crisis they are the two systems that need to be restored most rapidly. They are also frequently dependent on one another. Water pumps often run on electric power which can impose varying demands on the power distribution system. Electric power generation typically requires water for system cooling and lubrication (e.g., gas turbine generators). Distribution components may be geographically co-located which makes them susceptible to mutual failure events, such as flooding. These and other water-power interdependencies make it so water emergencies can also cause power emergencies, and vice versa. Thus, where interdependencies exist, the joint operation of water and electrical distribution systems must be considered when planning for future emergencies

This thesis presents a model of interdependent water and power operation, with sufficient detail and fidelity to assess interdependent infrastructure performance under a variety of emergency scenarios. In particular, we want to identify vulnerabilities in each individual system and also gain an understanding of how their interdependence can lead to unexpected outcomes. We focus on systems at the scale of a military installation or a small island territory. Our ultimate goal is to assess and improve the operational resilience of these interdependent infrastructure systems.

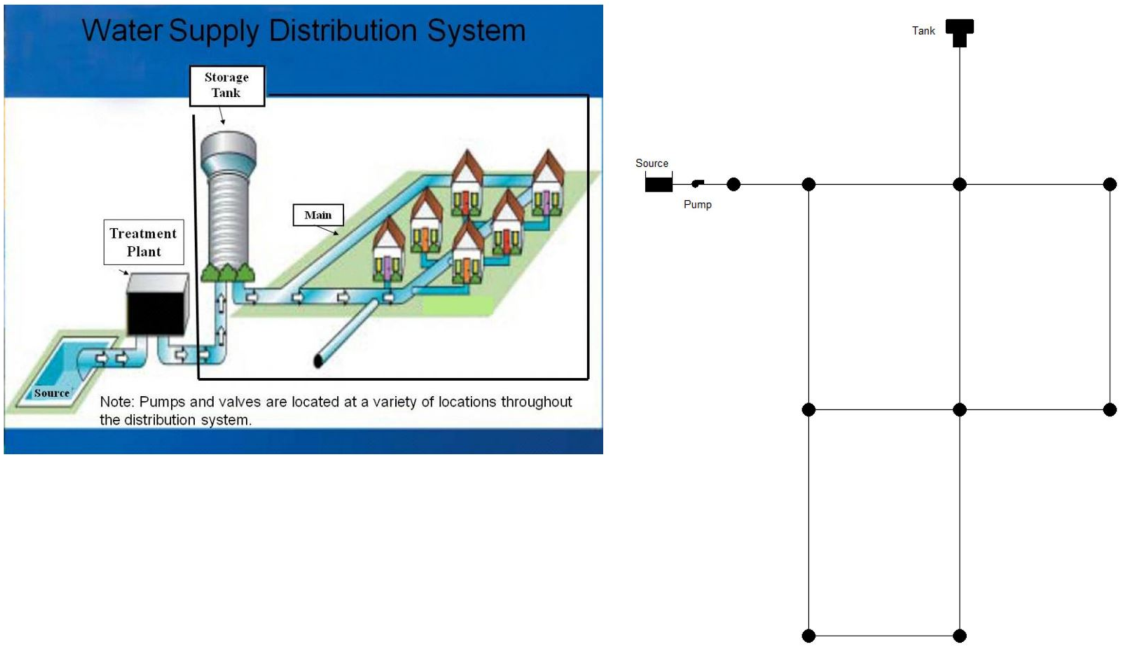
CHAPTER 2:
Background

We begin with a review of key features and past work in the study of water infrastructure and electric power systems. We then review work on interdependent infrastructure systems, particularly models of interdependent water and power. We also review mathematical and computational techniques for analyzing infrastructure systems, including Attacker-Defender (AD) and Defender-Attacker-Defender (DAD) models. We specify our technical contribution to interdependent infrastructure modeling and analysis in this context.

2.1 Water Distribution Network Models

The design and management of water systems encompasses a broad range of models and analysis techniques from source to sink, including models for weather patterns, watersheds, large-scale resource management (e.g., dam systems), treatment, provision, flood management, wastewater sewers, and discharge. For the purposes of this thesis, we focus on only one part of the larger water system, specifically utility-owned water distribution systems that deliver potable water to customers (e.g., drinking water to households). These systems generally receive water from large-scale resource management systems and discharge water into end-of-pipe wastewater treatment and sewer systems.

Figure 2.1(a) presents a general diagram for the structure of a water distribution system. Water distribution systems obtain water from a source that is either natural fresh water (e.g., from a lake reservoir) or "produced" (e.g., desalinated from ocean salt water). Source water is then pumped to water treatment facilities where the water is made fit for human consumption and industrial use. Treated water is often pumped to a storage unit like a large water tank. These storage units are usually held at a higher elevation and feed water via gravity to the rest of the water distribution system. As water is distributed through larger diameter pipes, additional pump stations are required to maintain pressure to deliver water to later distribution stages, and in some cases booster pumps are used to send water for end use at higher elevations. Throughout the network, pipe diameters vary in order to accommodate proper pressure at different distribution stages. Maintaining proper pressure for end usage is the primary operator consideration. The operation of pumps and valves, and the maintenance of adequate water storage levels support this objective.



(a) (b)

(a): General components of a water distribution system and its connectivity, including water source, treatment, storage, piping, and household delivery. Pumps and valves are not shown (Source: U.S. Environmental Protection Agency (2018)). (b): Representation of a generic water distribution system as a water distribution network using the EPANET format. Nodes represent pipeline junctions where customers access water and links represent system connectivity via pipes. Water source, pumps, and storage are also represented as additional system features.

Figure 2.1. Water Distribution

We refer to the connected physical infrastructures that comprise a water distribution system and enable water provision as a *Water Distribution Network (WDN)* (Figure 2.1(b)). WDNs are typically described by their topological structure (e.g., branch, loop, or grid networks) and are comprised of pipes (material used, lengths, and diameter), tanks (locations and elevations), pumps (types, locations, and power), and sources (fresh water or processed); see Boulos et al. (2006). Pipes, pumps, valves and tanks are generally described as *links*. Pipes are joined at junction *nodes*. Extraction and supply of demands occur only at junction nodes. Most models focus on the ability to satisfy demands under conditions of interest.

These are pressure dependent demand conditions where the withdrawal rate at a pipe or node is related to pressure. Figure 2.1(b) shows a common representation of WDNs for the purposes of our study. For more information on the engineering implications for a WDN, refer to Boulos et al. (2006).

With knowledge of WDN components, connectivity, and consumer use, it is possible to calculate water distribution hydraulics (i.e., water flow physics) and quality with empirical methods to evaluate how well a WDN meets planned demand. Two common optimization models for studying WDN hydraulics are Demand Driven Flow (DDF) and Pressure Driven Demand (PDD) models. As this thesis focuses on ensuring water flow and access, we do not study additional WDN models for water quality. For more information on modeling water quality, please see Boulos et al. (2006).

In DDF models, node demands are assumed to be known and satisfied, which is a reasonable assumption during normal operating conditions. Pressure in the system is assumed to be dependent on node demands such that demand dictates flow over the WDN even if the predicted flow requires system operation to exceed safety thresholds (e.g., maximum pressure in pipes). This is the most common modeling approach for measuring flow in a WDN, and is the underlying model used of the well-established WDN analysis software EPANET (U.S. Environmental Protection Agency 2000). However, DDF models are unable to measure WDN hydraulics when demands change in uncommon operating conditions like system disruptions (e.g., pipe breaks) or during emergency operations to protect overloaded assets. In these situations, PDD models are more appropriate because they are based on the assumption that delivered water demands depend on network pressures and flow rates (i.e., demands are calculated based on model assigned flow rates and pressures). PDD models more accurately capture WDN operator behavior to balance customer and system needs, and allow for flow situations where demand is not met to maintain infrastructure safety thresholds. These conditions include rapid demand increases (such as fire hydrant use) and pipe breaks (too much pressure in a pipe segment).

In addition to using optimization models to predict water physics, optimization models are also used to determine effective ways to operate a WDN with respect to energy and other input costs to run real-world systems. Singh and Kekatos (2018) use mathematical programming to find the optimal water flow with respect to the operation of fixed-speed pumps, tanks, and pipes in consideration of fluctuating energy costs. A minimum cost objective is applied to the problem while considering control decisions for regulation of service pressure. The modeling done to obtain a solvable solution space shows how complex programming water models can be, necessitating the use of convex relaxations to account for non-linear pressure drops. These techniques are important to consider when understanding the scheduling of pressure control mechanisms in a water system. Though the optimization proposed in the study shows application of advanced mathematical programming techniques, its greatest contribution is the consideration of optimal pump scheduling and how it changes with respect to dynamic pressure as demands fluctuate. Pressure fluctuations are very important characteristics to consider when studying the physics of a WDN and necessary for our study. Similar work is done for reference in Fooladivanda and Taylor (2017) where variable speed pumps and the energy losses associated with friction head loss are included in pump scheduling.

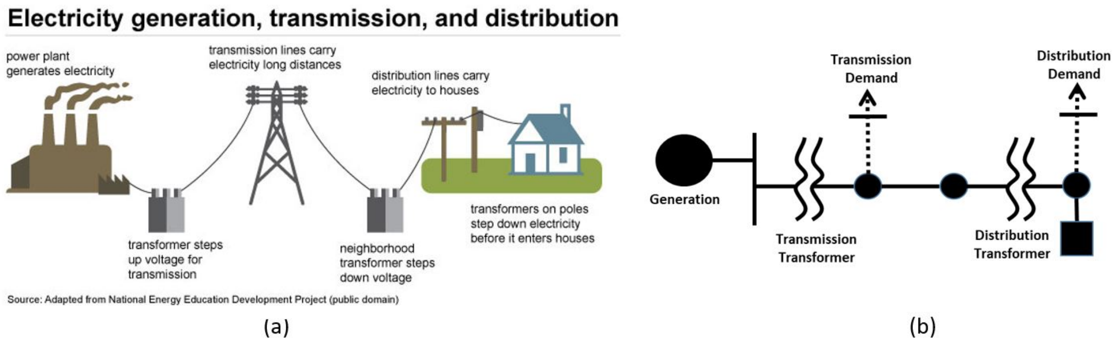
Network topological measures are also useful for characterizing how well a WDN may serve consumer needs when subject to infrastructure failures (e.g., leaks, subsidence, pipe breaks, pump failure, and contamination) in addition to WDN hydraulics. Understanding the topological structure helps pinpoint choke points and specific critical links in a system that provide insight into potential vulnerabilities. Such choke points may not be obvious in an interconnected WDN such as in a looped or grid layout. However, studying strictly the topology does not consider the hydraulic implications of a system, as pressure fluctuations not obvious from WDN topology can cause cascading failures. Studying how cascading failures propagate is a key consideration for the robustness of a WDN.

Recent studies demonstrate the validity of integrating hydraulic and topological perspectives to understand WDN robustness to continue providing service when faced with unexpected failures. Shuang et al. (2014b) assess the performance and reliability of a WDN from a network theory perspective by assigning water sources, tanks, pumps, valves, and junctions as nodes in a topological directed graph connected by edges that represent the pipes. They use topological methods to assess the mechanical reliability of the system, then apply topological results to an extended period simulation to assess hydraulic reliability. The study ultimately shows how propagation characteristics of cascading failures can be assessed using methods that help identify critical pipes in a network via a combination of hydraulic and topological analyses that are often not considered together. Similar work was performed in Shuang et al. (2014a) with a focus on extending the study to strictly node-related failures in a network. The study focuses on using a PDD simulation to assess how node-related failures propagate and cascade through a system by describing methods for node connectivity losses. The authors argue that PDD simulation represents real world systems in a more realistic fashion and helps to consider decisions from an operator's perspective. Shuang et al. (2014a) is also notable for being applicable when considering damage to nodal structures in the network due to natural disasters or intentional attack.

2.2 Electric Power Network Models

Similar to water systems, electric power systems are also comprised of large-scale, interconnected sub-systems designed to serve customer needs. In general, electric power delivery is comprised of three stages: generation, transmission, and distribution (see Figure 2.2). Electric power is generated at a low voltage with a wide variety of infrastructures such as hydro-electric dams or gas powered turbines. Generated power is then stepped up to a higher voltage via power transformers and delivered long distances via high-voltage transmission lines. High-voltage power is then stepped down with transformers to lower voltage distribution lines that are used at the local level to deliver electricity to customers. Throughout this system, substations act as central locations where generation, transmission, and distribution systems meet and electricity is transferred between infrastructures.

In general, electric power transmission and distribution systems are comprised of similar components rated for different voltage levels, yet their behavior is represented using different Optimal Power Flow (OPF) models for evaluating how electricity meets demand. Analysis of transmission systems requires single phase (1-phase) Alternating Current Optimal Power Flow (AC-OPF) or Direct Current Optimal Power Flow (DC-OPF) models to evaluate power flow physics. Single phase models are used in transmission systems because high-voltage power lines are often transposed, i.e. each phase occupies the same physical position in space for one-third the line, and carry balanced loads across each line. Single phase AC-OPF models can be simplified further to DC-OPF models by assuming that line resistance is negligible relative to reactance, line voltages are constant between substations, and voltage phase angles are small. Numerous studies show that these simplified models perform well for analyzing power flow and robustness of transmission grids, such as in Salmerón et al. (2004, 2009, 2011).



(a) Source: U.S. Energy Information Administration (2017). The figure shows how electricity is delivered from generation to consumers. (b) Displays a single line diagram of a simple generation, transmission, and distribution network which models electric power infrastructure for analysis.

Figure 2.2. Generation, Transmission, and Distribution

Still, these assumptions cannot be made in electric power distribution systems which must be studied with more complicated 3-phase AC-OPF optimization models. Distribution power lines (commonly referred to as feeders) occupy more complicated physical geometry and serve unbalanced loads, making it unrealistic to assume transposed and balanced power flow. Instead, evaluating electricity distribution requires full, 3-phase AC-OPF models with higher fidelity data for analysis. For detailed explanation of 3-phase AC-OPF analysis of distribution systems, we recommend Kersting (2001a). For the purposes of this thesis, we refer to the connected physical infrastructures that comprise an electricity distribution system analyzed with 3-phase AC-OPF as an *Electric Distribution Network (EDN)*. EDNs are typically described by their topological structure such as radial or meshed, and are comprised of generators (power supplied), power lines (voltage, resistance, reactance, and length), transformers (voltage, windings, and power leakage), customers (power demand), voltage regulators (voltage, tap changers, bandwidth, and compensators) and shunt capacitors (power supplied), among other infrastructure. For further information on understanding electrical power systems and their electrical engineering considerations, we recommend Sadhu and Das (2015).

2.3 Interdependent Infrastructure Models

There is a growing literature in the modeling of interdependent infrastructure systems. Rinaldi et al. (2001) were among the first to discuss interdependent infrastructures from the system-of-systems perspective, to include physical, cyber, geographic, and logical categories.

- Physical dependencies are based on the physical flow of a commodity (e.g., power needed to run a pump).
- Cyber dependencies are based on transmitted data (e.g., remotely operated Supervisory Control and Data Acquisition (SCADA) systems).
- Geographic dependencies are based on geographic co-location (e.g., Reverse Osmosis (RO) plant co-located with power generation).
- Logical dependencies are based on market, policy or legal obligations (e.g., regulatory code enforced water pressure limits).

For a recent review of the variety of interdependent infrastructure models, see Ouyang and Dueñas-Osorio (2014).

Most relevant to the work in this thesis, Dixon (2011) expands on Rinaldi et al. (2001) by introducing network flow notation and terminology to model the interdependent relationship between infrastructure systems utilizing minimum-cost network flow models. Specifically, different types of interdependence are observed: *input*, *mutual*, *shared*, *exclusive-or*, and *co-located* types of interdependence. These interdependencies help represent the relationships between layered infrastructure systems by modeling the flow of a commodity between systems and by observing how sufficient flow of a commodity aids in the operation of another activity with their own respective commodity. Most importantly, Dixon (2011) solves a sequence of models to illustrate how dependence relationships between infrastructures create vulnerabilities that are not apparent when modeling infrastructure interdiction in isolation.

Dickenson (2014) builds on Dixon (2011) concepts with further consideration to how interdiction algorithms are executed in interdependent critical infrastructure systems. Creating and solving a monolithic system-of-systems interdiction model can be unrealistic because of the size of the infrastructures involved, or it may be too complex to implement. By iteratively executing one infrastructure model and then passing the solution to the next infrastructure model to solve, the complexity of the model can be reduced and would be more indicative of how systems owned by different operators share information between each other. Consideration must be given to the ability of the two models to converge to a solution and how penalties for excess commodities and/or unmet demand are applied which can lead to waste.

Ruether (2015) adapts the models of Dickenson (2014) to the Python programming environment (Python Software Foundation 2018) using the Pyomo optimization software package (Hart et al. 2011). The object-oriented nature of the Python-Pyomo environment creates novel opportunities for the modular development of stand-alone, but reusable infrastructure models that can be combined with the additional specification of appropriate links.

