CRITICAL NODE ANALYSIS FOR WATER DISTRIBUTION SYSTEMS USING FLOW DISTRIBUTION

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ABSTRACT

Critical Node Analysis for Water Distribution Systems using Flow Distribution

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The expansive nature of water distribution system makes them susceptible to threats such as natural disasters and man-made destructions. Vulnerability assessment research efforts have increased since the passing of “Bioterrorism Preparedness and Response Act” in 2002 to harden WDS. This study aimed to develop a method that locates critical nodes without hydraulic analysis of every failure scenario, applicable for any size WDS, incorporates critical infrastructure, and capable of verifying method accuracy. The Flow Distribution method is the application of the gravity model, typically used to predict traffic flows in transportation engineering, to a distribution system. Flow distribution predicts the amount of demand and population that would be affected if any node in the system were disabled by solving for the distribution of each node’s outflow. Flow Distribution is applied to the hypothetical city, Anytown, USA using the computer simulation program WaterCAD to model two different disaster scenarios. Results were verified by analyzing sixteen failure scenarios (one for each node) to measure the actual demand and population effect, which was then compared to the nodes predicted by Flow Distribution. Flow Distribution predicted the critical nodes with 70% accuracy and can still be improved with future work.

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CHAPTER 1: INTRODUCTION

The United States' economy and human development are powered by receiving water through distribution systems, which was identified by the President's Commission on Critical Infrastructure as one of the eight key infrastructures (Qiao et al. 2005). Water distribution systems (WDS) are crucial to our society because they deliver clean water from storage facilities to consumers through a complex and extensive pipe network. Distribution systems consist of a water supply source, treatment facility, and a pipe network. The extensive manner of distribution systems makes them susceptible to physical disruption and chemical/ biological contamination threats caused by natural disasters and terrorism.

Natural disasters such as earthquakes and hurricanes can compromise several WDS components. The 8.8 magnitude earthquake in Chile on February 27th, 2010 caused several pipe main and lateral breaks preventing the system from operating leaving many people without water for several days (Tank et al., 2010). The power, transportation, and telecommunication systems also suffered damages, but their effects were 'overshadowed' by the direct seismic damage on the water distribution system. (Tank et al., 2010)

Chemical and biological contamination through purposeful or accidental means can expose consumers knowingly or unknowingly to pathogens and contaminants that cause diseases and death. In 1984, a water supply tank in Dalles, Oregon was poisoned by a religious cult resulting in 751 cases of Salmonellosis (Clark & Deininger, 2000). Lack of water quality monitoring throughout distribution systems allows toxins to be undetected for extended periods. The extensive pipe network creates numerous target access points for contaminants to penetrate the system. Although a major contamination has not occurred in the United States, the threat, accessibility to contaminant insertion points and the consequences of such an event make chemical contamination a considerable risk.

Despite importance of WDS and consequence severity, it is not practical or feasible to safeguard our distribution systems against all possible disruption and chemical/ biological contamination threats. It is important to efficiently utilize available resources to protect the weakest links and/ or high-risk areas. Vulnerability assessments are a critical component in the preparation and evaluation of emergency management plan for protection of WDS. Vulnerability, for this study, refers to system deficiencies that enable adverse events or attacks to cause system failure. A system failure occurs when not all of the consumer demands are met. Vulnerability assessments are performed to evaluate potential threats, identify consequences, and develop countermeasures aimed at hardening (reducing vulnerability) the water distribution system. These assessments are used to target high-risk areas so resources can be focused to combat possible worst cases of adverse consequences. In the past, vulnerability assessments performed primarily focused on minimal damage and low cost threats such as vandalism or disgruntled employees (EPA, 2003).

After September 11, 2001, people recognized the threat of terrorist attacks and began investigating strategies to protect distribution systems against both terrorist attacks and natural disasters. One of the first measures enacted to help secure distribution systems was the passage of “The Public Health Security and Bioterrorism Preparedness and Response Act” in 2002. This law requires cities to perform a vulnerability assessment on their distribution system against a terrorist attack or intentional action.

Safeguarding our WDS has since become a priority and an abundant of research has resulted in the creation of several methods that satisfy partial or all of the vulnerability assessment components defined by the Environmental Protection Agency (EPA). Research found three main types of methods that could be used for a vulnerability assessment: (i) analytical/ optimization methods that solved for variables deemed important to WDS characterization, (ii) heuristic methods that subjectively ranked distribution components resulting in system classification, and (iii) simulation based methods which uses hydraulic analysis as a main

catalyst to measure system vulnerability. Several of these research methods are discussed in the Literature Review section.

This study attempts to develop and presents a new method that can be applied to a vulnerability assessment with four main objectives. The first objective was to develop method that accurately identified critical nodes and/or pipes in a distribution system without performing hydraulic analysis on every possible failure scenario. For large distribution systems it would be incredibly time consuming and impractical to analyze every possible failure scenario. Critical nodes/pipes were defined as the nodes or pipes that if disabled would cause the greatest or worst system failure resulting in the most consumers to not be served or largest demand not be supplied. Secondly, the presented method was developed to be capable of incorporating critical infrastructure in the determination of critical nodes/ pipes. Hospitals, schools, and community centers are some examples of critical infrastructures that are imperative for protection, shelter, and support for a community during natural or man-made disasters. It was also desired to create a flexible and simple method that could be used by non-experts, city officials, and practicing engineers with different types of computer simulation programs and can be applied to any size WDS. The last objective was to create a program that allowed the results to be verified to check the accuracy and applicability of the developed method.

Current study applies the gravity model, typically used in the field of transportation engineering for trip distribution modeling, to water distribution systems. The gravity model is used to predict the distribution of trip destinations originating from one location to the remaining locations in a given area. When the gravity model is applied to distribution systems, it provides Flow Distribution. Flow Distribution, can calculate the outflow that any node or pipe will supply to the remaining the nodes/ pipes in the system. The information necessary to apply Flow Distribution includes pipe and node variables and parameters obtained from hydraulic analysis. The results derived from Flow Distribution can be used to predict the population and demand affected by each node if it were to be disabled, which quantifies the importance of each node or

pipe within a system. These results can help direct available resources to the critical nodes and pipes to harden the system.

A hypothetical system, Anytown, USA, was used to apply Flow Distribution and determine its accuracy because of its resemblance to a real system and its wide use in other literature such as Walski et al. (1987) and Chastain (2006). The goal for Flow Distribution was to predict correctly the critical nodes that prevented most demand from being supplied and prevented the most population from receiving water for two different disaster scenarios. The two disaster scenarios, one featuring a disabled node and a fire flow and the other featuring a disabled node, fire flow, and non-operational pumps, were modeled in WaterCAD V8i. These hydraulic analyses were performed during normal operating conditions and the results were imported into Matlab where the Flow Distribution calculation was performed. The results were then imported into Excel for documentation and the top five critical nodes were identified. Flow Distribution was verified by analyzing the demand and population effects when each node was disabled in a failure scenario and comparing them to the effects predicted by Flow Distribution. Sixteen failure scenarios (one for each node) were created and analyzed in WaterCAD. If the critical nodes Flow Distribution predicted matched the actual critical nodes found by analyzing the sixteen failure scenarios, then the method was deemed valid.

In this thesis, Chapter 2 (Background and Literature Review) contains background information about water distribution systems, vulnerability assessments, current laws, and the literature review on previous relevant research. Chapter 3, Methodology, presents the development of the Flow Distribution method, as well as, the hydraulic theory, and the modeling considerations used to evaluate the new method. Chapter 4, Results & Discussion, presents and interprets the results from evaluation of the Flow Distribution method. Chapter 5, Conclusion, includes implications of the results, recommendations for method improvement, and possible future works.

CHAPTER 2: BACKGROUND AND LITERATURE REVIEW

2.1. Water Distribution Systems

Water distribution systems serve the community and help power the economy by delivering water from source(s) to its consumers. WDS are comprised of three primary components; water source, treatment, and distribution network. Water sources can be reservoirs, rivers, and groundwater wells. Water treatment facilities disinfect the water to drinking water quality standards prior to delivering it to its consumers. The distribution network is responsible for delivering water from the source or treatment facilities to its consumers at serviceable pressures and mainly consists of pipes, pumps, junctions (nodes), valves, fittings, and storage tanks.

WDS are required to supply water to domestic, commercial, and industrial entities above or at a threshold pressure with consumer demands that vary throughout the day, week, season and year. The minimum pressure that should be observed at junctions throughout the system varies depending on the type of water consuming sector and regulations governing the distribution system, but a typical operating range is between 40–100 psi (AWWA, 2005). It is undesirable to have high pressures because it causes more leaks, breaks and causes water wastage.

The design of WDS including how the system supplies water to its consumers and the schematic layout is critical to their performance. WDS can be designed to supply to its consumers through gravity flow, using mechanical pumping, or both. Gravity flow can be used when there is an elevated water source (river or lake) with enough head to meet consumer demands. Gravity flow is rarely used to meet all demands in urban WDS because of the lack of practicality and flexibility. Gravity flow is more common in rural areas that lack pumping capability. A system could use pumps to supply to its consumers, but solely using pumps is problematic because it requires pumps to fluctuate constantly to satisfy the vastly varying consumer demands. Due to varying water demand patterns, most urban distribution systems utilize pumps with elevated

storage tanks. These tanks help meet fluctuating consumer demands, accommodate fire flow during emergency conditions, and stabilize operating pressures. Typically, tanks are used during peak hours of the day and refilled during low demand times. Systems can also be designed to have loop or branch schematics. A branched network (Figure 1) includes several independent links with many terminals that prevents circulation of water throughout the entire system and water is supplied to end users through one pipe. One problem with a branched network is if one pipe is disabled even for routine maintenance, some consumer demands will not be met. A looped network (Figure 2) is one that has multiple pipes at every single node so that water can be supplied to any point through more than one pipe. The problem with a looped network is the additional cost of constructing and maintaining redundant pipes. Most networks are a combination of these two of schematic layouts.