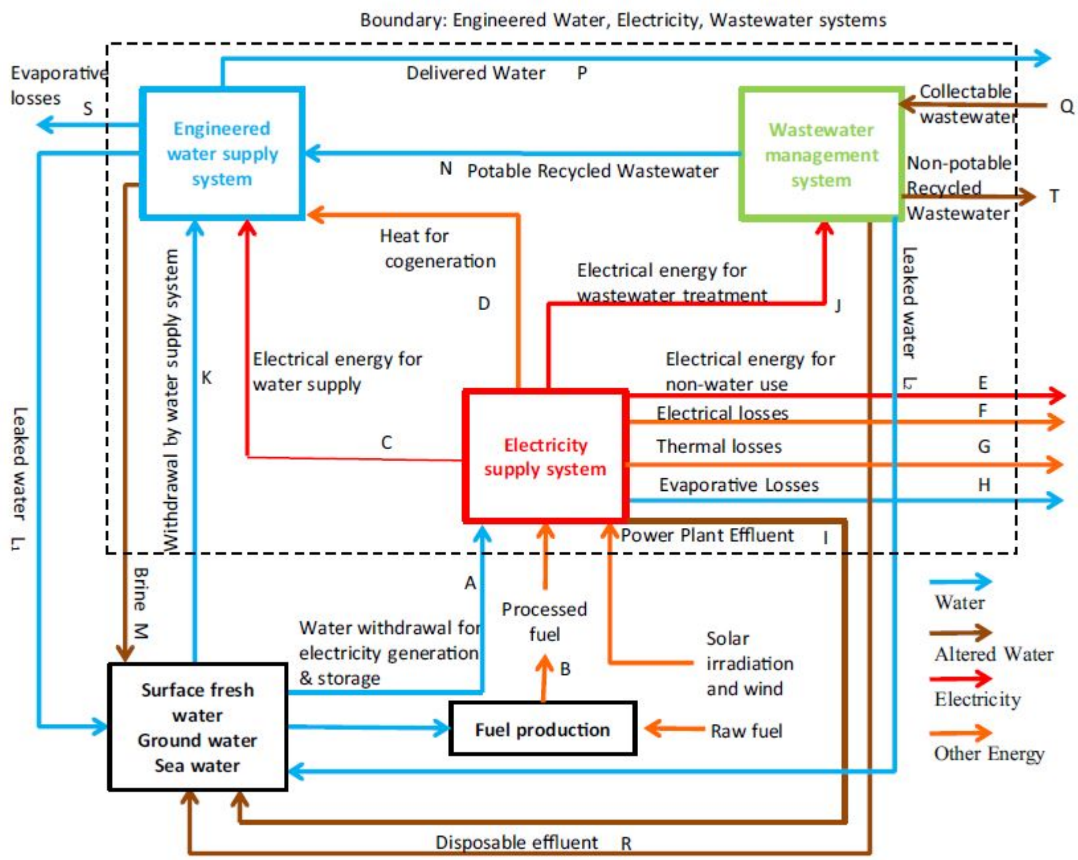
2.4 Interdependent Water-Power Models

There is limited technical literature specifying interdependencies across water-power systems, requiring interdependent model development for specific water and power sub-systems to rely on guidance from qualitative frameworks. Lubega and Farid (2016) presents a useful framework that delineates possible linkages between water and power systems that influence WDN and EDN modeling and analysis. The study introduces the concept of the Water-Energy Nexus by presenting a descriptive system-of-systems framework for energy, water, and wastewater systems. Furthermore, because the framework emphasizes different aspects of water and electric power systems, it provides a useful perspective to guiding interdependent model development.

Water and energy systems share interdependencies across the four interdependency types defined in Rinaldi et al. (2001). Physical interdependencies include how electricity is used by water treatment facilities, pumps, tanks, sensors, etc. The elevation and depth of surface and groundwater treatment plants determines the energy requirements and efficiencies for pumps. The salinity of drawn seawater determines the energy required for thermal desalination plants, specifically determining the thermal energy above the boiling point of pure water required for evaporation. For RO plants, the salinity determines the pressure required to drive water across the system membrane. Pumping is the primary power consumer for surface and groundwater treatment plants, thus they can be viewed as large pumping systems. Pipe friction loss (a function of diameter, length, and material) in pipes determines the required energy for pumps in the network to make water flow. Physical interdependencies also include how water is used by power systems. At generation facilities that produce electricity, water is both a working fluid (after converted to steam) and a cooling fluid (for coal, gas-fired, nuclear, and solar thermal power plants). Water is also used at multi-purpose and hydroelectric dams to generate electricity. Finally, some very high-voltage transformers use water for cooling.

In addition to physical interdependencies, water and electricity systems share geographic, cyber, and logical interdependencies. Both systems are geographically interdependent as pumping stations and water treatment plants are commonly sited near electric power substations and generation plants due to their high load requirements. They have cyber interdependencies such that large water mains that feed industrial power facilities may use sensors and controls that are also hooked into power grid SCADA systems. They are logically interdependent as many utilities own and operate both power and water systems. These utilities are subject to government regulations that influence water infrastructure requirements and efficiencies, which in turn affect power grid functions (and vice versa depending on cooling or other requirements for power systems).

The framework developed by Lubega and Farid (2014, 2016) presents known physical interdependencies via flows of matter and energy across water and power system boundaries (see Figure 2.3). The authors define a system boundary for water-energy dependencies to comprise three engineered systems – power, water, and waste-water. A modeling strategy is proposed where activities of the systems are each represented by an activity diagram. Independent and dependent power variables are then identified. Finally, a structured representation of all systems' activities is developed. This is considered for each aspect of a system with respect to the dependencies and interdependencies of the system represented by the matter and energy crossing the boundary. Detail is given to each activity and the physics of the respective systems with the goal to create a quantitative engineering system model. The model shows how a change in variables, like changes in demand, has subsequent and predictable changes in the water intensity of energy technologies and the energy intensity of water technologies. This allows for sensitivity analysis for any change to the interdependent system. Figures are used to express the interdependencies of the two systems and provide a reference point for our work to model water-power interdependencies and physics.



Source: Lubega and Farid (2014). System context diagram for combined electricity, water and waste water systems

Figure 2.3. Energy-Water Boundary

Beyond qualitative frameworks, there has been limited development of physics-based models to study water-power interactions, and none have focused on physics- and topology-based vulnerability of interdependent WDNs and EDNs. To the best of the our knowledge, only four papers currently develop optimization models for water-power systems, but all studies focus on optimal water-energy dispatch without consideration of system vulnerability. In Zamzam et al. (2018), an optimal water power flow problem utilizes DC-OPF to study how power transmission systems perform in multi-period optimization of energy costs for both water and energy networks. Santhosh et al. (2013) and Santhosh et al. (2014) develop an interdependent WDN DDF and power transmission DC-OPF model to study optimal dispatch decisions for system operators in water (pump dispatch), power (generator dispatch), and co-production systems. Oikonomou and Parvania (2018) consider multiple water system operators who share information with a singular power system operator. They use day-ahead demand forecasts for water system operators' decisions on pump usage and find energy efficiency with the use of water storage tanks with DDF. Potential efficiencies are shared with the power system operator who finds the optimal decision set to minimize energy costs.

Despite these advances in the literature, no framework or model takes into account how water and power operators will experience and respond to interdependent WDN-EDN failures. Specifically, no interdependent water-power study that includes WDNs use PDD for its fundamental operator model. This means existing interdependent infrastructure models are inappropriate for studying how water systems respond to surprising situations because it is unrealistic to assume that WDN operators will meet all demand during an emergency (which is fundamental to DDF). Likewise, no interdependent water-power study considers power flow in EDNs with 3-phase AC-OPF, despite power distribution systems being the actual infrastructures that connect electricity to WDNs - not transmission systems. Because EDNs have more complicated flow properties and distinct design considerations from power transmission systems, it is inappropriate to assume that a water-energy model using 1-phase AC-OPF or DC-OPF will be able to assess electric power delivery to a WDN. This is particularly true for smaller power systems (e.g., on islands) that lack extra-high-voltage power transmission infrastructure, and rely entirely on unbalanced 3-phase power lines.

2.5 Attacker-Defender Models

Another technique for analysis of critical infrastructure uses large-scale optimization and game theory to identify worst-case disruptions to infrastructure operation. The starting point is the development of an *operator model* that reflects the decisions made by an infrastructure owner or operator who chooses the activities that yield the best performance for the system. Generally speaking, one uses a network flows perspective with nodes and edges representing junctions and components. The activities on the edges are the flows of commodity and the capacities of the edges are operational constraints on each edge section. Balance-of-flow constraints define the individual node capacities. System performance is then measured by the total flow of commodity from the source node to the termination node (sometimes a collection of nodes). These formulations vary per the system being analyzed with the objective function representing maximum flow or minimum cost of operating the system. See Alderson et al. (2014) for a general introduction.

An attacker-defender (AD) model wraps an adversarial decision maker around the operator model to find the worst-case disruption to system performance. In the case where the operator solves a minimum cost network flow problem, the attacker chooses activities (e.g., arcs to attack) that result in the maximum minimum cost achievable by the operator. A defender-attacker-defender (DAD) model wraps yet another decision maker around the AD model; the defender seeks the best set of budget-constrained investments (e.g., hardening of components) to mitigate the worst-case attack.

These AD and DAD models have been used extensively to model power disruptions and address hardening decisions. Salmerón et al. (2004, 2009, 2011) specifically use this framework to find critical vulnerabilities in a power network with consideration for varying degrees of complexity.

2.6 Our Contribution in Context

This thesis considers interdependent water and electrical distribution systems, with emphasis on WDN and EDN models. We wish to integrate hydraulic and topological perspectives to our WDN in order to understand the robustness of the system, much like Shuang et al. (2014a,b). Similarly, we execute our WDN models in extended period simulations with respect to PDD analysis. We consider the objectives of prior optimization models (Fooladivanda and Taylor 2017; Singh and Kekatos 2018) to handle the scheduling of pumps and their costs, but we do not use least-cost dispatch models for our WDN.

We study an EDN as a 3-phase AC-OPF model designed to minimize the loss of customer demand, as developed in Petri (2017). By integrating switching and adherence to a full 3-phase AC model, we capture a realistic power flow across an EDN and operational decisions during system disruptions.

We link water and power systems by considering varying water demands on the power system and co-location of water and power assets. The resulting water-power model is one-of-a-kind in the literature and advances a new perspective on operator decisions for both water and power network operators during emergency events.

CHAPTER 3:
Models for Water and Electric Distribution Networks

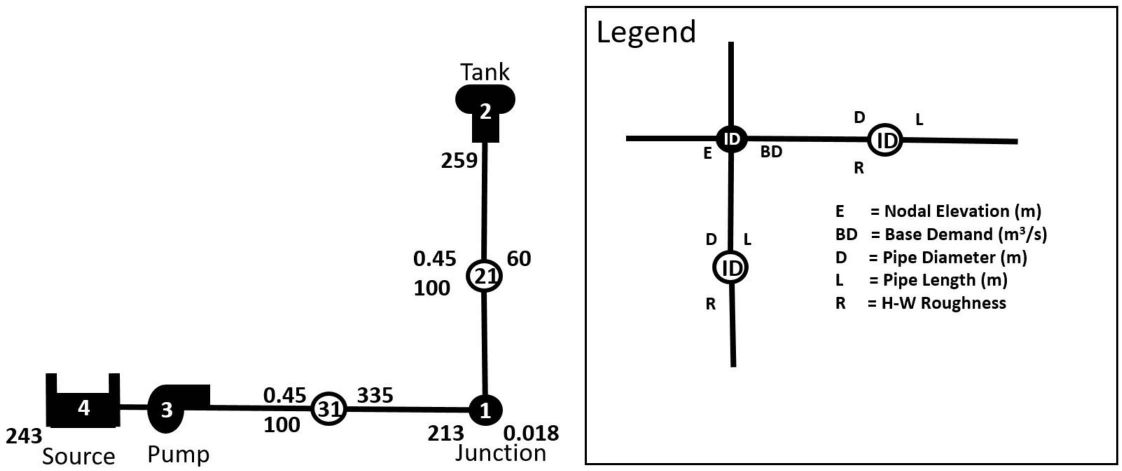
The goal of this work is to represent the key attributes and essential interdependencies of a WDN and EDN with enough fidelity to represent real infrastructure physics, measure how networks perform in various scenarios, and present new insights on infrastructure interdependencies. We achieve these goals by developing an interdependent model that links engineering models for water and power networks together and by studying a representative interdependent water-power system across a series of emergency scenarios (referred to excursions hereafter) that interrupt normal operations.

Due to the complexity of interdependent infrastructure models and analysis, we build up to the analysis of realistic water-electric distribution networks by first studying water and power networks separately. In this section, we implement our models using the Python programming environment (Python Software Foundation 2018). We demonstrate how to leverage its capabilities and various packages to study water and power models and analyze their outputs during emergencies. We define a series of water and power failure excursions and demonstrate how they result in losses within individual networks with a simplified WDN and EDN.

3.1 A Simple Water Distribution Network

Our starting point for the study of WDNs is a specific model called EPANET that is commonly available to system operators (U.S. Environmental Protection Agency 2000). A computer program developed and distributed for free by the U.S. Environmental Protection Agency (EPA), EPANET helps water utility operators and owners meet regulatory requirements and customer expectations. The program has a graphical user interface (GUI) that allows WDN models to be created from scratch and saved for future analysis. For any given duration or time step, EPANET can simulate and evaluate water hydraulics and quality.

Figure 3.1 depicts a simple WDN in EPANET. Beginning with a source (4), water is pumped through a pipe (31) to a demand junction (1). The pump operates according to a performance curve that adjusts flow based on the head (pressure and gravity) drop across the pump inlet and outlet. The pressure drop forces water to flow through a pipe link (21) to a large tank (2) at an assumed 259 meter elevation. Tables 3.1 and 3.2 display relevant tank and pump characteristics used in EPANET.



Simple toy network. A single demand junction (1) is supplied by a single tank (2) and a water source (4) with a pump (3). The demand junction can be fed by either the Tank or Pump.

Figure 3.1. Toy Water Model

We use the Water Network Tool for Resilience (WNTR)—a Python-based library based on EPANET (Klise et al. 2017)—to model water hydraulics for the Toy Water Model. WNTR was developed by the National Technology and Engineering Technology Solutions of Sandia National Labs (NTESS) to provide a flexible platform for modeling water distribution systems. It provides a platform for modeling a wide range of disruptive events and repair activities. PDD hydraulic simulation is included to model the system during low pressure conditions using WNTR's native simulation package. WNTR uses an extended period simulation that is primarily deterministic but can incorporate stochastic elements such as the failure probability of a tank or pipe section. WNTR simulates WDNs using either the EPANET simulator (both hydraulic and water quality simulations) or WNTR's native simulator (only hydraulic simulation) that uses the same methods as EPANET but also utilizes other Python packages.

Table 3.1. Toy Water Model Pump Data

			Point Paramter	
Pump	Type	Curve	Head (m)	Flow (m^3/s)
3	Head	Single-Point	76	0.094

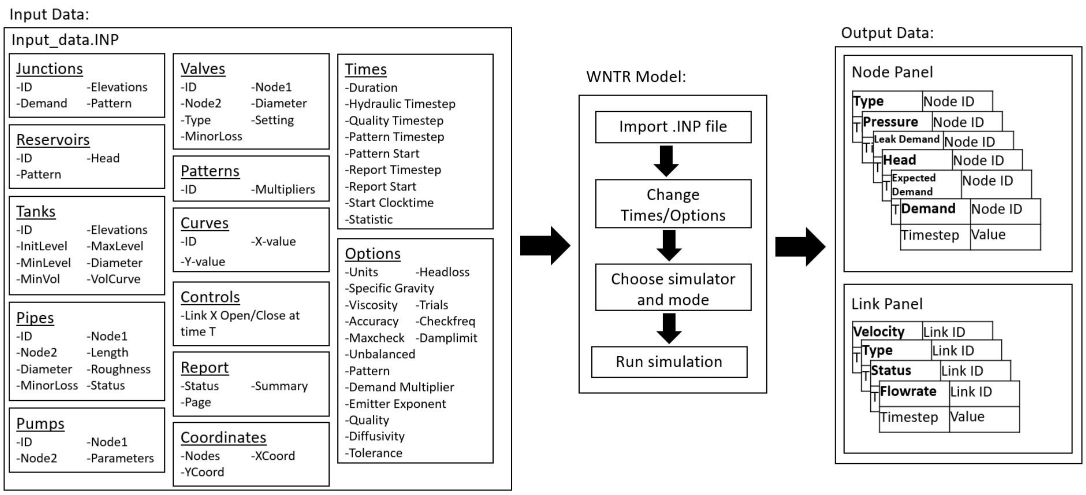
Table 3.2. Toy Water Model Tank Data

Tank	Diameter (m)	Maximum Level (m)	Minimum Level (m)	Initial Level (m)
2	15.39	30.48	45.72	36.57

EPANET network data can be exported to an input file for WNTR hydraulic analysis. Input files include all relevant WDN data for hydraulic analysis, and these are categorized by Networks, Controls, Rules, and Conditions. Network data is essential for analysis and can be built and tested directly within EPANET. Network data specify nodes (water sources, tanks, and junctions) and links (pipe sections and pumps) including their relevant attributes, such as the maximum capacity of storage tanks or the internal diameter of a pipes. Network data also specify water demands at junctions and their varying patterns during a set time duration (e.g., over a 24-hour period). Control data are if/then conditional statements about nodes and links in the network that dictate possible operational states (e.g., close/open operations of a valve). Rules are if/then/else conditional statements about nodes and links that can dictate operational decisions and prioritize them (e.g., how system operators may set a pressure regulation valve for different system states). Finally, condition data are conditional statements for the hydraulic simulation itself, such as changing a pipe link status (open or closed) at a certain period of the simulation (e.g., for maintenance).