Figure 1: Branched Network

Figure 2: Looped Network

2.2. Threat, Risk, and Vulnerability

It is important to distinguish between the terms threat, vulnerability, and risk. A **threat** is the indication that an attack or event causing a system disruption such as broken pipes, failed nodes, and poor water quality may occur. Examples of threats to a WDS would be natural disasters, chemical contamination, and terrorist attacks.

Risk is a measure of the system's exposure to given threats or the likelihood an event or attack is successful. If all the pipes are underground and hard to access the likelihood for a terrorist to contaminate the distribution system is lower than if many spots such as storage tanks were easily accessible.

Vulnerability, for WDS, refers to system deficiencies that enable the adverse event or attack to be successful. An example of a vulnerable system would be a branched network because if one link is disrupted, the rest of the system downstream will be affected. The threats, risks, and vulnerabilities are unique for each system. Haimes et al. (1998) identified seven key elements of WDS; (i) the physical components, (ii) management structure, (iii) operating rules and procedures, (iv) institutional structure, (v) control centers, (vi) laboratories, and (vii) maintenance and storage facilities. These seven components need to be properly protected against system specific threats, and the need of protection is identified through the evaluation of current vulnerabilities.

A system can be hardened by increasing a system's security, redundancy, reliability, and resilience. **Security** includes all efforts to prevent entry into the system such as fences, guards, and video surveillance. Hardening a WDS with just security would be difficult and inefficient because it requires an exuberant and impractical amount of work force and money to maintain the high alert necessary to prevent rare and unique events. **Redundancy** is the ability of the system to function with failed components without adverse system performance. Redundancy is any action of duplication including extra pipes, an additional gate to release water from a reservoir, or an extra pump. These duplications may not be necessary for the system to run during ideal conditions, but are crucial during any planned or unplanned disruption in the system from route maintenance to a simple pipe break to a significant system shutdown. All looped networks contain some amount of redundancy. Another approach to hardening a distribution system is increasing its **resilience**. A resilient system, after a performance disruption, would be restored to normal operating conditions swiftly due to quick recovery time. A disruption is certain to happen eventually, and a resilient system would ensure minimal outage time. Resilience is influenced more by the standards and operations of the distribution facility rather than the layout of the system. The **reliability** (robustness) refers to the system's degree of sensitivity. A very reliable system would be able to withstand some natural disasters and intentional attacks without adverse

effects being observed by consumers. A number of studies have focused on quantifying system reliability.

2.3. Vulnerability Assessments

Vulnerability assessments evaluate system deficiencies so available resources can be effectively utilized to protect against system threats. The EPA identified several key components to vulnerability assessments. First, the possible negative events and their adverse consequences need to be identified and prioritized. Then critical assets such as schools, hospitals, and community centers that might be at risk during these events must be determined. Next, the likelihood of such events from occurring must be measured. Then the existing counter measures for these events should be evaluated. Lastly, with all the information collected, the current risks should be analyzed and from that, a prioritized plan for risk reduction can be developed (EPA, 2002).

Although every vulnerability assessment aims to evaluate system deficiencies, there are several different approaches and methodologies. One approach to assessing vulnerability is with a heuristic/ranking approach. Typically, this approach identifies criteria deemed critical to system operation, and then ranks every pertinent system component for each criterion. The ranking scores are then combined in some fashion to result in a list of the most vulnerable components in the distribution system. The main concerns with this approach are the ranking is subjective so the results vary depending on the person conducting the assessment, the inability to verify the results, and evaluation from someone who has working knowledge of the system. Another approach is to use numerical formulas to quantify a system's vulnerability. These methods typically use hydraulic data and complicated equations to solve for variables deemed crucial to network evaluation. These variables are typically used to quantify reliability, redundancy, resilience, or vulnerability. One problem with this approach is the complicated equations may not be utilized or interrupted properly by a non-experts or city officials. The simulation approach could also be

used, which evaluates system performance under user-defined disaster scenarios. These disaster scenarios are modeled in a computer simulation program by skilled personnel and hydraulic performance is compared to normal operating conditions. Negatives to this approach are the results are typically valid only for the scenario modeled and subjective judgment from the modeler is required to create the disaster scenarios.

2.4. Legislation

Since the 1970's, laws have been passed mandating assessment and protection of water systems. One of the first was the 'Safe Drinking Water Act' (SDWA) passed in 1974, which mandated rural areas, cities, and large municipalities to assess water source contamination. Water communities were required to identify possible contamination origins and the systems vulnerability to contamination threats (Staudinger, et. al., 2006). In 1986, 'Critical Infrastructure Protection' executive order was passed addressing the implications that disruptions or incapacitations of the national infrastructure would have on the economy and security. The 'President's Commission on Critical Infrastructure' and water system operators were to evaluate system vulnerabilities to propose regulatory changes (Staudinger, et. al., 2006).

Although legislation has been implemented since the 1970's, most vulnerability studies focused on routine breaks, or threats of vandalism, and disgruntled employees rather than more costly threats like natural disasters and chemical/ biological contamination (EPA, 2003). Following the attacks on September 11, the EPA passed "The Public Health Security and Bioterrorism Preparedness and Response Act" in 2002. This law requires water communities (municipalities, cities, towns) serving over 3,300 customers to perform a vulnerability assessment on their distribution system against a terrorist attack or intentional action. The law demanded cities to, at least, evaluate the vulnerability of pipes, treatment and storage facilities, physical barriers, computer systems, use and handling of chemicals, system operation, and maintenance (EPA, 2002). Since methodology was not specified or required to perform the vulnerability

assessment and satisfy the law, the passage of this law led to an abundance of research on different approaches and methods for vulnerability assessments of WDS.

2.5. Literature Review

This section discusses different methods focusing on varying aspects of WDS vulnerability. Although each method is different, they each address vulnerability of one of the seven elements of WDS identified by Haimes, et al. (1998) and/ or measure a system's vulnerability based on reliability, resilience, and redundancy.

Jacobs and Goulter (1991) assessed reliability of WDS without the evaluation of all possible mechanical pipe failures. Traditional reliability methods used procedures that solved for reachability and cut sets, and are not practical for large urban networks. Jacobs and Goulter (1991) solved for the probability of a given number of pipes failing simultaneously using empirical data as basis for their estimations. Next, the probability that the removal of a given number of pipes would fail the system was solved using simulation of failure scenarios. It was assumed that every pipe had an equal failure probability and that failures were distributed uniformly over the system. This method provided means for assessing distribution reliability, but failed to incorporate reliability to natural disasters and terrorist attacks.

Jowitt & Chengchao (1993) developed a prediction method to identify the most influential pipe elements without performing hydraulic analysis for every possible failure scenario. Microflow Distribution was instituted to solve for the flow that each pipe, water source, or node supplied to each node in the system. Microflow Distribution required the use of the flow rates for each pipe, the node demands, and the inflow at each node. In addition, it was assumed that the inflows at each node were completely mixed meaning the flow to meet the demand of a supply node was a percentage of each connected pipe's flow. This analysis was performed on a simple network and the critical pipes were identified. The accuracy of the method was tested by hydraulically analyzing failure scenarios featuring one of the pipes in the system disabled to

compare the actual results with the Microflow Distribution prediction. The use of Microflow Distribution correctly predicted the critical nodes with 60% accuracy. The accuracy could have been improved by calibrating the pressure dependent demand equation that was used. This method provides a basic approach for identifying critical failure scenarios without analyzing every possible failure scenario.

Ezell, Farr, & Wiese (2000) developed a four-pharse process called the Infrastructure Risk Assessment Model (IRAM) to evaluate water distribution vulnerability. First, the risks are identified by dividing the distribution system components into categories; hierarchical structure, function, state, and vulnerability. The vulnerabilities are then subjectively ranked based on the components of exposure and accessibility. Next, scenarios are created to serve as initiating events in event trees or ‘what if’ risk models. A risk model helps to determine the sequences that lead to adverse consequences and are used to produce probability density functions. The risks are assessed using the Partitioned Multiobjective Risk Method (PMRM) to generate expected values of damages, losses, and consequences. IRAM concludes with generating alternatives to improve system performance. The decision maker involved in the execution of IRAM can then evaluate the risks and alternatives to decide the actions that are necessary to deem the system safe. Although IRAM provides a systematic approach to solve for the vulnerability of distribution systems, it requires an abundance of subjective user input about disaster scenarios and consequences that may be impossible to predict and may vary from person to person.

Bahadur et al. (2003) developed a ranking method to optimize chemical sensors locations in a distribution system using PipelineNet and Geographic Information System (GIS). Optimal locations for monitoring equipment were found by implementing scoring matrices for node variables, population density, and proximity to critical infrastructure (hospitals and schools). The node variables matrix considered flow, velocity, and pressure. Each component of the scoring matrix is ranked from one to ten. PipelineNet provides guidance in assigning scores, but also allows users to input values as necessary. The allocation of the score is determined by the user

using Natural Breaks, Equal Interval, or Quantile, and all three were used in this model. The nodes with the highest scores were deemed suitable candidates for chemical sensor equipment locations. This method was applied to a hypothetical system with several parameters being approximated and the ninth hour of a 24 hour extended period simulation time was used for the analysis. This method demonstrates that population and critical infrastructure can be implemented in the criteria for suitable monitoring locations. This research did not provide any information on the accuracy of the strategy used.