WNTR can parse input files for hydraluic simulations. Once imported, network, control, rule, and condition data can be changed before the simulation is run. Once the simulation type is chosen and run, the output creates a node and link dictionary, each holding a Pandas data frame (McKinney 2011) for each attribute of the WDN. Within the data frames, the attribute records for each node or link at each simulation time step are accessible. Figure 3.2

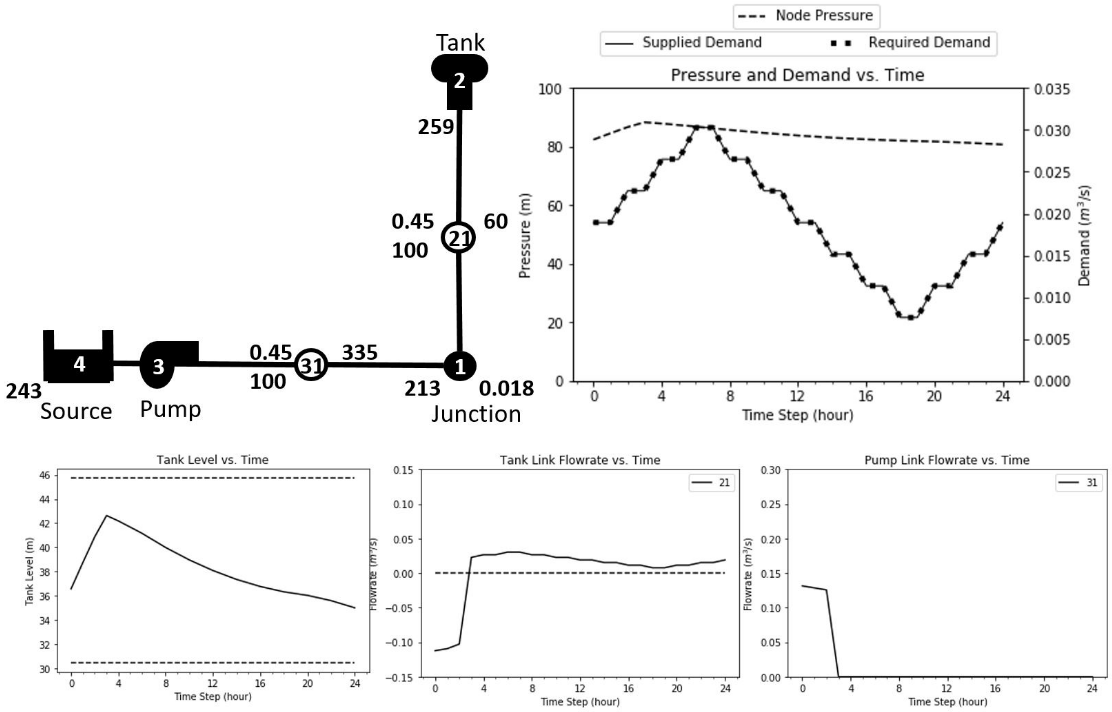
provides a visual representation for how input data is organized and processed in WNTR.



WNTR imports input data in a standard, EPANET format that includes supply, demand, and network attributes for the WDN. WNTR executes a time-step simulation and produces two output files containing information about the behavior in the nodes and links of the network.

Figure 3.2. WNTR Execution

For our Toy Water Model, we run a 24-hour PDD base case simulation with one-second time steps (Figure 3.3). When assessing the operational state of a WDN, we visualize how pressure and demand changes over the 24-hour period while also tracking if required demand is being met. We are also concerned how the water inventory in the tank (i.e., the tank level) changes over time relative to its maximum and minimum levels. In practice, rules for pump operation are often dictated by tank levels. Finally, we observe how critical links are opened or closed as the WDN dynamics change. Figure 3.3 displays this information for the Toy Water Model under normal operating conditions. The pump operates until the tank reaches 95% of its maximum level. The pump link is then closed, turning off the pump to save energy and cost, and making the WDN reliant on the tank to meet demand. The pressure in the system starts to fall as the tank head decreases but never reaches its minimum level, fully supplying the WDN demand for the duration of the simulation.

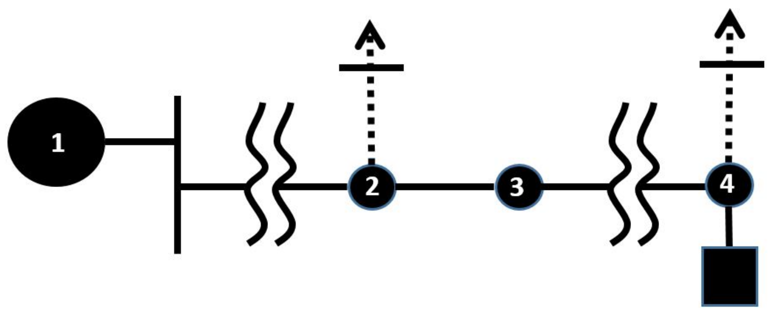


Simple toy network under normal (base case) conditions for a 24-hour period. Pump operation is dictated by water level in the storage tank. The pump operates until the tank fills to 95% of its capacity. When the tank has sufficient volume, the pump shuts off to save energy and the tank feeds the demand junction via gravity for the remainder of the day. This operation serves all water demand within the network in the most efficient, least-cost manner.

Figure 3.3. Toy Network Base Case

3.2 A Simple Electric Distribution Network

We study EDNs for electric power utilities with respect to 3-phase AC-OPF. Recent work by Petri (2017) develops an AC-OPF model that minimizes the cost associated with all real and reactive load shedding due to the loss of generation capacity at a given bus while maintaining balance of electricity flow. Consideration is given to the tolerances of flow for each of the three phases, thermal limits for power lines, flow losses across all possible phases, nominal voltages at each bus, and the opening and closing of switches to test different network configurations and possible least-cost operational states. Only active buses are considered for generation and load shedding. Flow is ensured to go in at most one direction with respect to switch settings and voltages (i.e., in the direction from high to low voltage). Finally, a cycle breaking constraint is implemented for each incumbent solution of the model. By integrating switching and adherence to a full 3-phase AC-OPF model, we capture a realistic measure for how power is managed across an EDN and how the EDN responds to any disruption.



Source: Petri (2017). The "Basic Test Circuit" consists of a substation at bus 1 with functionally infinite generation capacity, a step-down transformer linking the substation to the distribution circuit at bus 2, a power line connecting bus 2 to a service transformer at bus 3, and a local bus serving a community with a shunt capacitor bank for reactive power support at bus 4. Electric power load is drawn at bus 2 for large commercial entities (e.g., manufacturing facilities) and at bus 4 for the local community. No load is shed in the network during normal operating conditions.

Figure 3.4. Basic Test Circuit. Source: Petri (2017).

Table 3.3. Basic Test Circuit Bus Data

Bus	Type	Power Generation (kW)	Base Demand (kW)	Nominal Voltage (kV)
1	Substation	∞	0	69
2	Connection	0	0	7.62
3	Connection	0	0	7.62
4	Load, Shunt Capacitor	0	57.55(a) 55.48(b) 60.65(c)	0.277

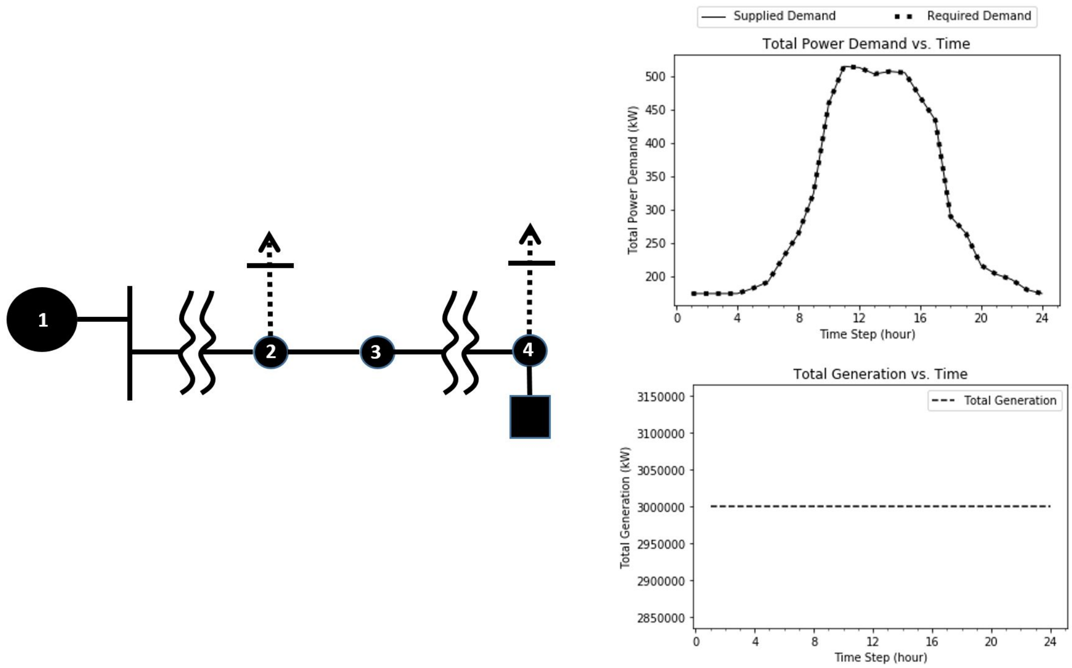
Table 3.4. Basic Test Circuit Edge Data

Edge	Type	Phases	Thermal Limit (Amps)	Impedance (Ohms)
(1,2)	Transformer	a, b, c	120.773	0.0217
(2,3)	Line	a, b, c	498.75	0.1334(a) 0.1354(b) 0.1343(c)
(3,4)	Line	a, b, c	32.808	0.0009

The AC-OPF model is implemented in Pyomo (Hart et al. 2011), a Python based optimization modeling language that is open-source and has the capability of using multiple solver packages. We build a model of "Basic Test Circuit" from Petri (2017) with no switches or cycles (depicted in Figure 3.4) in Pyomo for model testing and power flow analysis. For simplicity, only real power is used in the Basic Test Circuit. Tables 3.3 and 3.4 provide the characteristics of the system. The model is solved using the IBM (2018) solver package.

Petri (2017) demonstrates an instantaneous computation of zero load shedding for the Basic Test Circuit. Flows from the substation to the load for all phases match the required demand. All demand is satisfied, confirming proper model operation.

However, we wish to observe how the system operates for a 24-hour time period. Unlike Petri (2017), we run the AC-OPF model with new demand inputs for each time-step. For the Basic Test Circuit, we develop input files to describe changing power demands over a 24-hour demand period (hourly data based on realistic electricity demands). We solve the AC-OPF model for each hour and associated input file. Figure 3.5 presents results for the Basic Test Circuit Model iterated over the 24-hour demand period. We combine all phases when plotting the results, and we only show aggregate demand and network-level trends.



Basic Test Circuit under normal (base case) conditions for a 24-hour period. The demand curve of required demand is based on real data for a small distribution system. The model iterates every hour and solves to make sure new demands are met with power flow. Generation is functionally infinite and all demand is delivered with no load shed.

Figure 3.5. Basic Test Circuit Base Case

Based on our observations, the AC-OPF model iterates successfully for the Basic Test Circuit. There are no reactive loads and no load shedding for each of the 24-hour iterations. The trends hard coded into each data input file are successfully processed and match the expcted required demand pattern. Our functionally infinite power generation is also successfully measured and displayed.

3.3 Modeling Water and Power Emergencies

In addition to normal operations, we wish to understand how individual models for water and power systems perform under various emergency excursion scenarios. We define emergency excursions that are common for both systems and compare their results to normal operating conditions. This section builds the underlying base line on how viewing emergency results and extend the models to larger networks.

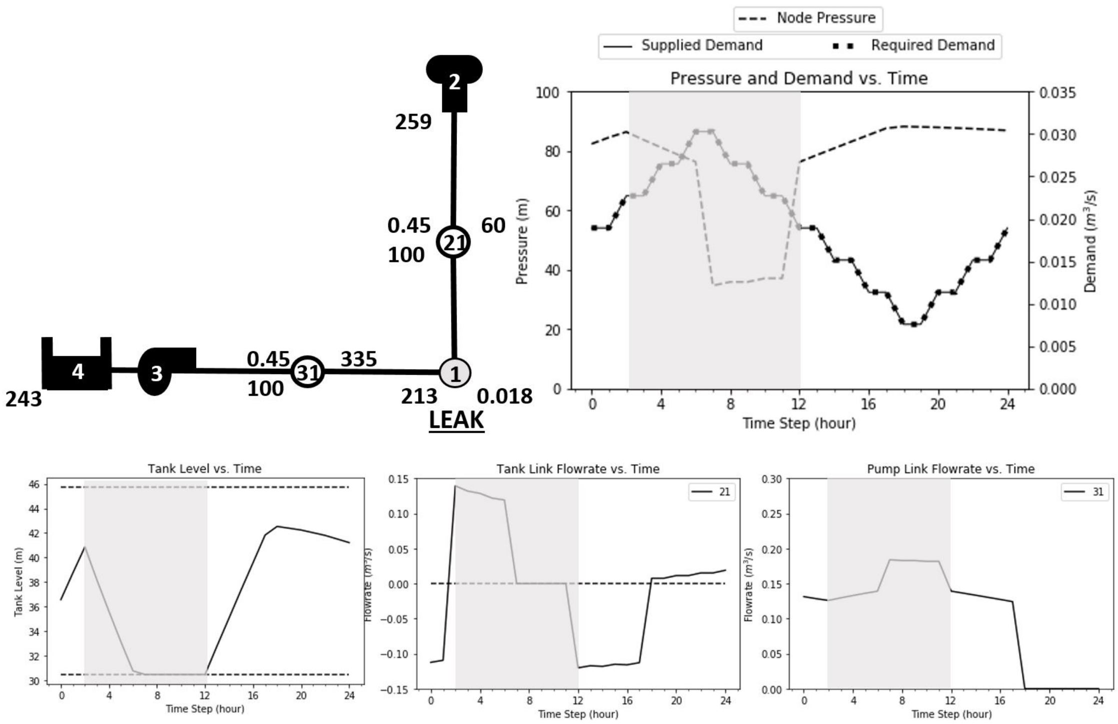
3.3.1 Water Distribution Emergencies

A broad range of emergencies impact water distribution systems including catastrophic infrastructure failures (e.g., pipe breaks), significant changes in water demand (e.g., fire flow demands), or unanticipated water quality issues (e.g., boil water warnings). In this thesis, we focus on how emergencies impact water flow from source to customer and ignore water quality related issues, because the water-power interactions developed in the next chapter rely more on water availability than treatment quality. Specifically, we consider three emergency excursions that impact water service delivery and electric power service availability: (1) leaks, (2) pipe breaks, (3) demand spikes (e.g., fire flow demand), and (4) power outages.

Note: we demonstrate all excursions using the Toy Water Model developed above. Refer to Figure 3.3 for the base case scenario.

Water Leaks

Figure 3.6 presents a large leak at demand junction 1 that starts at hour 2 and continues to leak for 10 hours. The tank never reaches 95% capacity so the pump continues to operate. The large leak exhausts the tank water stored in the first two hours and reaches its minimum capacity. At that point, the tank link closes, making the demands reliant on pumped water. After the leak is repaired, the tank link is opened. Water continues to pump to the tank to reach 95% capacity, and then the pump link is closed. The pump is able to handle the required demand at the demand junction for the duration of the leak.

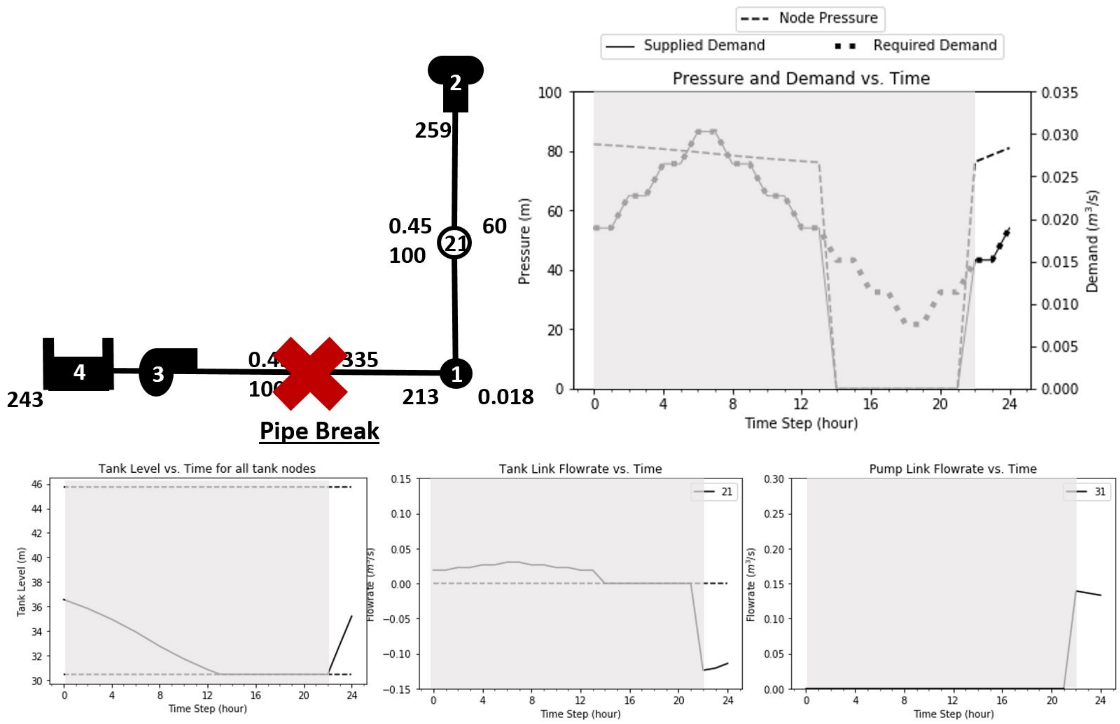


A large leak occurs at the demand junction at t=2 for 10 hours (grey region) requiring the pump to operate in an unscheduled way to help meet required water demand. Initially the pump serves demand and fills the tank. After the leak begins, both the tank and pump serve demand until the tank drains to a minimum capacity and shuts off via automatic valves. The pump then increases its flow rate to satisfy leaky demand until the leak is repaired. After the leak is repaired the pump serves demand and fills the tank to its 95% capacity, then the pump shuts off and demand is served by the tank.