Kalungi and Tanyimboh (2003) describe the importance of using both redundancy and reliability to measure a system's performance. The reliability of a system is assessed using Critical Head Driven Simulation Method rather than a demand driven analysis during normal conditions. A demand driven analysis assumes nodal demands will be provided regardless of the pressure in the system. The head driven analysis used defines every node as either no-flow, partial flow (pressures between $H_{\min}$ & H_{res} , H_{res} can be set to a desirable pressure below which flow cannot be fully satisfied with typical values being about 14-15m), fully satisfied flow, and key partial-flow nodes (nodes that affect outflows of other nodes). The redundancy calculation is based on the performance of the system with any given pipe, valve, pump or tank disabled. The main problem with this assessment is the redundancy equation requires a separate calculation for each network disturbance being analyzed. This would be entirely impractical for majority of WDS to solve for all possible combination of disabled network components.

Little (2004) describes a holistic strategy that identifies and quantifies the amount of risk in any urban infrastructure. First step is to identify the possible risks. Risk is defined as the 'probability of an adverse event multiplied by the consequences of that event'. To help identify risks one can ask What can go wrong? What is the likelihood it would go wrong? and What are the consequences if it did go wrong?. A decision matrix can be used to identify which risks are unacceptable and require countermeasures. For this assessment the decision matrix ranks the likelihood and the consequences to identify which risks need attention. This research aimed to

identify a process and concepts that should be implemented to harden all infrastructure systems. There is not scientific proof behind this heuristic approach, but this could still be effective if it were used by knowledgeable and experienced decision makers.

Lippai and Wright (2005) performed a criticality analysis on a water distribution system. Analysis was first performed under normal operating conditions to record the demand, head, pressure at each node. Failure scenarios, which consisted of one pipe closure, were then analyzed. The pressure percent difference between normal and failure conditions was then multiplied by the demand at each node to find the penalty at the demand junction due to a failed component. Failure scenarios were run for eighty percent of the pipes and their pipe penalties were summed and the pipes with the highest number were deemed to be the most critical. The main problem with this method is it requires hydraulic analysis of every failure scenario, which would be impractical for large urban distribution systems.

Qiao et al. (2005) presented a quantitative approach to optimize security resources for WDS using a cost-based approach. The cost of a proposed attack and the consequences of the attack were estimated. Components in a distribution system were deemed resilient if economic consequences were small in comparison to the attack cost. The attack consequences were estimated using Pressure-Based Heuristic, which consists of disabling the node with the lowest pressure until all the nodes are above the threshold pressure. The basis of the method consisted of solving main four equations. The solution provides the minimum resilience across all network subsets, constraint for minimum resilience, constraint for budget limit for security investment and solves for the attack cost. A Genetic Algorithm was used to generate new constraints, which were then evaluated in a hydraulic simulator, and if the constraints were violated then the process was repeated. The Genetic Algorithm results can help decide the allocation of security funds to create a more resilient system.

Chastain (2006) developed a method to optimize sensor monitoring station locations to minimize contaminant exposure to consumers. This procedure was modeled in WaterCAD using

a generic town called Anytown, USA (Walski et al., 1987), which has been used to test several other methods. First step created a contamination scenario based on design basis threat by identifying the contaminant and its properties, mass of the contaminant, duration of injection, and when the contaminant was exposed to the system. Next, simulations were run in WaterCAD with point source injections at every junction. The nodes that detected a contaminant concentration greater than the threshold were recorded in an evaluation matrix. The concentration threshold was predetermined based on the pollutant simulated and limits of available detection technology. The evaluation matrix identifies how many nodes detect a concentration greater than the threshold for each time step. A ranking algorithm was used to identify nodes that minimized time of detection and limit the exposure to customers. This research provides a method that seems feasible for cities and communities to adopt easily, but the population density and critical infrastructure should be considered when seeking optimum sensor locations.

Jun et al. (2006) developed an algorithm that calculates the impact of pipe failures and valve placements throughout water distribution systems to improve their serviceability and reliability. The impact of each pipe failure (considered to be a pipe or valve failure) has on the system is calculated by considering the number of pipes that need to be disabled to isolate the broken pipe. The more pipes that need to be shut down to isolate the disabled pipe, the more consumers must be without water. The algorithm also takes into account critical infrastructure (hospital, school, community centers, etc.) that are affected by a pipe break by assigning each critical facility an equivalent number of customers (i.e. one school could equal one thousand households). This study mainly considered routine pipe break down and not disaster scenarios that could result in multiple pipes being disabled at one time, but could easily be used as part of a vulnerability assessment.

Wang & Au (2008) quantify the reliability of WDS for various consumers after a seismic event and identifies critical pipes in the system. Reliability of a system to supply to consumers was emphasized to vary spatially and was dependent upon system configuration. Critical pipes

were defined as ones that significantly affected the water supply to critical infrastructure. Critical links were found by using two probability equations, Damage Consequence Index (DCI) and Upgrade Benefit Index (UBI). The DCI reflects the consequence from damaging a pipe and UBI is a measure of a pipes impact on certain consumers. These two equations were implemented to simulate a hypothetical system. Monte Carlo simulations were used with GIRAFFE (Graphical Iterative Response Analysis of Flow Following Earthquakes) and MatLab to evaluate the seismic performance of the hypothetical system. A cost-benefit analysis was conducted with the use of the “efficient frontier”, which diagrams the most efficient and effective upgrade option. This method would only be useful if the effects of seismic activity on WDS, specifically on the critical infrastructure, were the primary concern.

The EPA released the ‘Threat Ensemble Vulnerability Assessment and Sensor Placement Optimization Tool’ (TEVA-SPOT) developed by Sandia University, which optimizes sensor locations for large distribution systems to protect against chemical contamination (Berry et al., 2009). TEVA-SPOT offers a range of modeling inputs making it flexible and adaptable to different systems and modeling objectives. The modeling process includes inputting sensor characteristics, defining the design basis threat, selecting the impact measures for the contaminant warning system, planning utility response to detection, identifying practical sensor locations, and evaluating sensor locations. TEVA-SPOT uses Monte Carlo simulations to help create disaster scenarios seamlessly by quickly solving trial and error calculations. TEVA-SPOT is a powerful and effective program that can optimize chemical sensors, but does not consider physical disruptions in its assessment.

Nazif and Karamouz (2009) calculated the reliability, resiliency, and vulnerability using the System Readiness Index (SRI) to evaluate WDS readiness to one or more water main breaks. The index is based upon calculating the reliability, resiliency, and vulnerability using probability and system failure data. The critical nodes (nodes with high demand and/or pressure variations) were then selected. The nodes with water demands in the twentieth percentile and nodes with the

highest head loss were deemed the critical nodes. The critical nodes were revised during the simulation if the hydraulic state remained unchanged. Failure scenarios were generated and using Probabilistic Neural Network (PNN) structure the SRI was calculated. The result of the SRI calculation was a class rate score ranging from one to five, and these classes corresponded to a probability of failure. The results between normal and disaster situation were compared using the demand pressure relationship (Pressure Dependent Demands) at critical nodes.

Baoyu, Xinhua, and Yuan (2009), presented the Vulnerability Assessment Model for Regional Water Distribution System (VAMRWDS) to identify sub-region and entire distribution system vulnerability to chemical contamination. The method uses the theory of Monte-Carlo stochastic simulation to generate random values for variables with uncertainty such as bulk and wall reaction coefficients. Once the necessary information is gathered such as demand patterns, chlorine concentrations, and bulk and wall reaction coefficients the data is analyzed in EPANET2. After the simulation, four variables that quantify hydraulic and water quality aspects of WDS are calculated. These factors are junction flow weight, supply level weigh, residual chlorine weights, and water age weight. These factors are used to calculate the vulnerability index for each node on the sum of weighted coefficients that are predefined for each WDS. The value of the vulnerability index indicates the system's risk level.

The literature review shows the variability of approaches and the methodologies previously developed. Examples of simulation, analytical/optimization, and ranking approaches were discussed in Kalungi and Tanyimboh (2003), Jowitt & Chengchao (1993), and Ezell, Farr, & Wiese (2000) (as well as others) research. As previously mentioned, vulnerability assessments should include evaluation of all the present risks and threats, as well include all the components stated by the EPA, but only a few methods were all an inclusive vulnerability assessment and focused on one component of system vulnerability and/ or considered only one threat (i.e. chemical contamination).

Despite the abundance of developed methods, the gravity model, which is typically used in the field of transportation engineering to predict the flow of traffic from one zone to another, has not been applied to water distribution system to determine critical nodes or pipes. The main objectives of this current research are to develop a method to locate critical nodes or pipes without analyzing every failure scenario, incorporate critical infrastructure, be adaptable to other systems, and be able to verify the accuracy. It was initially hypothesized that the gravity model due to its accuracy, acceptance in the transportation engineering community, and flexibility would allow these objectives to be met. The following chapter, Methodology, presents the development and application of the method in detail.

CHAPTER 3: METHODOLOGY

Present study aimed at developing a method that would identify critical nodes in a water distribution system. An integral part of identifying critical nodes is determining how the outflow of each node is distributed to the rest of the system. The distribution of outflow for each node can be used to predict how much demand or population will be affected if any node were to be disabled. This study believed that the gravity model, which is typically used in the field of transportation engineering for trip distribution, could be modified and applied to a WDS. This section presents the theory, development, and execution of the method, as well as, the fundamentals of WDS hydraulics and the process developed and programs used to apply and verify the model.

3.1. Flow Distribution

The basis of the gravity model is Newton's Law of Gravitation (Eq. 1), which states that every mass in the universe attracts every other mass with a force that is proportional to the product of the masses and inversely proportional to the distance squared between the masses. This equation is part of classical mechanics and was published in July 5th 1687 in 'Netwon's Philsohiaie Natrualis Prinipia Mathematica' (Transportation, 1983). Then late in the 19th century theories by H.C. Carey and work by E.G. Ravestein and E.C. Young showed that gravitational function applies to human migration (Transportation, 1983). One of the first applications of the gravity model with human interaction was done by W.J. Reilly in the field of retail trade (Reilly, 1953). It was not until the 1920's when Swedish Investigator Pallin used the gravity model to determine traffic flows and used a distance exponent of two to solve for trip distribution (Transportation, 1983). Then a short time later, Alan Voorhees adapted the concepts of Netwon's equation and applied them to predict traffic patterns based on land used in "A General Theory of Traffic Movement" (Voorhees, 1955).

$$F = G \frac{m_1 m_2}{r^2} \quad (\text{Eq. 1})$$

F = Force (pull) between the masses

G = Gravitational constant

m_1 = Mass of object one

m_2 = Mass of object two

As stated previously, the objective of the gravity model is to solve for the number of trips that will travel between two zones. To solve for the number of cars that will travel from their origin to other zones, the number of trips that each zone attracts, the number of trip produced by the origin, the impedance (friction) factor, and sometimes a socioeconomic factor must be known. The impedance factor is typically a function of the travel time, which is most commonly used, or cost associated between the two zones. The socioeconomic factor includes the economic and social factors that influence the movement of people. The gravity model equation (Eq. 2) is shown below.

$$T_{ij} = P_i * \frac{A_j F_{ij} k_{ij}}{\sum_{i=n} (A_j F_{ij} k_{ij})} \quad (\text{Eq. 2})$$

T_{ij} = Number of trips from zone i to zone j

P_i = Number of trip productions generated from zone i

A_j = Number of trips attracted by zone j

F_{ij} = Friction Factor from zone i to zone j

k_{ij} = Socioeconomic factor from zone i to zone j

Travel time represents the spatial separation between the zones. The farther away something is the less likely or less attracted someone is to travel there. Multiple routes can be used to arrive at the same destination and the path that results in the least amount of time is the path used for the travel time calculation. The friction factor can be calculated several ways and usually a trial and error process is performed. The general formula that is typically used is provided (Eq. 3). The value of α is usually around two but varies depending on the purpose of the

trip. All gravity models require calibration to ensure that the theoretical relationships match existing conditions. One limitation of the gravity model is it cannot be confirmed scientifically and is an observation-based model.

$$F_{ij} = C_{ij}^{-\alpha} \quad (\text{Eq. 3})$$

C_{ij} = Time travel from zone i to zone j

α = calibration factor (usually around 2)

The application of the gravity model to water distribution system was believed to be feasible and reasonable for several reasons. The first being the primary objective of the gravity model applied to transportation systems matches the goal of solving for the distribution of node outflow. Instead of solving for the distribution of traffic outflow to every destination, gravity model applied to a distribution system would solve for the distribution of outflow at every node. Although the water distribution systems lack the human interaction that the gravity model replicates, the principals of the theory should still apply. The outflow of a node is more likely to supply to a node with close proximity and relatively low resistance factor, than a node across the entire system with a relatively high resistance factor. Despite not being able to confirm the gravity model mathematically, its flexibility and applicability make it the most commonly used trip distribution method. The gravity model has also already been applied to several other fields including economics and marketing.

To apply the gravity model to a water distribution application, the variables required adjustment. Instead of solving for the number cars moving from one region to another, *trip distribution*, the goal was to solve for the flow ‘supplied’ by one junction (demand node) to another, coined **Flow Distribution**. ‘Supplied’ in this context means the water is a junction’s outflow. The number of trip productions from a zone was substituted by the outflow of the node. Demand replaced the number of trips attracted by a zone. The friction factor from one zone to another was modeled by taking the path of least resistance, and is explained in detail in the subsequent paragraph. The socioeconomic factor was not used in this study’s application of Flow

Distribution, but could be utilized to implement critical infrastructure. The modified gravity model or Flow Distribution equation is shown in Eq. 4.

$$F_{ij} = O_i * \frac{D_j I_{ij}}{\sum (D_j I_{ij})} \quad (\text{Eq. 4})$$

F_{ij} = Flow supplied from junction i to junction j

O_i = Outflow at junction i

D_j = Demand at junction j

I_{ij} = Impedance from junction i to junction j

The impedance variable is a function of the pipe resistance factor and was calculated with the equation shown below (Eq. 5). Resistance factor refers to the pipe characteristics that contribute to friction loss. Three methods can be used to calculate friction loss: Hazen-Williams equation, Manning's equation, and Darcy-Weisbach equation. Hazen-Williams (Eq. 6) was used because, as will be discussed shortly, the hypothetical city used to test the gravity model had the C-factor coefficients available for the pipes. If another method were to be used, information on the Darcy's friction factor or Manning's roughness coefficient would have been necessary. The minimum sum of resistance factors from one node to another is used, which assumes that all the flow that one node provides to another is supplied through the route of minimum resistance. As stated previously, α is typically found through calibration, but for this study, it was assumed a value of two.

$$I_{ij} = \frac{1}{\min \sum R_{ij}^\alpha} \quad (\text{Eq. 5})$$

R = Pipe resistance for each pipe

α = Calibration factor (assumed to be 2)

$$R = \left[\frac{\phi L}{C^{1.85} D^{4.87}} \right] \quad (\text{Eq. 6})$$

ϕ = 4.73 for U.S. Units & 10.66 for SI units

D = Diameter of pipe (ft or m)

C = Hazen-Williams roughness coefficient

L = Length (ft or m)

3.1.1. Calibration

Calibrating the gravity model consists of identifying the trip types occurring for each zone. Then for each type of trip, a different calibration factor is used. A crucial part of gravity model calibration is properly identifying and linking trips to the correct trip type so the proper calibration factor is used. The calibration factors are solved using an iterative approach by adjusting the calibration factor until the model data closely resembles observed data.

This study hypothesized that the results yielded from Flow Distribution using the standard α factor of two would produce results accurate enough to determine if Flow Distribution is suitable to determine critical nodes in a distribution system. The calibration of α would correlate the node outflows that Flow Distribution predicts to the modeled or actual node outflows. Calibrating Flow Distribution would be difficult because of the dynamic variables that constantly change throughout the 24-hour simulation and was believed to be outside the scope of this research. Several methods and approaches could be utilized for calibration when using Flow Distribution and recommended for future research.

3.1.2. Demand and Population Affected

Applying Flow Distribution calculates the amount of flow that each node supplies to every other node. A simple equation (Eq. 7) was applied to predict the amount of demand and population affected if a node were disabled. The amount of flow that node 'i' supplies to node 'j' is divided by the inflow of node 'j' and then multiplied by the population or demand at node 'j'.

$$DemAff_{ij} = \frac{F_{ij}}{I_j} * D_j \quad (\text{Eq. 7})$$

DemAff_{ij} = Predicted demand affected by node i on node j

F_{ij} = Flow distributed from node i to node j

I_j = Inflow at node j

D_j = Demand at node j

If the population affected were desired, the equation would be multiplied by the population at node j instead of the demand at node j .

This research is aware of the simplicity of the equation and that it assumes that if a node were to be disabled then all the water that previously passed through it would not reach any of the nodes in the distribution system. In practice, it is possible for a WDS with an average degree of redundancy and pressure to redirect the water to meet the demands of the system. This equation was not expected to solve for the actual demand or population affected, but to determine the nodes that would have the most impact. This study assumes that nodes that supplied the most demand and/ or served the most population in the distribution system would cause the greatest impact to the system because it would force the greatest quantity of water to be rerouted to meet the demands of the system (that might or might not be possible).

3.1.3. Critical Infrastructure

Critical infrastructure in a water distribution system includes facilities that are vital to the function of the city or is valued high by the city. For example, school, hospitals, fire departments, and community centers may be considered critical infrastructure. This research wanted to incorporate a way to value nodes that supplied to critical infrastructure. Implementing a critical infrastructure factor is important because a node's importance is not solely dependent on the demand and population it supplies. The ramifications for the demand of a node that supplies to a critical infrastructure may be greater than a node that solely supplies to the general population. For example, a node that supplies water to a hospital that cannot meet its demands would be more detrimental than a node supplying water to a golf course, especially during a disaster scenario.

One way to accomplish this is to adopt Jun's (Jun, et al., 2008) method that assigns an equivalent number of customers to each critical infrastructure (i.e. one school could equal one

thousand households). The equivalent number would be based on the modeler's judgment and may be difficult to quantify. Another way incorporate the importance of critical infrastructure is to develop a factor that would be used in the Flow Distribution equation in place of the socio-economic factor that is used in the gravity model.

Although critical infrastructure is important, it was not modeled and implemented in this research because a hypothetical system was used. If a real distribution system is modeled critical infrastructure should be considered and Flow Distribution allows several different ways for critical infrastructure to be incorporated.