Figure 3.6. Toy Model Leak Condition

Pipe Breaks

Figure 3.7 depicts a scenario involving a pipe break between the pump and the demand junction. The tank is at the same initial level, but flow from the pump cannot be provided due to the pipe break. Water from the tank is used to meet demand for a period of time until the tank meets its minimum level. The system is then drained by the demand until the pipe is repaired and the pump can refill the system.

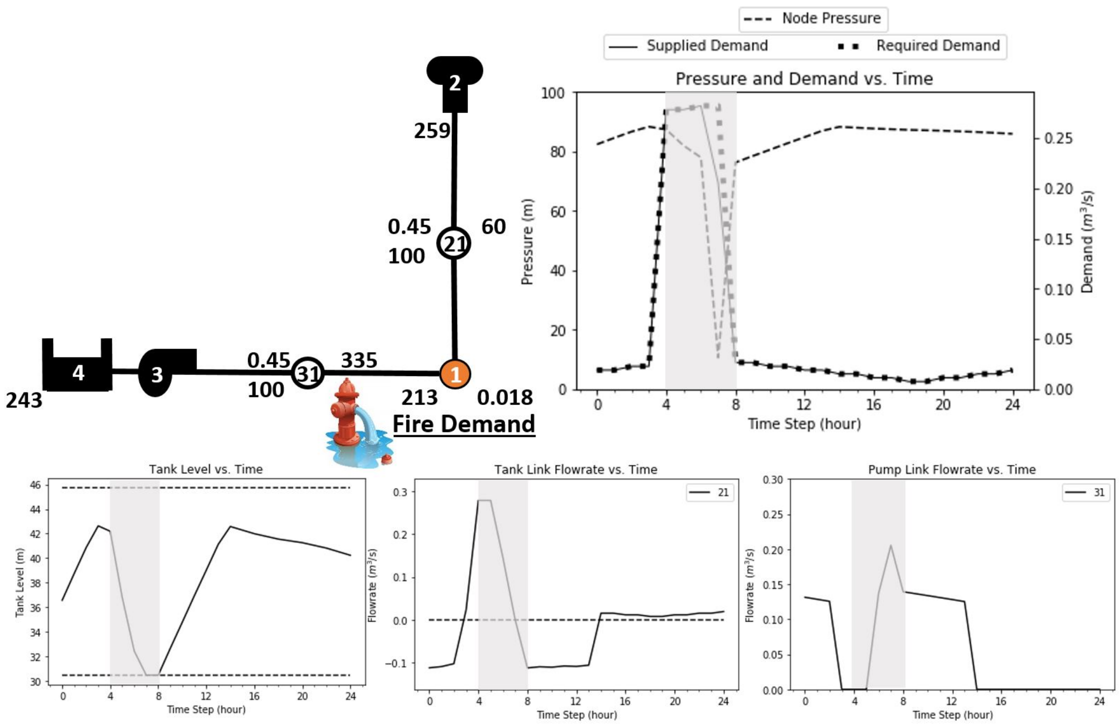


A break occurs at demand junction at t=0 for 22 hours (grey region). The pump cannot serve water demand, so the tank serves all demand until the water level in the tank drops below its minimum service level. The system is drained and there is no pressure in the system until the pipe is fixed and the pump can flow water into the system to meet demand.

Figure 3.7. Toy Model Break Condition

Fire Flow

Figure 3.8 depicts a scenario involving a “fire flow” demand (i.e., a large demand, as might be used to fight a fire) is introduced in hour 4 and runs for 4 hours. This represents a major spike in demand for the system during this period. The tank reaches 95% capacity and the pump link is closed. During the fire flow demand the tank is rapidly emptied to its minimum capacity. The pump is then turned on, but there is short period of time before it reaches its maximum flow rate when demand is not met. When the fire flow demand ends at hour 8, the pump resumes meeting demand and filling the tank to 95% capacity.

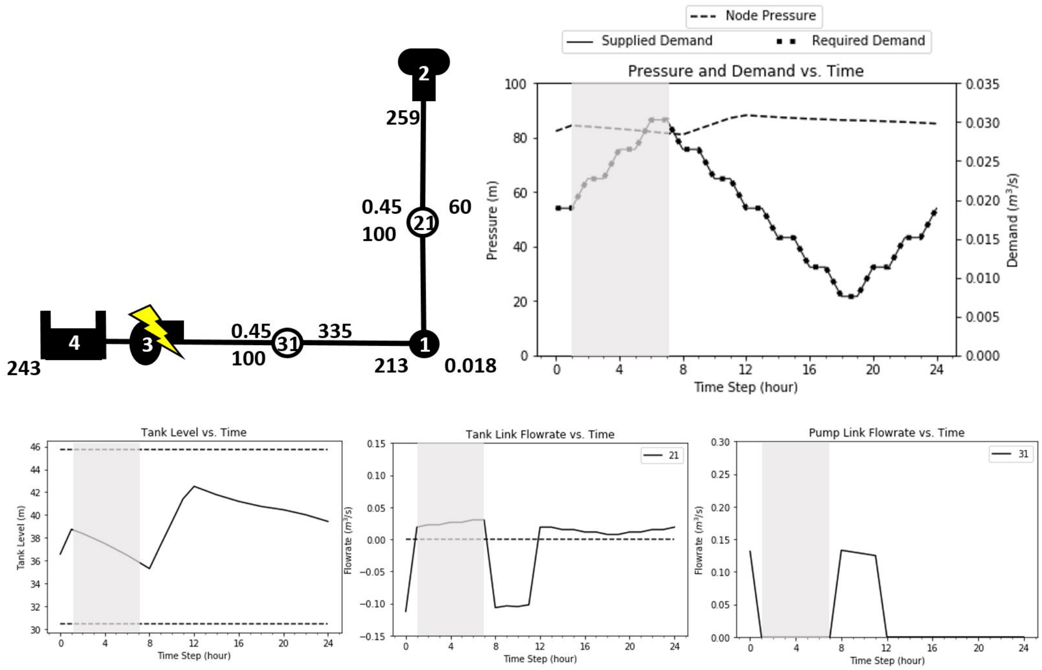


A fire flow event occurs at the demand junction from t=4 to t=8 (grey region). The fire flow creates a demand spike that exceeds network water service capacity. Even with the pump and tank feeding the junction, demand is not met until the fire flow event ends.

Figure 3.8. Toy Model Fire Flow Condition

Pump Failure

In Figure 3.9, we consider an electrical outage that shuts off the pump from t=1 to t=8. During this period, demand is met by flow from the tank until power is restored, after which the pump turns on to supply demand and fill the tank.



An electrical outage occurs and shuts off the pump from t=1 to t=8. Demand is met by flow from the tank until power is restored, after which the pump turns on to supply demand and fill the tank.

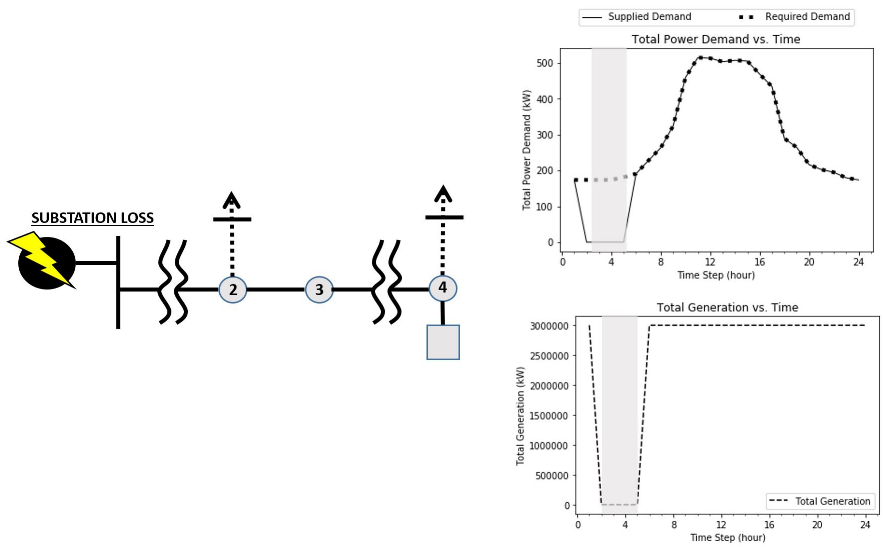
Figure 3.9. Toy Model Pump Outage Condition

3.3.2 Electric Distribution Emergencies

Much like the Toy Water Model, we wish to test the behavior of the EDN Basic Test Circuit during certain excursion scenarios. Specifically, we wish to model how power outages and sudden demand shifts affect network operation. These types of events can impact each other over time and are important to consider for interdependent water-power emergencies.

Substation Loss

Figure 3.10 depicts the situation where a substation is suddenly shut off due to an imbalance in the system. The rest of the distribution network is cut off from power and demand is not met for three hours until the system is brought back on line.



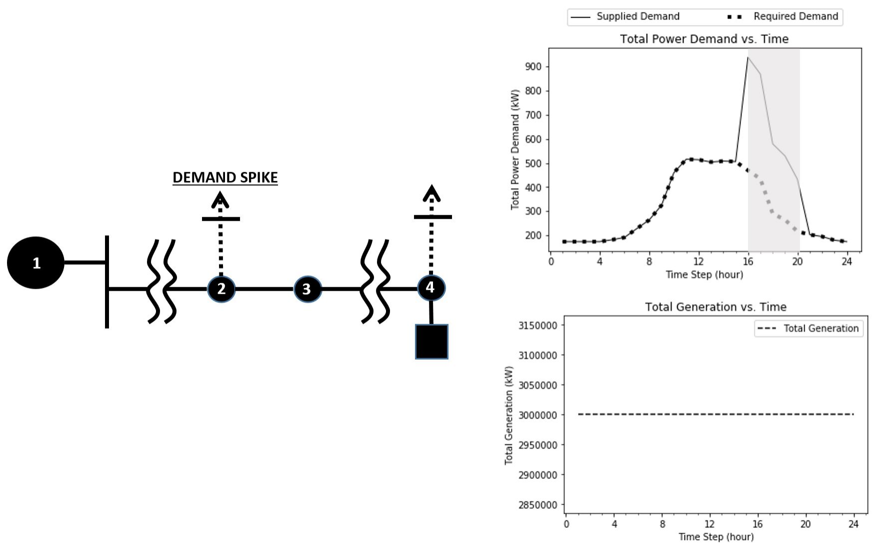
Generation capacity is halted in the EDN from t=2 to t=5. The entire system cannot operate for the duration and demand is not met. A small fluctuation in the system can cause an imbalance that results in system failure. Many singular generation systems require extended periods to properly restart the system.

Figure 3.10. Basic Test Circuit Substation Loss Condition

This scenario is indicative of many power generation networks where imbalances in the system or changes in weather cause systems to malfunction and loss of access to electricity. Safety measures require full system shut down in order to manage unplanned fluctuations and many turbine based generation systems require an extended period to restart safely. These networks incur a loss to the utility from unmet demand and the resources required to adjust and restart the system.

Demand Spike

In Figure 3.11, we consider the case where an unplanned event results in a sudden spike in demand in the system for four hours, extending peak demand time.



A sudden spike of unexpected demand occurs at t=16 to t=20. The fluctuation represents possible consequences for the utility if unplanned events are not balanced properly.

Figure 3.11. Basic Test Circuit Demand Spike Condition

Such large fluctuations in demand from what is projected throw off both the general management of the EDN and the economics of utility rates. Such an unplanned event can result in an outage, such as in the Figure 3.10, or it can result in a loss of economic opportunity for the utility.

3.4 Summary

In this chapter, physics-based models for WDNs and EDNs are described in detail, tested with two simple networks, and a series of emergency excursions are developed to understand their consequences. The individual models provide a tool to understanding how these systems work without regard to their interdependencies. In the next chapter, we build on these isolated models to develop an integrated model that measures the behavior of both systems with interdependencies.

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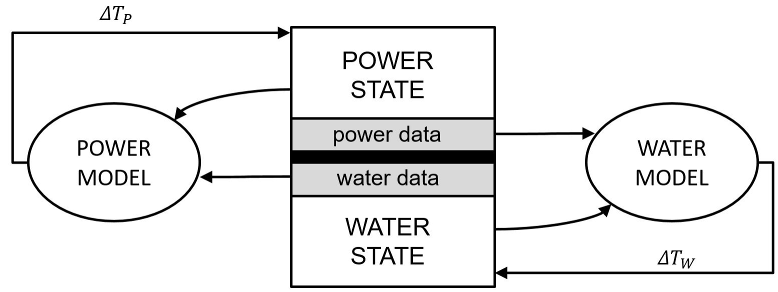
CHAPTER 4: A Simple Water-Electric Distribution Network

Interdependencies can result in surprising outcomes across water and power networks that are otherwise unpredictable when studying infrastructure systems in isolation. We combine our individual models from Section 3 to understand these effects from a system-of-systems perspective. In this chapter, we define interdependencies across WDNs and EDNs, implement them in our Python-based computational environment, and run a simple model for case-study analysis.

4.1 Representing Water-Power Interdependencies

Water and power systems each have their own dynamics that evolve over time according to their respective physical characteristics. In practice, an EDN typically reaches equilibrium in less than one second, whereas a WDN can often take minutes or hours before reaching equilibrium. Figure 4.1 depicts the way in which we implement the interaction between a WDN and an EDN across time. In particular, there is a hydraulic calculation loop dictated by time-step ΔT_W and a power flow analysis loop dictated by time-step ΔT_P. The speed at which real WDNs and EDNs operate dictates the speed of these loops, how often model state and data are updated, and resulting interactions. For our interdependent model, we choose to run the WDN PDD simulation at one-hour intervals; for each iteration of the WDN, we run one iteration of the EDN. Because $\Delta T_P << \Delta T_W$, each iteration of the power system appears to reach equilibrium instantaneously compared to the water system.

We make a variety of additional assumptions that affect interdependent model parameters and dictate analysis. Demand data is also time-dependent; each hour within a 24-hour period has different system needs. We distinguish between “required” demand and “delivered” demand. Required demand is based on predicted system state, not actual system state. Specifically, demands anticipated in base case scenarios dictate what the interdependent system expects to deliver in all other scenarios. Delivered demand is based on what the system is able to support; the difference represents a shortfall (equivalently, an unmet gap) in service.



The power model is quasi-steady state while the water model is dynamic. The water model pauses its simulation at set time steps to feed data into the power model. The power model is then instantaneously solved to feed data back into the water model.

Figure 4.1. Interdependent Model Application

We also assume failures have a known start and end time, that water and power operators make decisions independently of each other, recovery of infrastructure is automatic once failures end, and there are no additional unpredicted failures that occur during emergency events. Thus, once a known failure duration is over, the WDN and/or EDN is assumed to be automatically recovered based on best practices within each individual system.

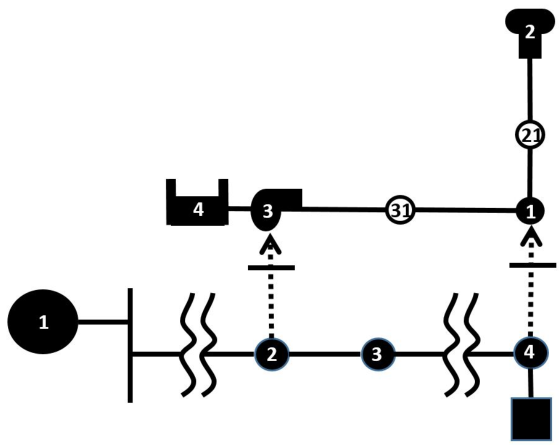
To model interdependencies, we introduce new variables and data that need to be passed from one model to the other, represented as the grey portion of Figure 4.1; these include physical and geographic interdependencies. For physical interdependencies, pumps are dependent on electricity to function. The water model and calculated water state adjusts pump characteristics, and consequentially pump electricity needs. Specifically, the head and flowrate of a pump needs to be converted to electrical demand of work using equation 4.1 from Fooladivanda and Taylor (2017):

$$P_{h(kW)} = q\rho g h/3600, \tag{4.1}$$

where $P_{h(kW)}$ represents hydraulic power (kW); q is flow capacity (m^3/s); ρ is fluid density (km/m^3); g is gravity (9.81 m/s^2); and, h is differential head (m). This new electrical load is updated and treated as an additional load on the power system at a specified distribution bus.

We represent geographic interdependencies for water infrastructure and power buses that are co-located in terms of an additional piece of input data that does not require additional calculations. Emergency scenarios that are geographically localized (e.g., fires) are also defined by location to indicate which water and power infrastructure are affected.

Finally, we define a simple simulation algorithm to run the interdependent model and generate results. We initiate analysis runs by solving the initial conditions for the EDN instantaneously and pass the relevant data to the WDN to begin the simulation. If there is enough power to a pump, the pump will operate normally for the next hour until the simulation is paused and hourly demands for both networks are updated. This process iterates over the 24-hour period. Results for each iteration are recorded for both the WDN and EDN.



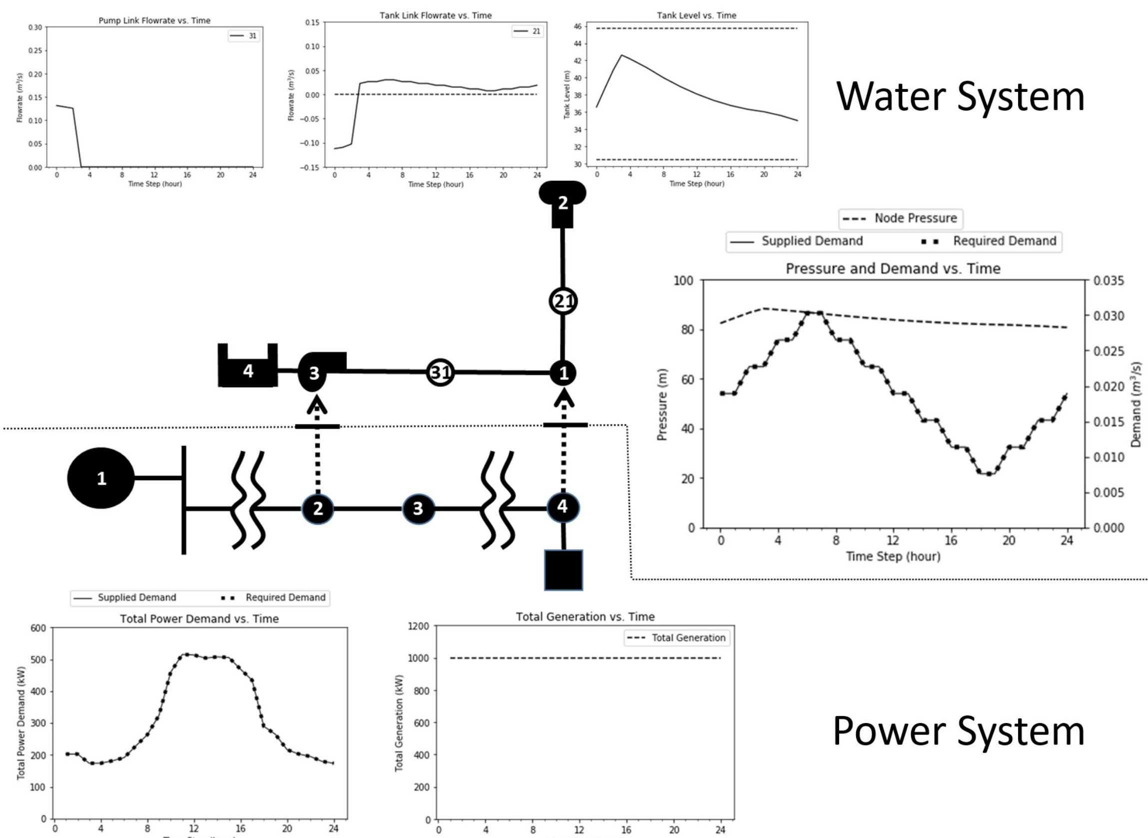
The Toy Water Model is connected to the Basic Test Circuit. We define a physical dependency from the EDN bus (2) to the WDN pump (3). We define a geographic dependency from the EDN bus (4) to WDN junction (1).

Figure 4.2. Toy Interdependent Model

4.2 A Simple Interdependent Water-Power Model

Following our above protocol for modeling interdependence, we can link the Basic Test Circuit (from Section 3.1) and the Toy Water Model (from Section 3.2) to construct a simple water-power model and explore interdependent operations. In Figure 4.2, the Toy Water Model pump (3) is connected to the test circuit at the Basic Test Circuit bus (2), a shared dependence type due to the variable affects the pump work has on the electrical system. Power also has a Basic Test Circuit demand at bus (4) which is a geographic type of dependence with Toy Water Model demand junction (1).

In Figure 4.3, we present the day-ahead, base case operation for the “simple” interdependent water-power model for a 24-hour duration. Because both systems operate normally with no failures, the interdependence across the WDN and EDN is only witnessed between the pump and bus at the transmission substation. Demand at the pump changes the normal, base case demand pattern and can be observed when the pump is shut off at t=3 and total power demand slightly dips lower than previous hours.

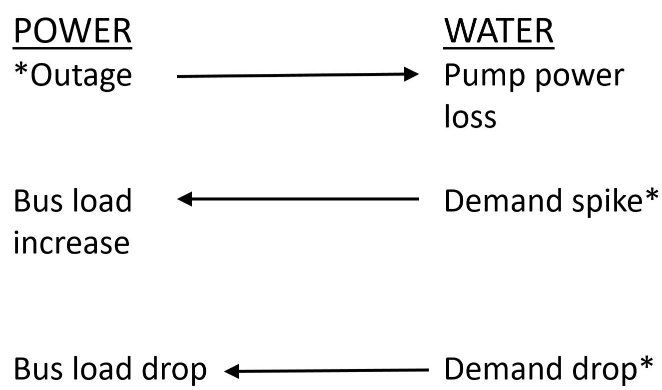


The water model follows the previous Toy base case. The Basic Circuit Model, connected with the water model, adds an increase in required and delivered demand to accommodate water pump electricity needs at the beginning of the 24-hour period.

Figure 4.3. Toy Interdependent Model Base Case

4.3 Interdependent Water-Power Emergencies

We test our interdependent model with emergency excursions to observe more complex water-power system behaviors. Figure 4.4 displays the originating failure events and their consequences across the system boundary. Specifically, we introduce three interdependent consequences, one originating in the power network (outage) and two originating in the water network (demand spikes and demand drops). These initiating events cause cascading failures across both systems that are difficult to predict prior to interdependent model analysis. We consider each of these cases in more detail below.

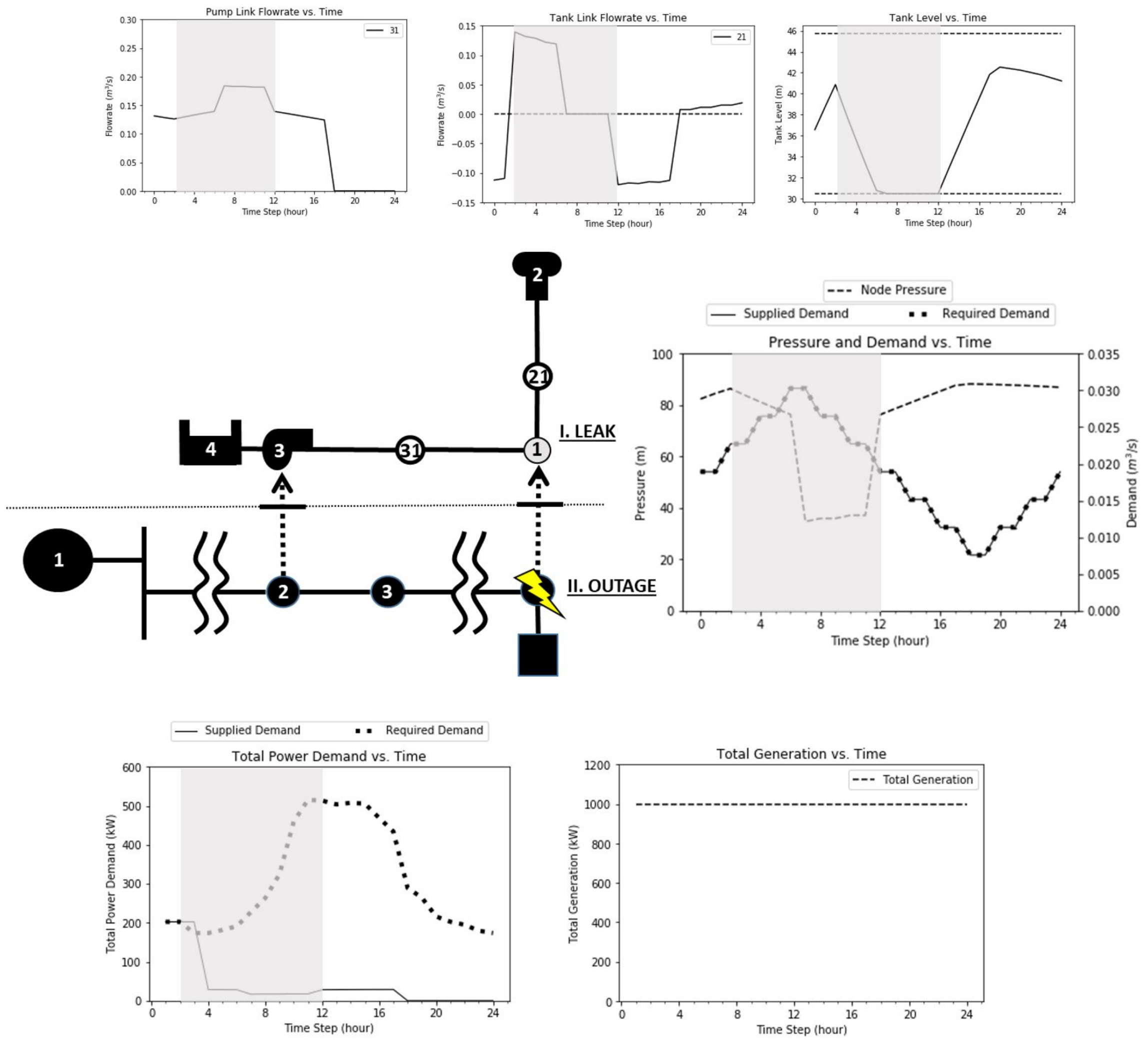


Excursions are denoted by originating failure events (asterisk) and their consequences across system boundaries.

Figure 4.4. Toy Interdependent Model Excursions

4.3.1 Interdependent Leaks

We revisit the water leak scenario from Section 3.3.1, now in the interdependent system. Due to the co-location of water demand junction (1) and the power bus (4), the electrical system is susceptible to flooding. When the leak occurs at this location, it starts to flood power infrastructure. After two hours, the electrical system fails due to nearby flooding and must be shut down and repaired for the duration of the day. The effects can be observed in Figure 4.5. Once the power system bus (4) is cut off, delivered power is affected and a significant electricity shortfall is witnessed. We observe that power recovery is dependent on the response time to repair the leak.



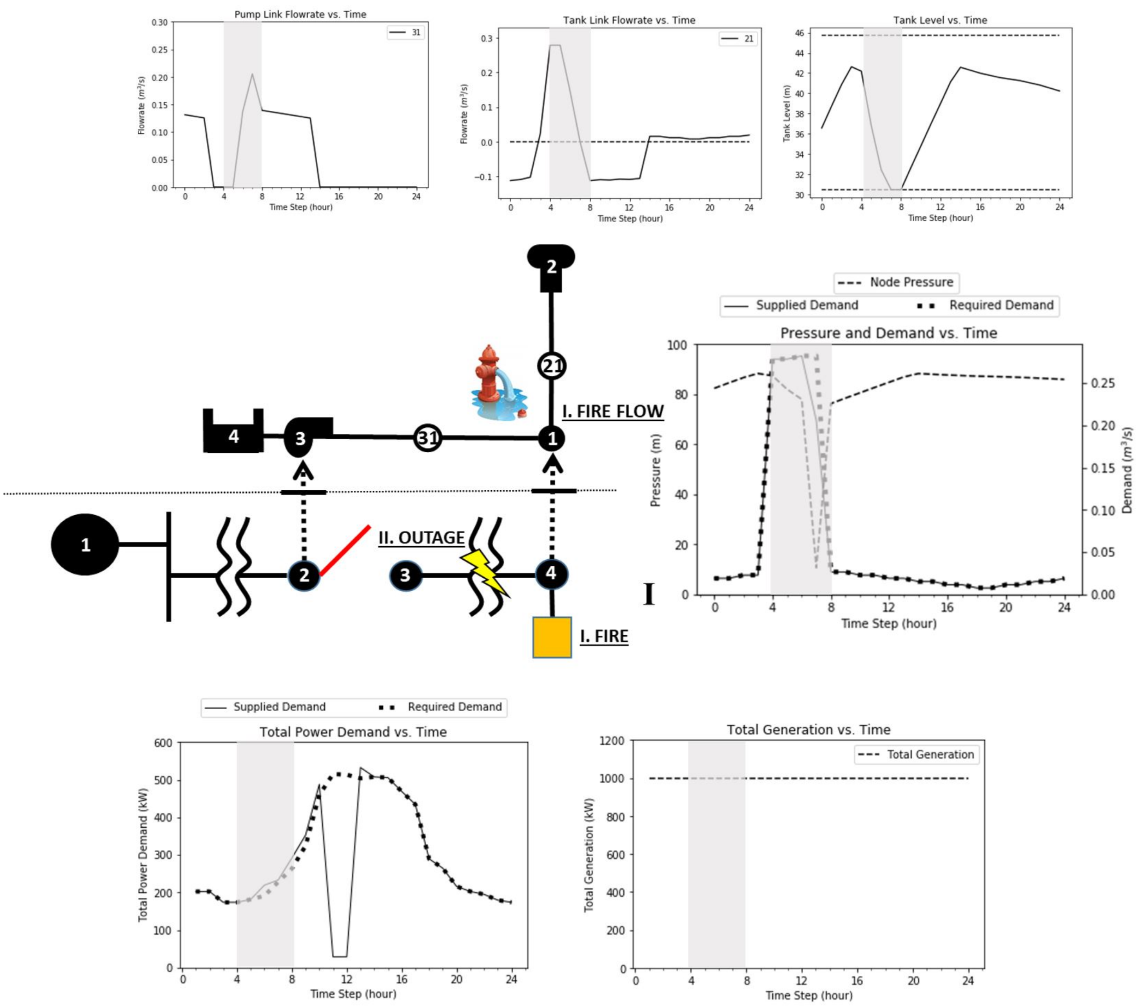
A large leak occurs at water junction (1) at t=2 for 10 hours. Flooding occurs at co-located power demand bus (4). Flooding causes electrical bus (4) to be shut down at t=4. The need for repairs causes a large shortfall in delivered power for the remainder of the 24-hour period.

Figure 4.5. Toy Interdependent Model Leak Condition

4.3.2 Interdependent Fire Flow

We revisit the case of a fire flow demand from Section 3.3.1 in the interdependent model; see Figure 4.6. In this scenario, a fire occurs at the shunt capacitor in the power system at bus (4) at t=4 and lasts for 4 hours. The fire at bus (4) draws fire flow from junction

(1) in the WDN such that pump (3) responds to the increased water demand. The new pump operation requires more electricity simultaneously as the EDN slowly approaches peak power demand and overload. Eventually, the combination of peak power demand and electricity needs at the pump causes bus (3) to trip itself at t=11 to protect overloaded assets. Electricity is not delivered to EDN bus (3) until it is reset after 2 hours, causing unexpected power shortfalls from t=11 to t=13.

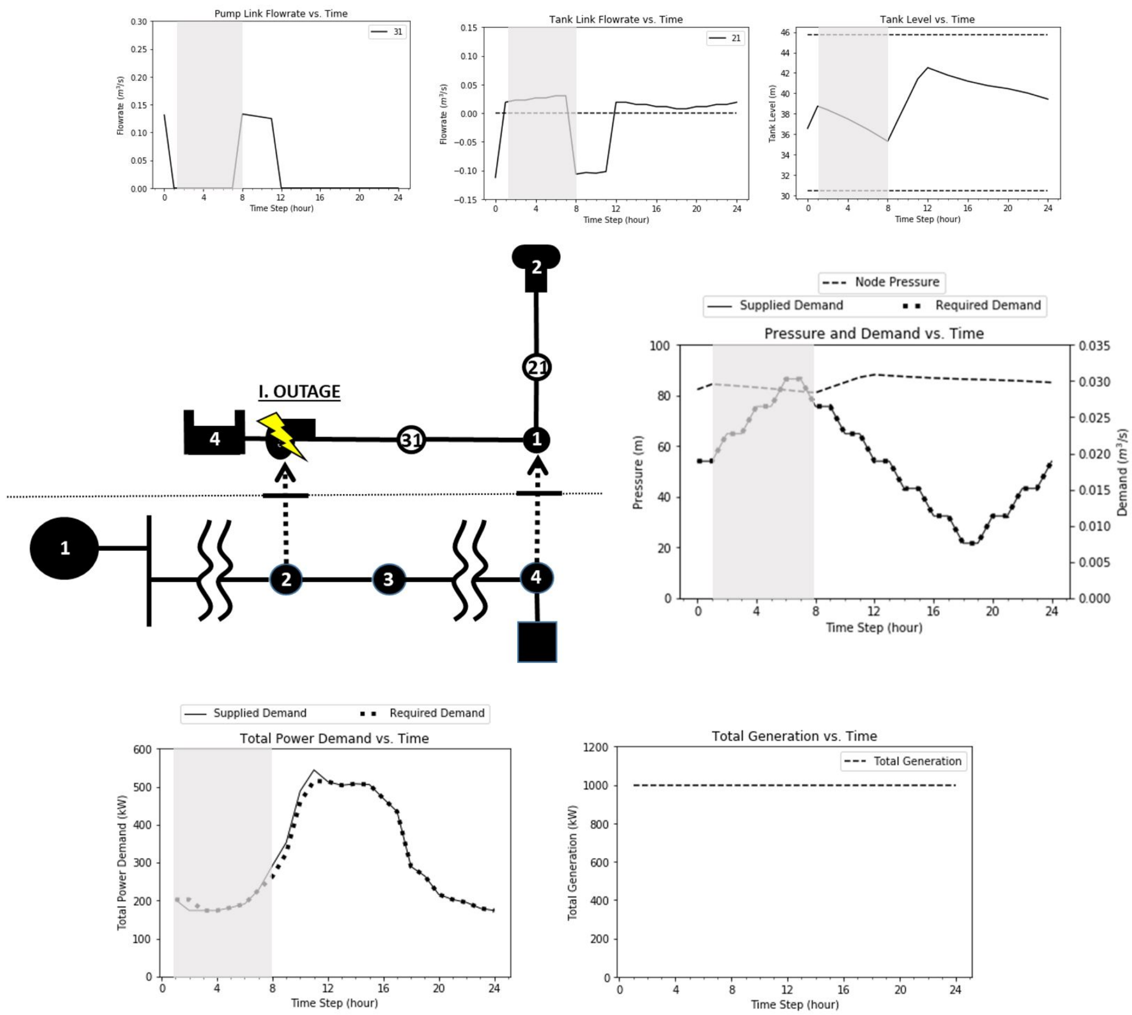


A fire occurs at the shunt capacitor at bus (4). The Toy Water Model fire flow condition at junction (1) is replicated for the water system in response to the electrical fire. The electricity needs at pump (3) exceed normal expectations during peak power demand and causes a 2-hour disruption from t=11 to t=13 at electrical bus (3).