3.2. Theory

The main way to show whether the gravity model could be used to identify critical nodes in a distribution system was to apply it to a hypothetical city, simulate disaster scenarios, and compare the predicted and measured results. Before the model, programs, and process used to test Flow Distribution are discussed, the theory behind the analysis tools are explained in the next sections. The following paragraphs will explain the basic hydraulic principles such as the conservation of mass and energy, friction and minor losses, pumps, network hydraulics.

3.2.1. Conservation of Mass

Network analysis was derived primarily from two basic laws of physics, the Law of Conservation of Mass, and the Law of Conservation of Energy. These basic laws can be applied to any control volume of fluid and the energy and mass within that system must be conserved. The basic idea of The Law of Conservation of Mass or continuity states the inflow minus the outflow equals the storage within the control volume. For pipe flow, this means what goes in must come out. Figure 3 helps explain the continuity equation for pipe flow. For this continuity equation to be valid, it is assumed that water is incompressible.

Figure 3: Continuity Diagram

$$A_1 V_1 = A_2 V_2 \quad (\text{Eq. 8})$$

V = average velocity (ft/sec)

A = cross-sectional area (ft²)

3.2.2. Conservation of Energy

The Principle of Conservation of Energy states energy can neither be created nor be destroyed. Thus, the energy difference between two points is the same regardless of the path taken. The energy in pipe flow is typically described in terms of head. The energy at any point in a distribution system is the sum of three components, pressure head, velocity head, and elevation head. In a frictionless environment, the energy between two points can be described with the following equation.

$$\frac{P_1}{\gamma} + \frac{V_1^2}{2g} + z_1 = \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + z_2 \quad (\text{Eq. 9})$$

P = Pressure (psf or Pa)

V = Velocity (ft/sec, m/s)

z = Elevation (ft, m)

g = gravitational acceleration constant (32.2 ft/sec², 9.81m/sec²)

γ = Specific weight of water (lb/ft³, N/m³)

3.3.3. Flow Classification

Water flow is influenced by several different factors including time, space, viscosity, and gravity. This subsection will describe the various classifications for both pipe and open channel flow, and discuss the classifications that are standard for pipe hydraulics. Table 1 below shows the various classifications for both pipe flow and open channel flow and the subsequent paragraph defines each term.

Table 1: Flow Classification	
Classification Criteria	Flow Classification
Time	Steady Flow
	Unsteady Flow
Space	Uniform Flow
	Nonuniform Flow
	Gradually Varied
	Rapidly Varied
Viscosity	Laminar
	Turbulent
	Transitional
Gravity	Subcritical
	Critical
	Supercritical

Steady flow occurs when the velocity does not vary in magnitude or in direction with respect to time at any point in the flow. Unsteady flow happens when the velocity at a point in the flow varies in magnitude or direction with respect to time. Flow is uniform flow when the velocity is constant (both magnitude and direction) at every point and the flow is non-uniform if the velocity is not the same at every point. Gradually varied and rapidly varied flows are the two types of non-uniform flow. Rapidly varied flow occurs when there is a substantial depth of flow and hence velocity changes over short distance and gradually varied flow occurs when the depth and velocity of flow changes gradually over a long distance. Both rapidly varied and gradually varied flow are typically used when describing open channel flow. Turbulent flow is created by eddies of varying size within the flow creating vigorous mixing. A fully turbulent flow is random,

chaotic, and cannot be repeated. Laminar flow travels smoothly and in regular paths. Transitional flow is when the flow is in between laminar flow and turbulent flow. Reynold's number, discussed later, can be used to determine if the flow is laminar or turbulent. Subcritical, critical, and supercritical are typically used to describe open channel flows and can be distinguished by the Froude number. Subcritical flow has high flow depth and low velocity while supercritical flow has low depth with high flow velocity.

Pipe flow is typically pressurized resulting in the classification of steady, turbulent or laminar, and non-uniform flow. It is possible for pipe flow to act similar to open channel flow if the pipe is not full and is gravity driven, but typically, pipe flow refers to full conduit flow under pressure.

3.3.4. Friction Loss

As water flows through a pipe, friction loss will occur. Three different formulas are widely used for this computation of friction loss: Darcy-Weisbach, Hazen-Williams, and Manning's equation. In 1845, Julius Weisbach published the Darcy Weisbach equation, which uses dimensional analysis and a friction factor f to account for pipe characteristics such as material and roughness (Brown, 2000). The Darcy Weisbach (Eq. 10) is most commonly used in Europe.

$$h_L = f \frac{LV^2}{D2g} \quad (\text{Eq. 10})$$

f = friction factor

L = Length of pipe (ft, m)

V = Average velocity (ft/sec, m/sec)

D = Diameter of pipe (ft, m)

g = Gravitational acceleration (ft/sec², m/sec²)

Friction factor can be found using several equations. One of the first and most common formulas is Colebrook-White's equation (Eq. 11). The friction factor is most widely commonly found using the Moody diagram (Figure 4). To solve for the friction factor using the Moody diagram, Reynolds number (Eq. 12), the pipe roughness height, and pipe diameter must be known. One disadvantage in using the Darcy-Weisbach equation is that the friction factor usually requires an iterative approach to be solved.

$$\frac{1}{\sqrt{f}} = -0.86 \ln \left(\frac{\varepsilon}{3.7D} + \frac{2.51}{Re\sqrt{f}} \right) \quad (\text{Eq. 11})$$

f = friction factor

ε = relative roughness (ft, m)

Re = Reynolds Number

$$Re = \frac{VD}{\nu} \quad (\text{Eq. 12})$$

V = Average Velocity (ft/sec, m/sec)

D = Diameter (ft, m)

ν = Kinematic Viscosity (ft²/sec, m²/sec)

Figure 4: Moody Diagram

Hazen-Williams equation is an empirically based equation and uses similar variables as the Darcy-Weisbach, but except a C-factor based on pipe material, diameter and condition is used in place of a friction factor. C-factors can be found in tables and the higher the factor the lower the friction loss. The Hazen-Williams equation was formed in the early 1900's by Gardner Williams and Alan Hazen. The Hazen-Williams equation (Eq. 13) is the most commonly used friction loss formula in the United States (Martorano, 2006).

$$h_L = \frac{\phi L}{C^{1.852} D^{4.87}} Q^{1.852} \quad (\text{Eq. 13})$$

C = Hazen-Williams roughness coefficient

L = Length of pipe (ft, m)

Q = Flow rate (cfs, cms)

D = Diameter (ft, m)

ϕ = Unit conversion factor (4.73 for English units, 10.7 for SI)

Robert Manning developed another empirically based formula in 1889 known as Manning's equation (Fishenich, 2000). Manning's equation utilizes roughness coefficients that can be found in tables, and the higher the coefficient the rougher the material. Manning's equation is primarily used for open-channel flow, and is rarely used for distribution systems, mainly used in Australia. Manning's equations is shown below.

$$h_L = \frac{C_f L (nQ)^2}{D^{5.33}} \quad (\text{Eq. 14})$$

C_f = Unit conversion factor (4.66 for English units, 10.29 for SI)

L = Length (ft, m)

n = Manning's coefficient

Q = Flow rate (cfs, cms)

D = Diameter (ft, m)

Hazen-Williams was the friction loss formula used in present study as it is most commonly used in the United States, and the C-Factors for the test city were given.

3.3.5. Minor Losses

Minor losses are caused by valves, fittings, bends and other accessories in WDS. Minor losses can be calculated by multiplying the velocity head by a minor loss coefficient as shown in Eq. 15. Minor loss coefficients are determined experimentally by the manufacturer of the equipment.

$$h_{lm} = K_L \frac{V^2}{2g} \quad (\text{Eq. 15})$$

K_L = minor loss coefficient

In water distribution systems, losses due to friction are generally much greater than minor losses. Due to their relative insignificance, modelers frequently choose to neglect minor losses (Walski, et al., 2007). Minor losses in this study were ignored because of their relative

insignificance and lack of information about the hypothetical city (Anytown). Minor losses can be included in the resistance equation (Eq. 16) by adding the below equation.

$$\left[\frac{K_L}{2g \left(\frac{\pi}{4} D^2 \right)^2} \right] \quad (\text{Eq. 16})$$

3.3.6. Pumps

The most common input of energy into a system is through pumping. Pumps are crucial to any distribution system that cannot supply acceptable pressures to consumer through the sole use of gravity flow. The most common pump used in water distribution system is a centrifugal pump because of their low cost, simplicity and reliability (Mays, 2005).

Pump selection is typically dictated by rotational speed, discharge capacity, pumping head, power input, and efficiency. Pump efficiencies influence the pump operating cost, and the higher the efficiency the cheaper the cost of operation. Pump efficiency is determined by the ratio of power delivered to the water to power input to the pump. The manufacturer develops and provides pump curves like the one shown in Figure 5. Pump curves show the head versus discharge relationship as well as the pump efficiencies. The pump curves for a pump of specific diameter/ size operating at a single speed can be approximated by using that quadratic equation (Equation 17).