Figure 4.6. Toy Interdependent Model Fire Condition

4.3.3 Interdependent Pump Power Outage

We revisit the case of a pump outage from Section 3.3.1 in the interdependent model; see Figure 4.7. The pump (3) is suddenly shut down and reset due to a breaker trip at the pump. As in the pump outage case from Section 3.3.1, water demand at junction (2) is met by flow from the tank (2) until electricity is restored, after which the pump turns on to supply demand and fill the tank. Total power demand is decreased (shortfall) from the required demand for the duration of the outage and increased (overshoot) for the time period when the pump is refilling the tank.



A breaker trips at the pump (3) at t=1 shutting the pump off. Power does not return to the pump until t=8, at which time the pump is restored. This issue leads to both shortfalls and overshoot in delivered electricity with respect to required power demand from t=0 to t=13.

Figure 4.7. Toy Interdependent Model Pump Outage Condition

4.4 Summary

In this chapter, we successfully implement a simple interdependent water-electric distribution model by identifying interdependencies, modeling their interactions, and observing how the systems perform. We are able to gain an operator's perspective on each system and observe how systems perform in a variety of interdependent emergency scenarios. To demonstrate that this model works for more realistic systems, we next expand the model to larger distribution networks with characteristics similar to those found on real islands and military bases. The next chapter shows an operator's perspective on how realistic water-power systems perform under similar emergency excursions.

CHAPTER 5:
A Realistic Water-Electric Distribution Example

In the previous chapter, we demonstrate the effect of water-power interdependencies, but with a simplified WDN and EDN that are unrealistic. To demonstrate the feasibility of our proposed model and analysis approach on more realistic water-power systems, we need to define additional assumptions and constraints that influence infrastructure network design and operation.

We focus attention on infrastructure systems in rural or islanded locations that are independent from larger, electric power transmission and water management systems. Their isolation lends themselves to focused study on interdependencies. Example locations that have these qualities include island territories like the U.S. Virgin Islands (USVI), rural locations in Alaska, and military installations at home or abroad that operate independently of the surrounding infrastructure systems. In this thesis, we further focus on water-power systems where there is a single water and power source co-located together, and the WDN and EDN experience sharp elevation changes between network nodes. We also assume resources for redundancy are scarce and limit the ability of water pumps to have emergency power. Together, these assumptions guide development of a realistic water-electric distribution network model.

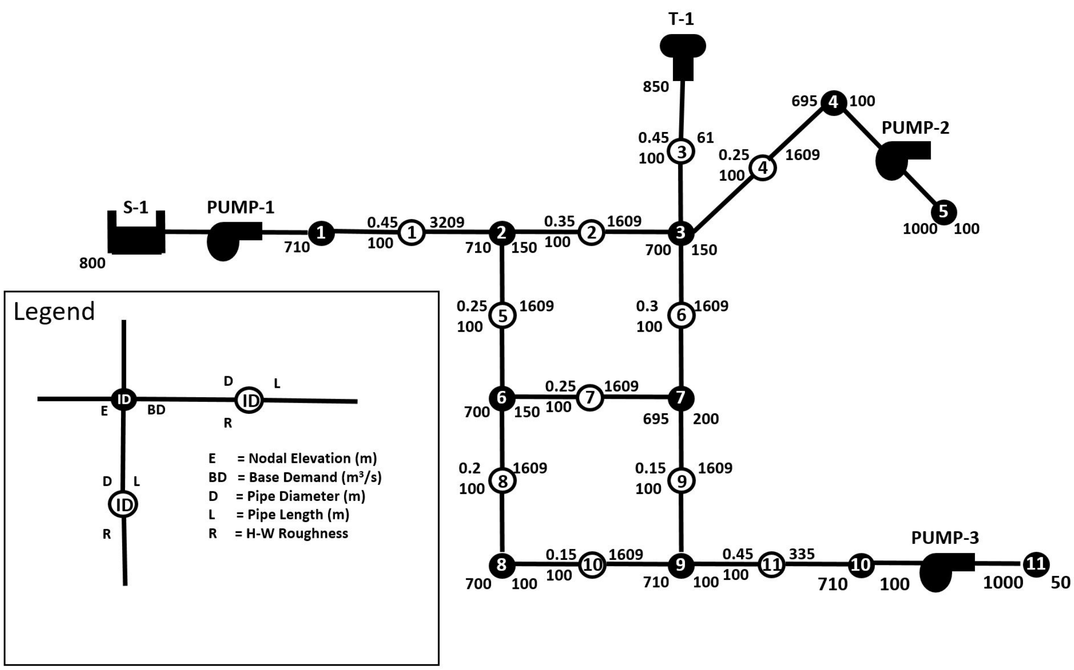
5.1 A Realistic Water-Electric Distribution Network Model

We begin with a description of stand-alone water and power systems, and then consider their interdependent operation.

5.1.1 A Realistic Water Distribution Network

In Figure 5.1, we present a realistic WDN that is a modified version of the EPANET Example Network 1 included in EPANET software (U.S. Environmental Protection Agency 2000). This WDN has a single RO plant that is the sole source of water for the network. A large pumping station (PUMP-1) provides adequate pressure to a mixed grid/branch distribution system that also feeds a large water tank (T-1) used for water distribution when it is at

95% capacity. Demand junctions (J-1 through 11) represent servicing districts at varying elevations and demands. The branching portions of the system are significantly higher elevation districts fed by booster pumps (PUMP-2 and PUMP-3). We refer to this system as the “Realistic Water Model.”



The realistic WDN represents a grid/branch distribution system that uses booster pumps to reach higher elevation demands. This is consistent with many isolated distribution systems that produce water from a single source and have varying topography between demand junctions.

Figure 5.1. Realistic Water Model

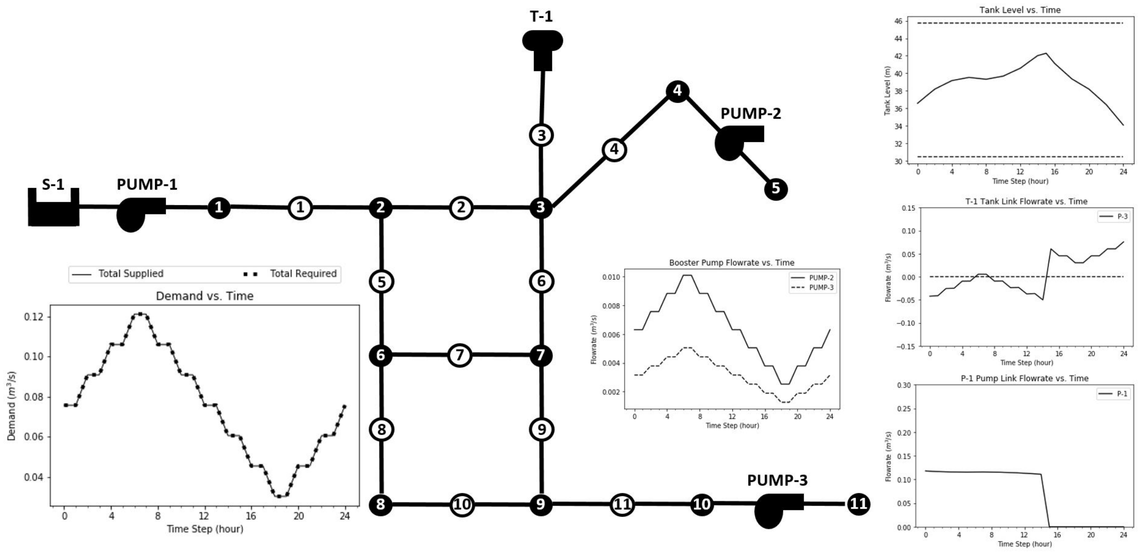
Table 5.1. Realistic Water Model Pump Data

			Point Paramter	
Pump	Type	Curve	Head (m)	Flow (m^3/s)
PUMP-1	Head	Single-Point	76	0.094
PUMP-2	Head	Single-Point	40	0.01
PUMP-3	Head	Single-Point	40	0.01

Table 5.2. Realistic Water Model Tank Data

Tank	Diameter (m)	Maximum Level (m)	Minimum Level (m)	Initial Level (m)
T-1	15.39	30.48	45.72	36.57

Figure 5.2 displays the 24-hour base case characteristics of the Realistic Water Model under normal operating conditions. Total demand is displayed to show how the system meets expected demand. The tank level shows how much water flows in and out of the tank and tank flow displays the rate at water fills or drains from the tank. Pump flow is displayed similarly, but only flows out. Finally, the booster pump flow characteristics are displayed to observe how water flows to higher elevation districts. With these combined observations, we can characterize the different emergency scenarios that affect realistic WDNs.



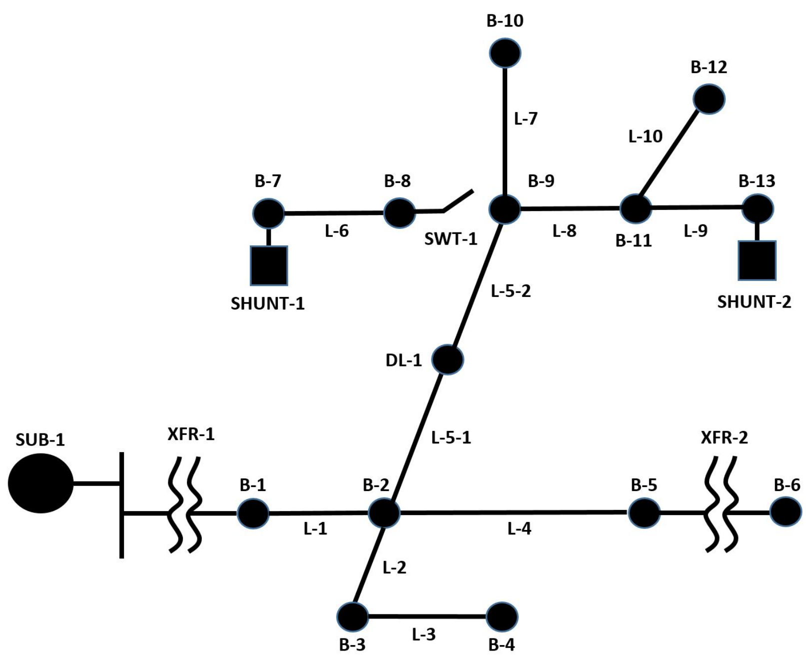
Realistic WDN under normal (base case) conditions for a 24-hour period. PUMP-1 operation is dictated by water level in the storage tank. The pump operates until the tank fills to 95% of its capacity. The tank (T-1) and PUMP-1 momentarily feed the network together at peak demand from t=6 to t=7. When the tank (T-1) has sufficient volume, PUMP-1 shuts off to save energy and the tank feeds demand junctions via gravity for the remainder of the day. Booster pumps (PUMP-2 and PUMP-3) push water up to a high elevation. This operation serves all water demand within the network in the most efficient, least-cost manner.

Figure 5.2. Realistic Water Model Base Case

Demand for this system follows a 24-hour period similar to the Toy Water Model base case in Section 3.1, but the system is larger with more combined demand. Demand peaks from t=6 to t=7 and bottoms from t=17 to t=18. Flow into the large tank (T-1) fluctuates as PUMP-1 responds to the demand changes in system. Shortly after the demand peaks, the tank provides additional flow into the system for a short time, only for it to begin to refill as demand trends down. When the tank reaches capacity, the pump link closes, and the tank serves all water demand for the duration of the 24-hour period. PUMP-2 and PUMP-3 have smaller capacity than the main pumping station in PUMP-1 because they each only serve one portion of the network, respectively. PUMP-2 operates at a higher rate than PUMP-3. Together, the WDN meets required demand for the 24-hour period.

5.1.2 A Realistic Electric Distribution Network

Figure 5.3 presents a one-line diagram of our realistic EDN. The Realistic Power Model is a modified version of an IEEE 13-bus model originally from (Kersting 2001b) adapted to connect with to the realistic WDN. Real and reactive power demands for each bus are available IEEE data. SUB-1 provides functionally infinite generation to the system. Transformer XFR-1 steps down the voltage for distribution from bus B-1 to various commercial and residential demand buses. Figure 5.3 displays the network and its components. Tables 5.3 and 5.4 provide applicable bus and edge data.



Source: Petri (2017). The "IEEE 13 Bus Network" consists of a substation at bus SUB-1 with functionally infinite generation capacity, a step-down transformer (XFR-1) linking the substation to the distribution circuit. A service transformer (XFR-2) at bus B-5 steps down voltage for bus B-6. The rest of the branched network of lines connect buses to service power demands at the same voltage (DL-1, B-1, B-2, B-3, B-4, B-6, B-7, B-8, B-9, B-12, B-13). Two shunt capacitors (SHUNT-1 and SHUNT-2) provide real and reactive power support at adjacent buses. A distributed load (DL-1) services demands across lines L-5-1 and L-5-2. A switch (SWT-1) controls power flow between buses B-8 and B-9.

Figure 5.3. Realistic Power Model

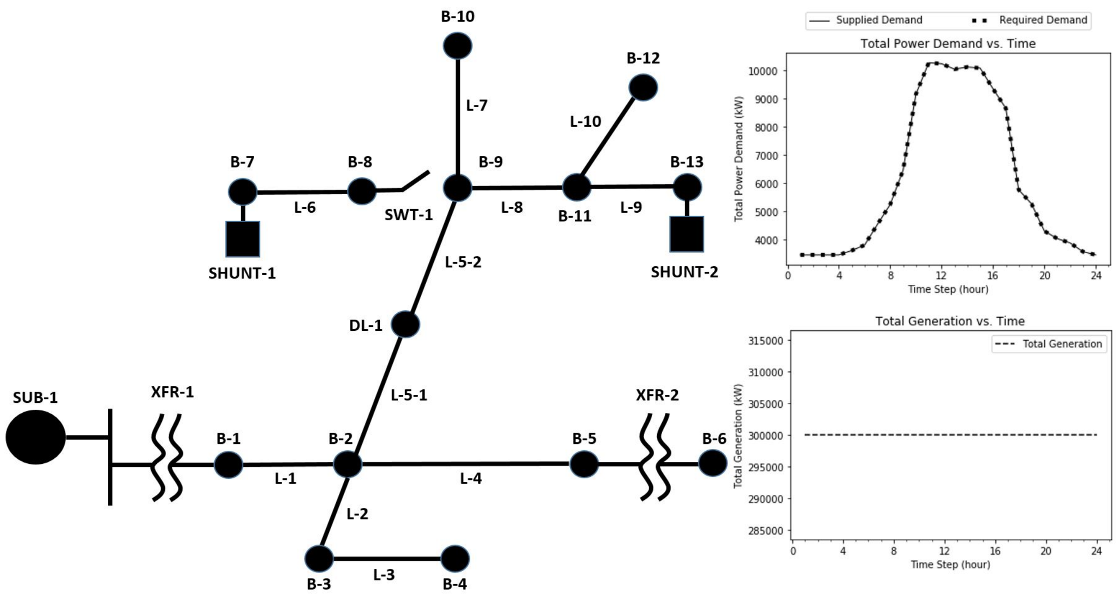
Table 5.3. Realistic Power Model Bus Data

Bus	Type	Power Generation (kW)	Base Demand (kW)	Nominal Voltage (kV)
SUB-1	Substation	∞	0	115
B-1	Connection	0	0	4.16
B-2	Connection	0	0	4.16
B-3	Load	0	0 (a) 170 (b) 0 (c)	4.16
B-4	Load	0	0 (a) 230 (b) 0 (c)	4.16
B-5	Connection	0	0	4.16
B-6	Load	0	160 (a) 120 (b) 120 (c)	0.48
B-7	Load, Shunt Capacitor	0	485 (a) 68 (b) 290 (c)	4.16
B-8	Load	0	0 (a) 0 (b) 170 (c)	4.16
B-9	Load	0	385 (a) 385 (b) 385 (c)	4.16
B-10	Connection	0	0	4.16
B-11	Connection	0	0	4.16
B-12	Load	0	128 (a) 0 (b) 0 (c)	4.16
B-13	Load, Shunt Capacitor	0	0 (a) 0 (b) 170 (c)	4.16
DL-1	Distributed Load	0	17 (a) 66 (b) 117 (c)	4.16

Table 5.4. Realistic Power Model Edge Data

Edge	Type	Phases	Thermal Limit (Amps)
XFR-1	Transformer	a, b, c	5000
XFR-2	Transformer	a, b, c	500
L-1	Line	a, b, c	730
L-2	Line	b,c	230
L-3	Line	b, c	230
L-4	Line	a, b, c	340
L-5-1	Line	a, b, c	730
L-5-2	Line	a, b, c	730
L-6	Line	a, b, c	260
L-7	Line	a, b, c	730
L-8	Line	a, c	230
L-9	Line	c	230
L-10	Line	a	165
SWT-1	Switch	a, b, c	1500

Figure 5.4 presents the base case for the Realistic Power Model over a 24-hour period. Required demand is consistent with real distribution systems. We display the total power demand by combining all demands across buses.