Figure 5: Typical Pump Curve

$$E_p = AQ^2 + BQ = H_c \quad (\text{Eq. 17})$$

E_p = Pump head (ft, m)

A,B = Pump Coefficients

Q = Pump Discharge (cfs, cms)

H_c = Pump Cutoff Head (ft, m)

Many pumps have motors that spin at a constant speed regardless of the head and flow demands of the system. If the system demand has highly variable demands, these pumps become extremely inefficient. To counteract that, many distribution systems utilize variable frequency drives (VFDs) that change the speed of the impeller(s) based upon system demands. To predict the VFD outputs the affinity laws (Eqs. 18-20) must be utilized in the design and pump selection.

$$\frac{Q_1}{Q_2} = \frac{n_1}{n_2} \quad (\text{Eq. 18})$$

$$\frac{H_1}{H_2} = \left(\frac{n_1}{n_2}\right)^2 \quad (\text{Eq. 19})$$

$$\frac{P_1}{P_2} = \left(\frac{n_1}{n_2}\right)^3 \quad (\text{Eq. 20})$$

Q = Pump Discharge (cfs, cms)

H = Pump Head (ft, m)

P = Pump Power (hp, kW)

n = Impeller Rotational Speed (rpm)

Many situations require two or more pumps to increase the amount of flow, pressure or both to meet the demands of the water system. A pump in series usually refers to multiple impellers installed inline in the same pump or a booster pump installed further down the pipeline. Either way, the head-capacity pump curve is obtained by adding the heads of the individual pumps or impellers together, while the flow rate remains the same. A pump in parallel refers to pumps that are not inline but their discharge flows into a common pipe or header. When pumps are in parallel, the flow rates for each pump are added together while the head remains the same.

3.3.7. Network Hydraulics

Distribution systems consist of a large set of pipes and nodes that has to be solved with a number of energy and continuity equations. Energy equation each loop and a continuity equation for each node must be solved. A small to medium size distribution system could require thousands of equations to be solved simultaneously. A systematic approach was first developed by Hardy Cross in 1936 (Ormsbee, 2006). This method divides the system into several closed loops, assumes initial flow rates to satisfy, and then uses successive iterations to solve for a flow correction until convergence. Several other methods have been developed with the advancement of computers, which solve the system of equations by utilizing matrices. The linear theory method is one of the most commonly used and most efficient matrix based methods. In 1972, Wood and Charles presented the linear theory, which solves for the continuity and head loss equations simultaneously (Ormsbee, 2006). This technique consists of a very stable procedure and nearly always converges on a solution.

3.3. Modeling

This section will detail the hypothetical city that was chosen for analysis and the programs utilized to apply and test Flow Distribution method.

3.3.1. Anytown, USA

The hypothetical city chosen to apply Flow Distribution was Anytown, USA. This hypothetical community was developed for the ‘Battle of the Networks’, a series of sessions that occurred at the “Computer in Water Resources” conference held in Buffalo, New York in 1985. It was the intention that Anytown would resemble and function like many real systems and solutions to the problems developed for the conference sessions could be applied to actual systems (Walski, et al., 1987).

Even though Anytown was the hypothetical city chosen for this study to apply Flow Distribution, several other options were also available such as creating a new hypothetical city, using a real water distribution system with GIS, or using a different model that has already been used for other research. Creating a new city is difficult because the schematic layout, component characteristics, demands patterns, and pump curves would need to be designed. It is important that the system used resembled a real system and creating a new model city seemed unnecessary since many other models already exist. Using a real WDS presents challenges as well because of the increased security concerns, obtaining water distribution layout, demand patterns, and component information is very difficult. Even if all that data were obtained, a connectivity analysis would need to be performed to ensure that all the pipes and nodes are properly connected. The model would also have to be calibrated so the observed data is the same as the modeled data. Skeletonization (explained later) would also be necessary so the analysis would be manageable.

Anytown was chosen instead of other model cities because of its resemblance to a real system. It has elevated storage, pumping station, pre-designed pumps to account for varying

demands, and was simple enough to perform the detailed analysis that was desired yet complicated enough that the critical nodes could not be easily identified. Anytown has been used to simulate a real distribution system when testing other methods. Anytown consists of one reservoir, two storage tanks, one pumping station, sixteen demand nodes, and forty pipes. The pumping station consists of two operational constant speed centrifugal pumps in parallel. Three pumps are shown, but the system was designed to meet demands with only two operational pumps. Figure 6 is a schematic layout of the city.

It may be advantageous to solve for the nodes that affect the most population, not demand, because nodes with the highest demand may be supplying water to industrial or commercial entities with minimal human consumption. Based on Anytown's average daily demand and the amount of water of water used per person stated by the EPA of 183 gallons per day (EPA, 2004), Anytown was calculated to have a population of 50,000 people. Using Excel, a random population value was assigned to each node, independent of the node's demand. Realistically, the amount of demand and population supplied are related, but using this approach would show that if they aren't Flow Distribution could still be applied.

Figure 6: Anytown, USA Schematic

3.3.2. Skeletonization

For most urban distribution systems, water is extracted from a very large number of demand nodes. It would be unreasonable to analyze a system with that degree of detail. If one were to model a real distribution system, skeletonization would need to be implemented. Skeletonization is the process of eliminating insignificant parts of a distribution system that do not affect the behavior of the system. When a pipe or node is eliminated, the flow and demand are distributed to the nearby nodes. For example, pipes in a neighborhood that supply water to each household, once eliminated, their flow may be distributed to a few nodes at street intersections. Modeling judgment plays a key role in determining which pipes should be eliminated because definitive criteria does not exist for determining whether something should be included in the model analysis. Almost all models are skeletonized to some degree and should always be considered so

modeling is feasible with a practical amount of detail. Anytown is a model city that only consists of larger diameter pipe, meaning skeletonization has already been implemented.

3.3.3. WaterCAD

In order to model Anytown and solve its complex set of equations, a computer simulation program was required. Several viable options are commercially available such as the United States Environmental Protection Agency's EPANET, Bentley's WaterCAD, and MWH's H2Onet. Any water distribution analysis program can be used for the proposed method. EPANET seemed to be the program of choice in most studies because of its free availability to the public.

WaterCAD allows users to design and analyze water distribution systems with its unique scenario management center, easy-to-use interface, versatility, and conversion capability between CAD, GIS, and other databases (Bentley, 2012). The scenario management tool allows the modeler to configure, analyze, and visualize multiple scenarios within one file. WaterCAD is capable of performing steady state and extended period simulations, as well as, offer three options for calculating friction loss through a pipe.

WaterCAD V8i was chosen because it is user friendly and is available at Cal Poly. The researchers also had familiarity with the program and it can be used in congruence with GIS. GIS is a program designed to store, manage, and analyze geographically referenced data sources to reveal trends, patterns, and relationships. GIS programs are commonly used by cities and counties to store the needed information to apply this method. WaterCAD would allow cities and counties to import their GIS data.

3.3.4. Water Characteristics

To simulate real world conditions, water characteristics needed to be considered. Water temperature affects several water characteristics such as specific weight and viscosity. For this simulation, the standard WaterCAD temperature of sixty-eight degree Fahrenheit was assumed constant throughout the entire distribution system. At 68 degrees, the kinematic velocity is 1.004

$\times 10^{-6}$ and a specific weight of 62.314 lb/ft³. It is also assumed that the temperature of the water remains constant throughout the day, which is a simplification because over a 24-hour period the temperature will fluctuate. Despite the fluctuation the same value was used because if the fluctuations in temperature were considered the results would vary minimally.

3.3.5. Network Simulation

WaterCAD is capable of performing two types of simulations, steady state and extended-period. Steady-state simulation is the simplest simulation type and solves the system of equations as if the system is in equilibrium. In other words, the dynamic variables such as pipe flows, junction demands, and tank elevations are kept constant. Steady-state simulations are commonly used to model peak demands or a short time period.

Extended-period simulations break up the simulation into time-steps. Each time step may feature different values for the dynamic variables (tank levels, pump operation, and junction demand). Real distribution systems have variable properties especially demand patterns; the amount of water that is consumed in the morning when everyone is getting ready for work is different at midnight. An extended period simulation models the variability of real water distribution systems, and was the simulation chosen for this study. The extended-period simulation was chosen for this analysis because of its capability to model varying demands. The total simulation time was 24 hours with a one-hour time-step.

3.3.6. MatLab

One limitation with WaterCAD is it does not allow you to modify the flex tables (tables that store system information) to create your own equations and solve for different variables. A different program had to be utilized to implement Flow Distribution. This program needed to run an analysis on information that could be imported from WaterCAD and then the results exported to Excel for documentation. Many computing languages would accomplish this task, but Matlab was the program chosen because of its availability and working experience of the researcher.

Matlab was created by Cleve Moler in 1976 as a simple educational program, but it did not become commercially available until 1984 (Haigh, 2008). Matlab is one of the most popular programs with students in the applied mathematics and engineering industries. Matlab features hundreds of built in commands that allow users to solve complex numerical equations without the need for tricky and time-consuming programming. Matlab also allows users to document easily their results with 2D and 3D graphics.

Matlab was used to perform the Flow Distribution aspect of the method. The Matlab program automatically imports the necessary information from the specified Excel file, runs the Flow Distribution, and exports the results to Excel. The most important aspect of the Matlab code was the use of undirected biograph. This was used to solve for the minimum path of resistance. Two options were available, directed and undirected. Directed restricts the path from only going in the current direction of pipe flow and undirected allows the path to go in any direction. Undirected was chosen because when a pipe or node is disabled water is not restricted (unless by a valve) to meet the demands of a node by traveling in the opposite direction it was during normal operating conditions. Figure 7 shows the undirected graph that Matlab generated. The numbers next to each line are the calculated resistance value. The code in its entirety is provided in Appendix A.

scenarios would need to be developed by the modeler, and should reflect feasible threats and possible risks that exist for that system.

It is impossible to predict correctly the adverse effects caused by natural disasters or terrorist attacks. A few adverse effects are junctions and nodes can be disabled, fires can start, and the region can be without power. This research wanted to model disaster scenarios that were feasible and likely to occur to any distribution system. The other goal was to create different disaster scenarios that would should Flow Distribution is suitable for a variety of disaster scenarios.

Although it is impossible to predict the adverse effects of damaging events, this study wanted to model a disruption that would cause a system failure. Disruptions from natural disasters or terrorist attacks can be modeled in several ways including disabling one junction or pipe, a random set of junctions or pipes, and a group of adjacent pipes or junctions. Other studies used pipe break data, or accessibility information to equate probabilities for each pipe and/ or junction failure. For this research, the probability for a node failure was the same for each junction because the goal was to determine the critical nodes regardless of the probability of their failure occurring. The modeler, as a conclusion of the study, could deem the critical nodes predicted by Flow Distribution unlikely to fail and not use its resources to strengthen that part of the system. For this research, the disaster scenarios were created to feature one disabled node, meaning Flow distribution would be solving for the most critical nodes not pipes or group of pipes or nodes. One node was deemed appropriate because Anytown, and most models of real distribution systems, features a skeletonized network, meaning one junction or pipe failure is really the loss of flow/ demand of multiple pipes and nodes.

3.3.7.1. Disaster Scenario 1

The first disaster scenario would model a moderate disaster, only one node would be disabled, and one fire would be created at node 120 of 1000 gallons per minute (gpm). Node 120

and 1000 gpm were chosen because this node and fire flow was one of critical fires listed in the ‘Battle of the Networks’ (Walski, et al., 1987), so it seemed appropriate to use for a disaster scenario.

Most of Anytown’s characteristics were unchanged for this simulation, except the pump curves were modified to meet equilibrium. With the original pump curves, the tanks did not fill up to their original starting elevation at the end of a 24-hour period and were drained (Figure 8). This is not realistic because storage tanks are designed to store water throughout the day and these tanks only stored water for a few hours, were empty the rest of the time, and never refilled to their original water level. The pump curves were adjusted using trial and error until the water level in each tank started at the same elevation every day for an entire week simulation (Figure 9).

Figure 8: Tanks' Hydraulic Grade Line with Original Pump Curve

Figure 9: Tanks' Hydraulic Grade Line with New Pump Curve

The tables on the following page (Table 2 - Table 5) display the pipe, junction, and tank characteristics, as well as the new pump curve that was developed and previously discussed.

Table 2: Pipe Characteristics for Disaster Scenario 1

Pipe	Length (ft)	Diameter (in.)	C-Factor
P-2	12,000.00	16	70
P-4	12,000.00	12	120
P-6	12,000.00	12	70
P-8	9,000.00	12	70
P-10	600	12	70
P-12	600	10	70
P-14	600	12	70
P-16	600	10	70
P-18	600	12	70
P-20	600	10	70
P-22	600	10	70
P-24	600	10	70
P-26	600	12	70
P-28	600	10	70
P-30	600	10	120
P-32	600	10	120
P-34	600	10	120
P-36	600	10	120
P-38	600	10	120
P-40	600	10	120
P-42	600	8	120
P-44	600	8	120
P-46	600	8	120
P-48	600	8	70
P-50	600	10	120
P-52	600	8	120
P-56	600	8	120
P-58	600	10	120
P-60	600	8	120
P-62	600	8	120
P-64	12,000.00	8	120
P-66	12,000.00	8	120
P-78	100	12	120
P-80	100	12	120
P-100	1	6	130
P-101	1	6	130
P-102	1	6	130
P-103	1	6	130
P-104	1	6	130
P-105	1	6.00	130

Table 3: Junction Characteristics for Disaster Scenario 1

Node Number	Elevation (ft.)	Average Demand (gal/min)
J-20	50	500
J-30	50	200
J-40	50	200
J-50	50	200
J-60	50	500
J-70	50	500
J-80	50	500
J-90	50	1,000
J-100	50	500
J-110	50	500
J-120	50	200
J-130	50	200
J-140	50	200
J-150	50	200
J-160	50	800
J-170	50	200

Table 4: Tank Characteristics Disaster Scenario 1

Tank	Min. Elev. (ft)	Initial Elev. (ft)	Max. Elev. (ft)	Dia. (ft)
T-165	215	225	250	90
T-65	215	225	250	90

Table 5: Pump Curve for Disaster Scenario 1

Flow (gpm)	Head (ft)
0	375
2,500	365
5,000	337.5
7,500	287.5
10,000	226.25

3.3.7.2. Disaster Scenario 2

This research wanted to simulate a scenario that disabled power to an entire region leaving the distribution system to meet demands only by gravity flow from the elevated storage tanks. Anytown was designed to supply demand through the congruent operation of pumps and tanks. Hence, several model characteristics were adjusted to satisfy demands and pressures were satisfied under gravity flow during normal operating conditions.

Tank sizes and elevations were adjusted so that the pressures would not drop below the threshold pressure (40 psi for this analysis), tanks would not empty, and demands would be met for the entire 24-hour period. It was desired for the normal operating condition to meet the necessary demands and demands not met to be recorded only in the failure scenarios. Each tank diameter was increased from ninety feet to one hundred and fifty feet. The tank sizing calculation can be found in Appendix B. Tank elevations were adjusted using a trial and error process until the nodes received reasonable pressures during normal operating conditions. It was desired to have the pressures at the nodes be above the threshold for the 24 hour period, but not exceed it by an impractical amount. The minimum elevation for both tanks was adjusted from a level of 215 ft. to 135 ft., and the initial elevation was changed to 185 ft. to 225 ft. The tank elevations were lowered so that the pressures recorded at the nodes during the normal operating condition did not exceed the threshold pressure by an unreasonable amount (over 100 psi).

Table 6 - Table 8 list the adjusted pipe, junction, and tank characteristics for Disaster Scenario 2 that were modeled in WaterCAD.

Table 6: Pipe Characteristics for Disaster Scenario 2

Pipe	Length (ft)	Diameter (in.)	C-Factor
P-2	12,000	16	70
P-4	12,000	12	120
P-6	12,000	12	70
P-8	9,000	12	70
P-10	600	12	70
P-12	600	10	70
P-14	600	12	70
P-16	600	10	70
P-18	600	12	70
P-20	600	10	70
P-22	600	10	70
P-24	600	10	70
P-26	600	12	70
P-28	600	10	70
P-30	600	10	120
P-32	600	10	120
P-34	600	10	120
P-36	600	10	120
P-38	600	10	120
P-40	600	10	120
P-42	600	8	120
P-44	600	8	120
P-46	600	8	120
P-48	600	8	70
P-50	600	10	120
P-52	600	8	120
P-56	600	8	120
P-58	600	10	120
P-60	600	8	120
P-62	600	8	120
P-64	12,000	8	120
P-66	12,000	8	120
P-78	100	12	120
P-80	100	12	120

Table 7: Junction Characteristics for Disaster Scenario 2

Node Number	Elevation (ft.)	Average Demand (gal/min)
J-20	50	500
J-30	50	200
J-40	50	200
J-50	50	200
J-60	50	500
J-70	50	500
J-80	50	500
J-90	50	1,000
J-100	50	500
J-110	50	500
J-120	50	200
J-130	50	200
J-140	50	200
J-150	50	200
J-160	50	800
J-170	50	200

Table 8: Tank Characteristics for Disaster Scenario 2

Tank	Min. Elev. (ft)	Initial Elev. (ft)	Max. Elev. (ft)	Dia. (ft)
T-165	135	185	195	150
T-65	135	185	195	150

Fire flows were incorporated into both disaster scenarios to simulate a disaster and to show the impact of disabled nodes on firefighting/ emergency management. In a redundant distribution system, when a node is disabled the flow is rerouted so the other nodes still receive their required pressure and meet their necessary demands. When a node is disabled, pressures at the other nodes in the system become higher. With fire demands however, stress is added to the system, which can cause pressure drops at other nodes in the system.

For both disaster scenarios, extended period simulations were used and the demand pattern (Figure 10) is shown below.

Figure 10: Hourly Demand Pattern

The original topography for Anytown consisted of varying elevations for the nodes, specifically it had a few nodes at a higher elevations than the rest. To ensure that those nodes experienced pressures above 40 psi, the rest of the nodes in the system had pressures well above 40 psi. When disaster scenarios were run, only the elevated node pressures dropped below 40 psi. To see the impact of disabled nodes across the entire system, not just with a few elevated nodes all node elevations were set to 50 ft. The node elevation change was done for both disaster scenarios for consistency.

3.3.7.3. Process

For each disaster scenario, the same process was used to apply and test the accuracy of the method. The process consisted of using WaterCAD, Matlab, and Excel to analyze, document, and display the desired results.

Figure 11 is a schematic of the process that was used and the following paragraphs will describe the process in detail. The blue background in the schematic denotes the process used to apply Flow Distribution and the green background shows the additional steps taken to test the accuracy of the method.

Figure 11: Process Flowchart

The first step in this process was previously discussed and that was to develop disaster scenarios to be modeled. The next step was to perform a hydraulic simulation of normal operating conditions in WaterCAD. Normal operating condition is meant to simulate a typical day with average demands and without failed pipes or nodes. For Flow Distribution to predict the critical nodes, the water sources in the normal operating condition and disaster scenario need to be the same. For example, if the same normal operating condition was used for Flow Distribution the predicted nodes would be exactly same, but the actual would be different because the water is routed through the system differently since the sources are different for the two scenarios. This research used two different normal operating conditions, one for each scenario.