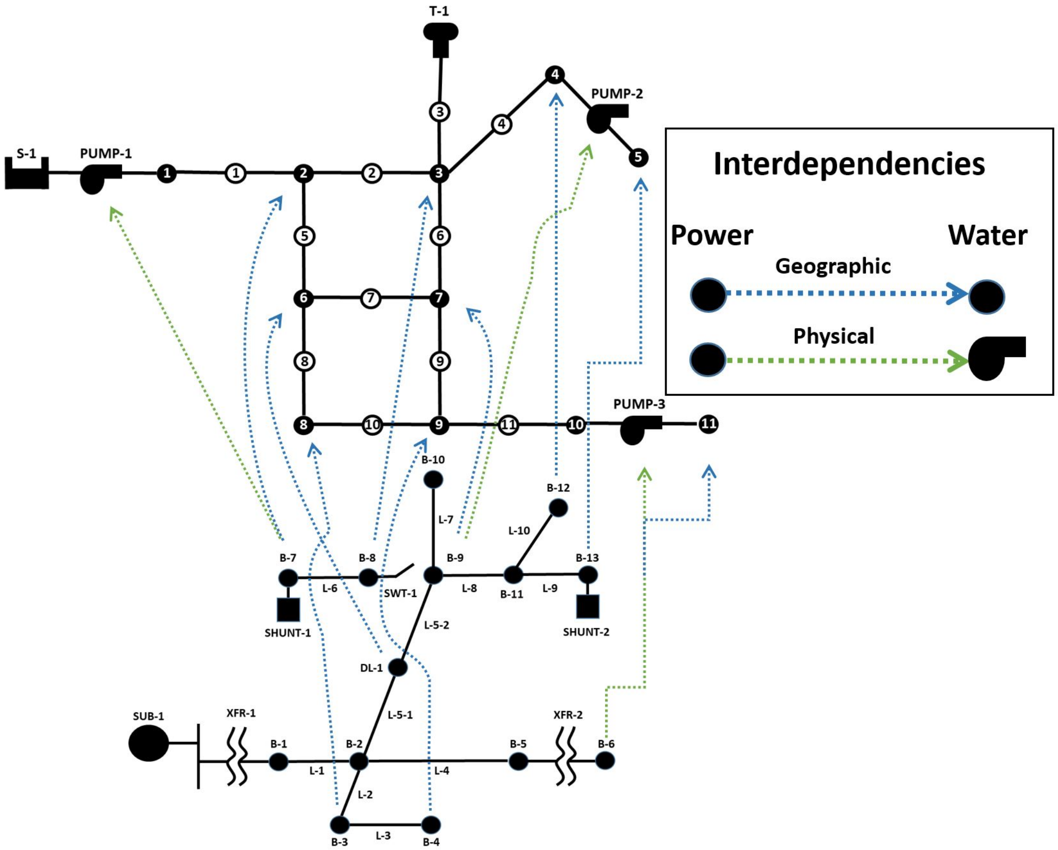


Realistic EDN under normal conditions (base case) for a 24-hour period. The required demand is based on real data for a real distribution system. The model iterates every hour and solves to ensure demands are met with power flow.

Figure 5.4. Realistic Power Model Base Case

5.1.3 A Realistic Water-Electric Distribution Network

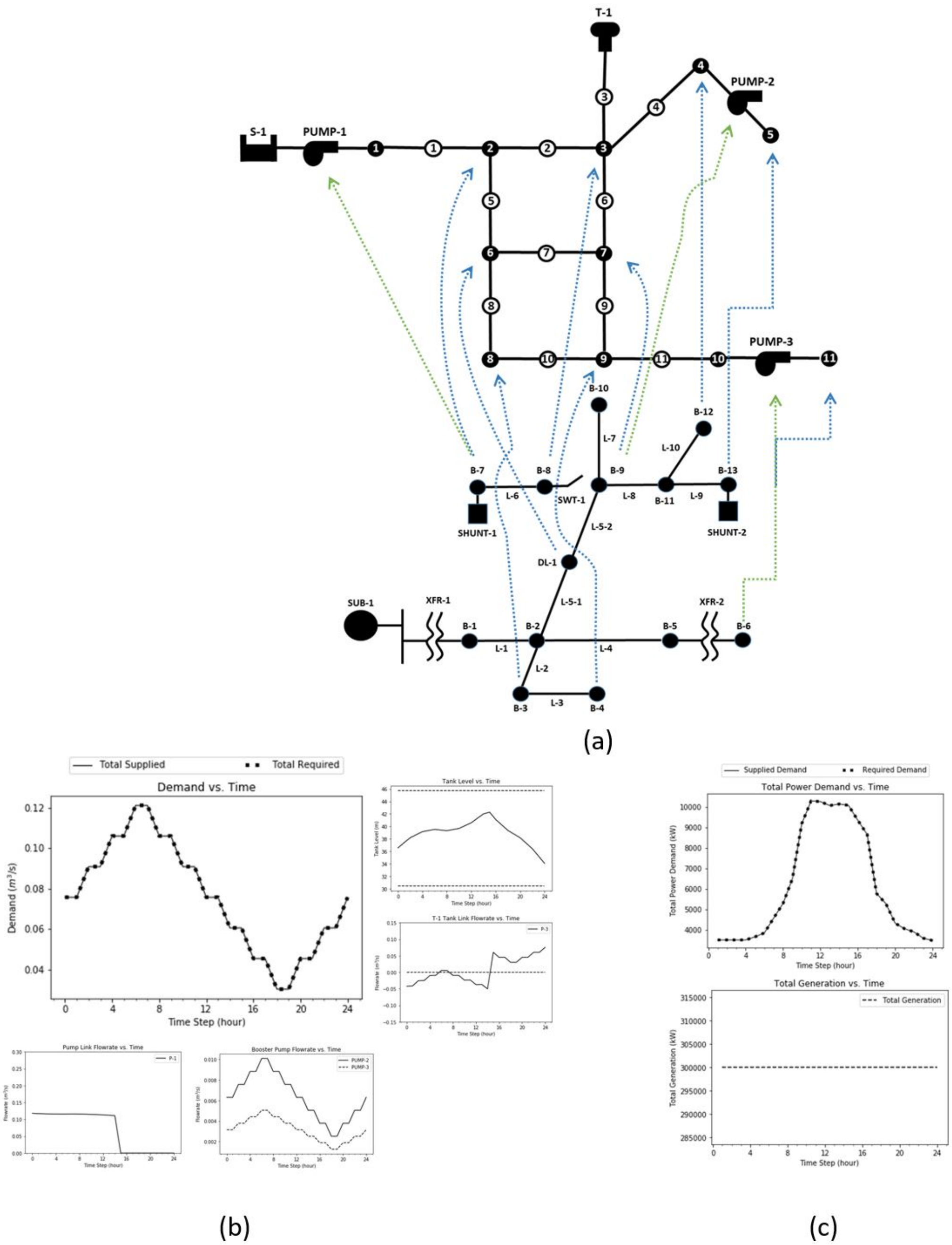
In Figure 5.5, the same modeling assumptions used to construct the simple interdependent model in Section 4.2 are scaled to produce a Realistic Interdependent Model. The Realistic Interdependent Model embeds geographic and physical interdependencies linking the realistic WDN and EDN. For physical interdependencies, all pumps produce additional power demands based on pump head and flowrate calculated using equation 4.1. Geographic interdependencies also have the same effect of co-located hazards and demands. We also pass information between the realistic WDN and EDN using the same sequencing and algorithms described in Section 4.1. Finally, we run each base case and emergency scenario for the same 24-hour time period with one-second time steps.



The Realistic Water Model is connected to the Realistic Power Model to create a Realistic Interdependent Model. The interdependent network embeds physical dependencies from bus B-7 to PUMP-1, bus B-9 to PUMP-2, and bus B-6 to PUMP-3. All other dependencies are geographic dependencies defined between water junctions and power buses.

Figure 5.5. Realistic Interdependent Model

In Figure 5.6, we present the base case for the Realistic Interdependent Model. The only visible change to results is the additional fraction of required electricity demand from the water pumps.



The realistic water-power distribution network is run for a 24-hour period. (a) displays the model. (b) displays the base case for the WDN (no change from the realistic WDN base case). (c) displays the base case for the EDN. In (c), power requirements of the WDN are added to the model for each hourly iteration due to their physical interdependency.

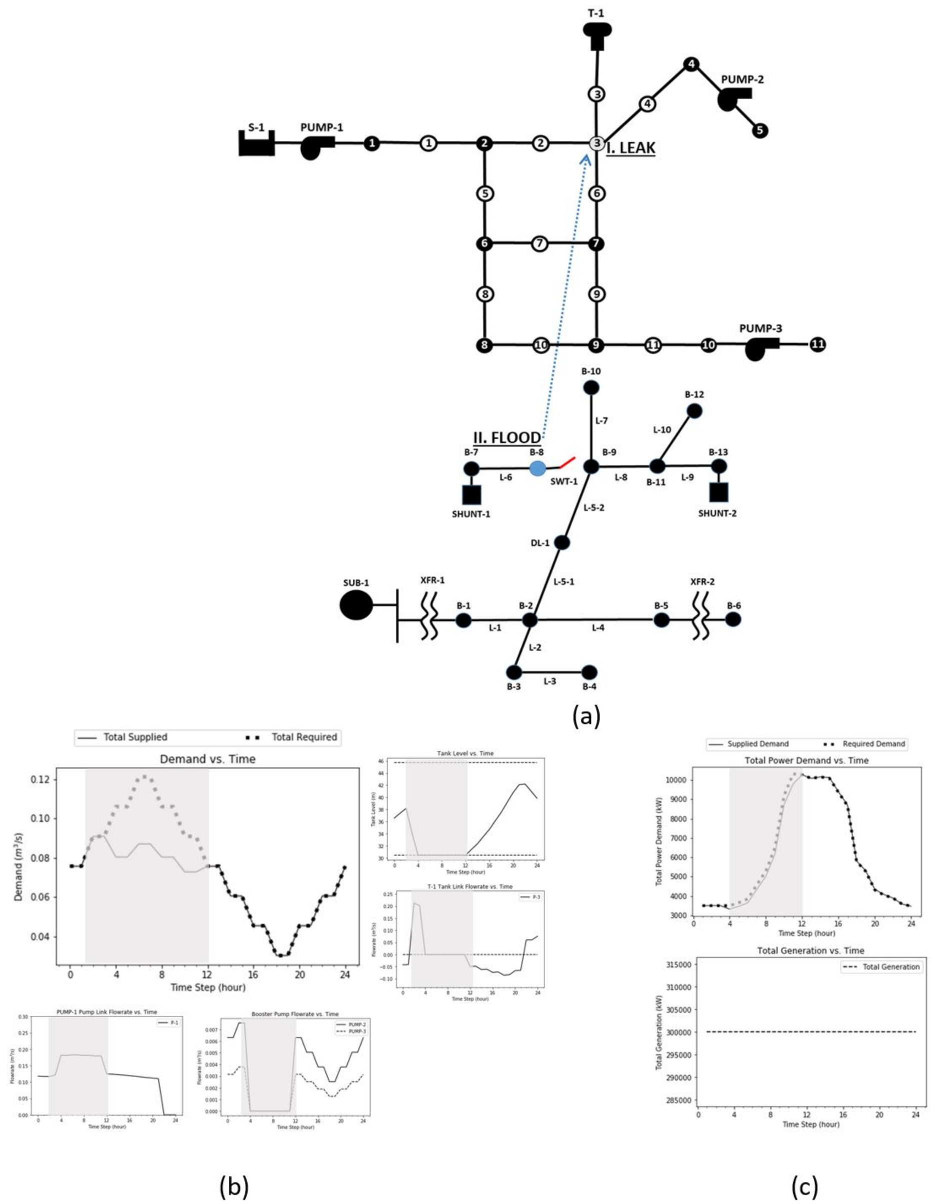
Figure 5.6. Realistic Interdependent Model Base Case

5.2 Interdependent Water-Power Emergencies

We study emergency excursions similar to those considered in Chapter 4 for the Realistic Interdependent Model. These scenarios are analyzed to reveal unforeseen events and cascading failures that interdependencies cause. In doing so, we also validate how well the model performs at realistic scale for specific events.

5.2.1 Interdependent Leaks

We consider the situation where a leak event occurs at junction J-3 at t=2 (event I) for a duration of 10 hours. Junction J-3 is co-located with bus B-8. After a 2-hour leak duration, a flood at B-8 occurs (event II) where power operators open switch SWT-1 to prevent equipment damage. Opening switch SWT-1 isolates bus B-7, but the emergency power capacity provided by SHUNT-1 continues to supply B-7 for the duration. Once the leak is repaired, flooding hazards are mitigated and power operators close the switch.



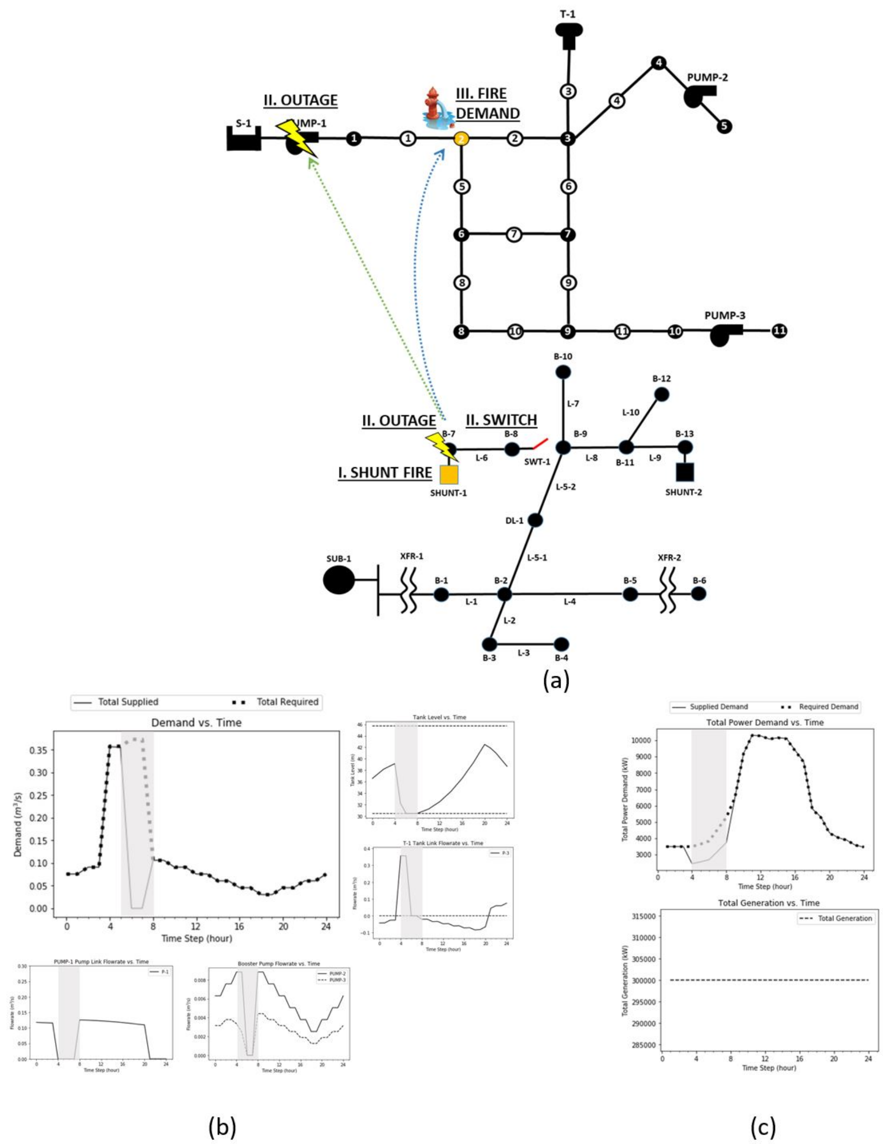
The Realistic Interdependent Model is run for a 24-hour time period with a large leak that occurs at t=2 located at junction J-3 (event I). A switch (SWT-1) opens to mitigate flood damage to power infrastructure after two hours (event II). This isolates B-7 and SHUNT-1 forcing emergency power activation. (a) displays the diagram and sequence of events. (b) displays water demand not met due to flow losses from the leak. The flow is not enough to supply booster pumps that feed higher elevation water demand. (c) displays how the loss booster pumps decrease electric power needs, leading to electricity shortfalls.

Figure 5.7. Realistic Interdependent Model Leak Condition

In Figure 5.7, we observe supplied water demand does not meet the required demand for an 8-hour period. Tank T-1 flow shuts off when the tank reaches minimum capacity at t=4. PUMP-1 increases to maximum flow output in an attempt to satisfy water demands without gravity-fed water. This lasts until t=12 when the leak is repaired and PUMP-1 can accommodate water demands and begin refilling tank T-1. During the leak, the booster pumps (PUMP-2 and PUMP-3) do not have enough flow to deliver water demand to higher elevation communities. The combined loss of power demand from the booster pumps is greater than the increase in power demand for PUMP-1. Thus, the pumps shutting off leads to both water and electricity shortfalls for the duration of the leak.

5.2.2 Interdependent Fire Flow

We now consider a fire at SHUNT-1 (event I) at t=4 until t=8. When the fire starts, SHUNT-1 is rendered inoperable and switch SWT-1 is opened to isolate the branch and halt live wire concerns for firefighting. Junction J-2 is co-located with bus B-7 where a fire flow demand is drawn. However, both loss of SHUNT-1 backup power and access to the rest of the power network incurs a electricity demand shortfall at bus B-7 (event II). As bus B-7 has a physical interdependency with PUMP-1, the pump loses power and shuts off. Thus, fire flow demand is only met with water from tank T-1. When the fire event ends, switch SWT-1 is closed and power is restored.



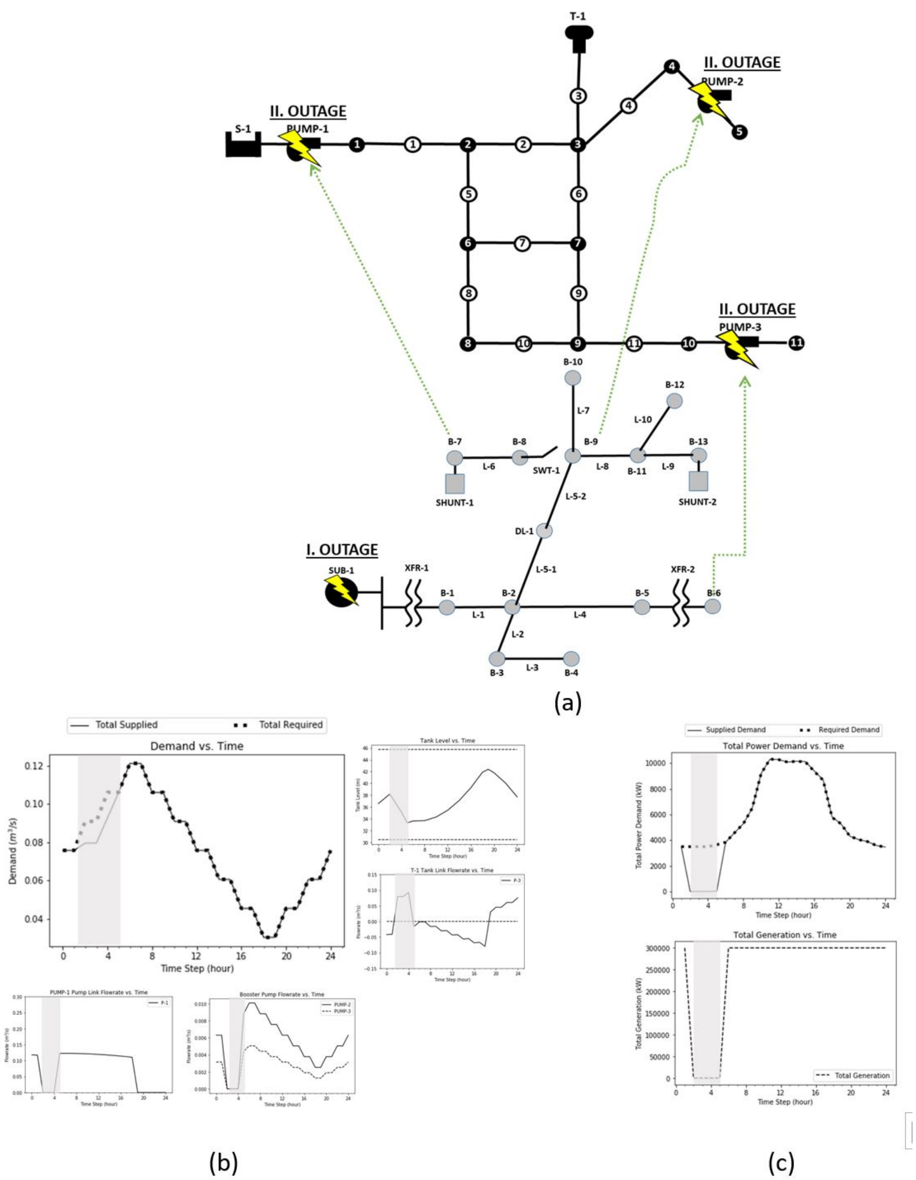
The Realistic Interdependent Model is run for a 24-hour time period when a fire occurs at t=4 located at SHUNT-1 (event I). Switch SWT-1 is opened to prevent live wire concerns for firefighters (event II) which isolates bus B-7 and SHUNT-1 (emergency back-up is not operational). Simultaneously the outage shuts off power to PUMP-1 as fire flow demand is imposed on junction J-2. The fire ends at t=8. (a) displays the diagram and sequence of events. (b) displays water demand not met due to the loss of flow from PUMP-1. The tank can only maintain water demand for one hour until it reaches minimum capacity. The system is emptied for three hours. (c) displays how the loss of demand from bus B-7 and all pumps create a significant power shortfall.

Figure 5.8. Realistic Interdependent Model Fire Flow Condition

In Figure 5.8, the loss of power demand from PUMP-1 and bus B-7 incurs a large shortfall in delivered electricity that lasts for the duration of the fire. The WDN is reliant on tank T-1 to provide flow for the WDN during the duration of the event. The increased fire flow demand at junction J-2 makes it so tank T-1 can only sustain required water demand for one hour after the fire begins. The WDN is emptied for three hours until power is restored and PUMP-1 can begin providing flow for the WDN again. Water shortfalls last for the three-hour duration after the tank T-1 drains. This can have major consequences for a large fire that is dependent on consistent water flow. Additionally, the sudden and large drop in electricity demand can have major consequences for power system maintenance and operation.

5.2.3 Interdependent Power Outage

The final scenario we consider involves a power outage at the generation facility from t=2 to t=5. As a consequence, all physical dependencies are affected for the duration of the event and all pumps are no longer operational. The water tank T-1 is the sole provider of water flow. We assume no emergency power generation (e.g., no back-up power supply) for any pump. Such events can occur in rural and island power systems where there is only one power generator for the system and where fluctuating weather conditions can affect aging infrastructure.



The Realistic Interdependent Model is run for a 24-hour time period with a system-wide outage that occurs at t=2 (event I). All physical dependencies between the WDN and EDN are affected, resulting in outages for all three pumps (event II). The event ends after three hours. (a) displays the diagram and sequence of events. (b) displays water demand not met due to the loss of flow from from all of the pumps. The tank provides adequate pressure to all junctions except J-5 and J-11 which require the booster pumps to reach higher elevation. (c) displays both the complete loss of supplied power demand and the loss of generation capacity.

Figure 5.9. Realistic Interdependent Model Outage Condition

Such a power outage not only affects the demand across the system but also shuts down all generation capacity for a period of time, as observed in Figure 5.9. With all pumps shut down, the WDN is completely reliant on stored tank water which adequately provides flow for the system except the higher elevation junctions that require booster pumps.

5.3 Summary

In this chapter, we successfully implement a realistic interdependent water-electric distribution model by identifying dependencies, modeling their interactions, and observing how the systems perform. We are able to gain an operator's perspective on each system and observe how the systems perform interdependently under a variety of emergency scenarios.

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CHAPTER 6:
Discussion and Conclusion

6.1 Discussion

Our results for the simple and realistic water-power systems reveal a number of important insights for interdependent infrastructure modeling and analysis.

The water-power model development process revealed factors that must be considered when analyzing interdependent infrastructure models. Specifically, *the proper treatment of time for water and electric distribution networks is important for ensuring realistic interdependent emergency results.* Water and power operators work on different physical time scales—water flow operates on timescales larger than electricity flow. This means water data and models used by utilities monitor the dynamic state of the system less frequently than electric power. In contrast, from the perspective of electricity, water systems are observed like a series of steady power flow states— the power system, using the smaller timescale, appears instantaneous to the water system. Thus, time-based modeling assumptions must be made to run a coherent and observable interdependent system. To combine WNTR and an AC-OPF model, time steps needed to be in seconds and analysis could be conducted on any time step greater than or equal to one second, providing a nearly real-time output for studying normal and emergency operating conditions. This also requires different operating characteristics for individual systems be understood with respect to time and system state, such as matching power consumption (in watts) to water consumption (in liters).

An important result of both simple and realistic water and power infrastructure is that *impacts across the interdependent systems exist even when dependencies between individual systems are not strictly bi-directional.* Our water-power models only have physical dependencies from power to water (i.e., water requires electricity to operate pumps) and geographic dependencies from water to power (i.e., water could flood power infrastructure or put out fires). Several emergency excursions show events that create system imbalances across these simple dependencies that may have far reaching consequences on each system. For example, the loss of power at a critical pump in the water system requires re-dispatch of all other pumps shifting power demand. This new operational state can cause further electric power imbalances that are difficult to predict from the perspective of a power utility. Such impacts imply that system operators are better suited to respond to such situations by communicating operational responses across infrastructure systems.

In addition, results show that *different classes of interdependencies can lead to similar operational outcomes.* Though a pipe break is different than a pump outage, depending on the location of the break, the loss of supplied demands remains the same. This is easily understood for a simple network, but it is not so obvious when the model is extended to larger, more realistic, networks. This implies that the impacts of water-power coupling are difficult to discern from studying each system independently. This also implies that the number (more or less) interdependencies across systems might not dictate the types of emergencies and cascades witnessed. This is problematic for future interdependent system design, as there may be no ideal way to establish coupling across water and power systems. However, this might also reveal possible solutions as there may be only limited number of interdependent operational scenarios between two systems even when characteristically different failures occur.

Finally, *working within the Python environment provides an effective way to link models of infrastructure operations.* Due to the structure and simplicity of data input, data modification, and model objects as Python libraries, the water-electric distribution network model developed herein easily scales from smaller, simpler systems to larger, more realistic systems. Operational results are also easy to track with common Python packages like pandas (McKinney 2011) for managing data and matplotlib (Hunter 2007) for generating figures.

6.2 Conclusion

Our results for emergency excursions demonstrate that even simple models show interdependent and cascading failures across water and power systems. Overall, the final model provides both realism and simplicity, making it an ideal foundation for future analysis for more complex water-power systems.

Island water and power systems may benefit from future work using the water-power model developed in this thesis. One important possible case study is in the USVI. The USVI Water and Power Authority (WAPA) has real world data sets for each respective system.

In particular, the water network has been modeled in EPANET making data inputs ready for WNTR utilization. Their power operators have been collaborating with Los Alamos National Laboratory (LANL) and the U.S. Department of Energy (DOE) to model their power network. Having such a strong data set with characteristics like those utilized in this model creates an opportunity to observe system behavior for emergent events. The model can be scaled to observe the networks for St. Croix, St. Thomas, and St. John. Such observations may help WAPA make their system more resilient while balancing policy and budgetary constraints.

Military installations may also benefit from future work. Infrastructure resiliency is a key concern for installations, especially with new cyber threats emerging. Cyber dependencies may be incorporated into an interdependent water-power model that can give insights into the vulnerability of installation SCADA systems. Such a model could steer policy and resourcing decisions toward engineering solutions to mitigate such threats. This is especially applicable to installations operating in rural and isolated environments.

The nature of our water-power model lends itself to further interdependent infrastructure analysis. For example, future model extensions may utilize simulation modeling techniques. Such techniques extend the model from observing specific, well-defined excursions like those in this thesis to simulating a wide range of possible events, even as they occur. It may also yield results that show surprising trends. The model also has the opportunity to incorporate stochastic elements. For example, WNTR has stochastic modeling already incorporated and there are tools easily available in Python for extending the AC-OPF model. Including probability of system failures could lend more fidelity to the model and analysis results. This could also produce insights into engineering decisions aimed at system hardening or redundancy in planning and near real-time.

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APPENDIX A:
Data Tables for Water and Power Models

This Appendix includes the data necessary to populate and run the models in this thesis.

A.1 Water Model Data

Table A.1. Hourly Demand Multipliers for All Water Models

Hour	Demand Multiplier
0.0	1.0
1.0	1.0
2.0	1.2
3.0	1.2
4.0	1.4
5.0	1.4
6.0	1.6
7.0	1.6
8.0	1.4
9.0	1.4
10.0	1.2
11.0	1.2
12.0	1.0
13.0	1.0
14.0	0.8
15.0	0.8
16.0	0.6
17.0	0.6
18.0	0.4
19.0	0.4
20.0	0.6
21.0	0.6
22.0	0.8
23.0	0.8

Table A.2. Junction Data for Toy Water Model

Node	Type	Elevation (ft.)	Base Demand (GPM)
4	Reservoir	800	0
2	Tank	850	0
1	Junction	700	300
10	Junction	710	0

Table A.3. Link Data for Toy Water Model

Link	Start	End	Type	Length (ft.)	Diameter (in.)	Roughness (HW)
31	10	1	Pipe	200	18	100
21	2	1	Pipe	1100	18	100

Table A.4. Junction Data for Realistic Water Model

Node	Type	Elevation (ft.)	Base Demand (GPM)
J-1	Junction	710	0
J-2	Junction	710	150
J-3	Junction	700	150
J-4	Junction	695	100
J-5	Junction	1000	100
J-6	Junction	700	150
J-7	Junction	695	200
J-8	Junction	700	100
J-9	Junction	710	100
J-10	Junction	710	100
J-11	Junction	1000	50
S-1	Reservoir	800	0
T-1	Tank	850	0

Table A.5. Link Data for Realistic Water Model

Link	Start	End	Type	Length (ft.)	Diameter (in.)	Roughness (HW)
P-1	J-1	J-2	Pipe	10530	18	100
P-2	J-2	J-3	Pipe	5280	14	100
P-3	T-1	J-3	Pipe	200	18	100
P-4	J-3	J-4	Pipe	5280	10	100
P-5	J-2	J-6	Pipe	5280	10	100
P-6	J-3	J-7	Pipe	5280	12	100
P-7	J-6	J-7	Pipe	5280	10	100
P-8	J-6	J-8	Pipe	5280	8	100
P-9	J-7	J-9	Pipe	5280	6	100
P-10	J-8	J-9	Pipe	5280	6	100
P-11	J-9	J-10	Pipe	5280	12	100
PUMP-1	S-1	J-1	Pump	0	0	0
PUMP-2	J-4	J-5	Pump	0	0	0
PUMP-3	J-10	J-11	Pump	0	0	0

A.2 Power Model Data

Table A.6. Hourly Demand Multipliers for Basic Test Circuit

Hour	Demand Multiplier
0.00	1.00
1.00	1.00
2.00	1.00
3.00	1.00
4.00	1.04
5.00	1.10
6.00	1.31
7.00	1.52
8.00	1.87
9.00	2.64
10.00	2.97
11.00	2.96
12.00	2.90
13.00	2.92
14.00	2.91
15.00	2.70
16.00	2.50
17.00	1.67
18.00	1.52
19.00	1.24
20.00	1.17
21.00	1.12
22.00	1.03
23.00	1.00

Table A.7. Hourly Demand Multipliers for Realistic Power Model

Hour	Demand Multiplier
0.00	1.50
1.00	1.50
2.00	1.50
3.00	1.50
4.00	1.57
5.00	1.65
6.00	1.97
7.00	2.28
8.00	2.80
9.00	3.97
10.00	4.45
11.00	4.43
12.00	4.35
13.00	4.38
14.00	4.37
15.00	4.05
16.00	3.75
17.00	2.50
18.00	2.28
19.00	1.87
20.00	1.75
21.00	1.68
22.00	1.55
23.00	1.50

Table A.8. Edge List for Realistic Power Model

Edge	Start	End
XFR-1	SUB-1	B-1
XFR-2	B-5	B-6
L-1	B-1	B-2
L-2	B-2	B-3
L-3	B-3	B-4
L-4	B-2	B-5
L-5-1	B-2	DL-1
L-5-2	DL-1	B-9
L-6	B-8	B-7
L-7	B-9	B-10
L-8	B-9	B-11
L-9	B-11	B-13
L-10	B-11	B-12
SWT-1	B-9	B-8

A.3 Interdependent Model Data

Table A.9. Interdependency List for Toy Interdependent Model

Type	Power	Water
Physical	bus (2)	pump (3)
Geographic	bus (4)	junction (1)

Table A.10. Interdependency List for Realistic Interdependent Model

Type	Power	Water
Physical	B-7	PUMP-1
Physical	B-9	PUMP-2
Physical	B-6	PUMP-3
Geographic	B-3	J-8
Geographic	B-4	J-9
Geographic	B-6	J-11
Geographic	DL-1	J-6
Geographic	B-7	J-2
Geographic	B-8	J-3
Geographic	B-9	J-7
Geographic	B-13	J-5

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