Hydraulic information from the normal operating condition was necessary for the Flow Distribution analysis. The variables needed from WaterCAD include information about the pipes and junctions consisting of either static or dynamic variables. Static variables remain constant during the entire analysis. Static variables necessary for analysis include pipe length, diameter, and C-factor. Dynamic variables may change during each time step. Dynamic variables necessary for analysis are the start and stop node for each pipe, pipe flow, junction demand, outflow, and inflow. Flow Distribution can only analyze one time step, so the time step chosen needed to represent the entire simulation for analysis. For this research, the peak demand hours were deemed the most suitable. Peak hours for Anytown were the hours nine through twelve. The tenth hour was arbitrarily chosen for the analysis and the necessary information from this time step was exported from WaterCAD to MS Excel.

In Excel, a simple formula was written to calculate the total outflow and inflow at every node using the flow rate start node and stop node information for each pipe. The necessary information (Length, C-Factor, diameter, start node, stop node, demand, node outflow, and node inflow) was then imported into Matlab, which first calculated the resistance factors for each pipe using equation 6. Next, Matlab calculated the path of least resistance for each pair of nodes. The demand and population affected are also calculated using equation 7. The results were then

exported back into Excel. The results were tabulated and summarized to document the five nodes (arbitrarily chosen) that Flow Distribution predicted to be the most critical nodes.

If this analysis were to be used as a part of a vulnerability assessment, this would conclude the critical node analysis and the results should be used to develop countermeasures. This study wanted to verify the accuracy of the developed method. The accuracy of Flow Distribution was verified by comparing the amount demand supplied and population served during normal operating condition to all possible failure scenarios. As previously stated, each disaster scenario incorporated one disabled node, and to verify the results, sixteen failure scenarios (one for each node) were modeled to measure the impact of each node disabled.

Disabled nodes can be modeled by isolating that node, meaning that the pipes connected to that node are still operational, but that node does not receive any flow. This would not have much effect on the system except for the demand that the disabled node normally supplies to would not be met. In addition, disabled nodes could be modeled by having the pipes connected to the disabled node leak. Leaking pipes would force the system to supply the water that the pipe carries during normal operating conditions. This study decided to model node failures by stopping flows in all pipes directly connected to the disabled nodes, isolating the node and pipes from the system. This seemed reasonable because it seemed likely for the effects of either disaster event to cause more than pipe and/ or junction to be disabled. Adjacent pipes and junction seem logical to fail at once because the cause and conditions of the failure pipe or junction (i.e. ground shaking, bad soil conditions, high winds, explosions) would be more like seen at other nearby pipes and junctions. The pipes and nodes were isolated from the system because it seems reasonable to believe that a distribution system would have enough valves to isolate the failed region to prevent leaking. Although it would take time for the valves to be closed, node failures were modeled in this way.

The demand and population for every hour of simulation during the normal operating condition were previously calculated and the results were saved in Excel. To calculate the

demand and population affected during each disaster scenario, sixteen failure scenarios were created and analyzed in WaterCAD. A failure scenario incorporated the fire flow demand that the disaster scenario featured and one disabled node. Figure 12 is a schematic of a failure scenario that features junction 90 disabled for disaster scenario 2 at hour twenty-four of simulation.

Figure 12: Failure Scenario with Junction 90 Out for Disaster Scenario 2

The light blue nodes represent nodes that are below the chosen threshold pressure value of 40 psi. These nodes are not capable of supplying the necessary demand to consumers. To measure the change in demand between the normal operating condition and failure scenario, pressure dependent demands were implemented during the failure scenarios. If the pressure was above the threshold, the demand was recorded as unaffected and if the pressures dropped below the threshold pressure it was assumed that the demand was not completely met. The modeler could assume that the demand at a node with a pressure less than the threshold pressure is zero. For this research, when the pressure dropped below the threshold pressure, only a portion of the demand was supplied to the node. The method is based upon a user-defined power function

(Figure 13), and the default power value 0.5 was used for this model. Equation 21 is the piecewise pressure dependent demand equation.

$$\frac{D_{sup}}{D_{req}} = \begin{cases} 0 & P \leq 0 \\ \left(\frac{P_{act}}{P_t}\right)^{0.5} & 0 \leq P \leq P_t \\ 1 & P \geq P_t \end{cases} \quad (\text{Eq. 21})$$

D_{sup} = Demand supplied to node

D_{req} = Demand required at node

P_{act} = Pressure observed at node

P_t = Threshold Pressure (40psi)

Figure 13: Power Function for Pressure Dependent Demand

Using pressure dependent demands, the demand for each node, for every hour, for each failure scenario was exported to Excel. In Excel, the difference in demand between the normal operating conditions and each failure scenario was calculated. The difference in population between the failure scenario and normal condition for an individual node was calculated using

Equation 22. This allowed for a comparison in the population served between normal conditions and failure scenarios as well.

$$Pop\ Diff = Pop_{Ser} - \left(\frac{D}{D_{NOC}} * Pop_{Ser} \right) \quad (Eq. 22)$$

Pop Diff = Population difference at node between normal operating conditions and failure scenario

Pop_{Ser} = Population served at node during normal conditions

D = Demand supplied to node

D_{NOC} = Demand supplied to node during normal operating conditions

The best-case scenario was that Flow Distribution predicted the same critical nodes as the actual critical nodes found after analyzing every failure scenario. The process just described was used for the analysis of both disaster scenarios. To see all the data including the WaterCAD and Matlab outputs, see Appendix C and Appendix D. The results are presented and discussed in detail in the following chapter.

CHAPTER 4: RESULTS & DISCUSSION

This chapter presents the results from Flow Distribution for disaster scenario one and disaster scenario two and discusses their impact. It will also compare the results of Flow Distribution to the actual critical nodes found by analyzing failure scenarios, as well as, compare the accuracy of Flow Distribution to other research.

4.1. System Improvement

If Flow Distribution were to be used as part of a vulnerability assessment then, the results in Table 9, which shows the critical nodes that Flow Distribution predicted, would be used to evaluate how the current resources could be allocated to bolster the system's reliability. From these results, logic, modeler judgment, and risk probability analysis can be utilized to decide if countermeasures are necessary to strengthen weak points found in the system.

Table 9: Top Critical Nodes Predicted by Flow Distribution

Junction	Disaster Scenario 1		Disaster Scenario 2	
	Expected Populaton Effect (ppl)	Expected Demand Effect (gpm)	Expected Populaton Effect (ppl)	Expected Demand Effect (gpm)
J-20	22,811	3,910	3069	650
J-30	8,622	1,017	5923	593
J-40	7,089	372	6100	260
J-50	8,914	582	6486	310
J-60	5,620	1,170	14510	2588
J-70	5,646	1,738	1851	860
J-80	7,520	982	6499	840
J-90	6,164	1,312	6082	1300
J-100	1,873	808	1640	818
J-110	6,008	1,044	5149	746
J-120	5,039	273	4949	260
J-130	5,597	391	6194	458
J-140	5,729	335	6707	454
J-150	4,518	312	5419	539
J-160	3,951	1,282	19844	3146
J-170	1,901	260	2009	273

The top critical nodes are not the same based on the demand and population affected, thus to assess the results from Flow Distribution one would need to take precedence over the other. For this study, the demand affected took precedence over the population affected (Table 9). The demand affected was believed to represent the system more realistically than the population affected because the population at each node was randomly generated in Excel. Adding up the affected demand from each scenario for each junction, the results show that junctions 20, 60, and 160 significantly affect more demand than the rest of the nodes. To improve system reliability, additional pipes could be added between the supply tanks/ reservoir to other nodes in the system. Since nodes 20, 60 & 160 all supply water to the system, an additional supply source would decrease the effect that each of those nodes has on the system.

4.2. Flow Distribution Accuracy

The preceding section discussed how the results from Flow Distribution can be used to identify locations for system improvement. This section focuses on the effectiveness of Flow Distribution to identify the critical nodes. Table 10 and

Table 11 document the results from Disaster Scenario 1 and 2. Columns (3) and (6) are the expected population and demand effect, respectively, calculated using the Flow Distribution equation in Matlab. Columns (4) and (7) are the actual population and demand affected after analyzing the sixteen failure scenarios in WaterCAD. The highlighted cells represent the five largest numbers in each respective column.

Flow Distribution predicted Junctions 20, 60, 70, 90, and 160 to affect the most demand if they were disabled during a Disaster Scenario 1. The results after analyzing all the failure scenarios show junctions 20, 30, 70, 90, and 110 will affect the most demand (Table 10). Flow Distribution only correctly predicted three out of five critical nodes. The program was more successful predicting the critical nodes for population. Junctions 20, 30, 50, 70, and 80 were predicted to cause the most population to be without water if disabled. The junctions that actually

caused the most disturbances were junctions 20, 30, 50, 70, and 110. Flow distribution correctly predicted four out of five critical nodes for effects in population.

Table 10: Results from Disaster Scenario 1

Junction	Population (ppl)	Expected Populaton Effect (ppl)	Actual Population Effect (ppl)	Demand (gpm)	Expected Demand Effect (gpm)	Demand Effect (gpm)	Outflow
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
J-20	3069	22,937	48,259	650	3,905	140,579	5803
J-30	1421	8,629	11,443	260	1,016	32,285	1787
J-40	6100	7,091	6,124	260	372	5,028	301
J-50	5953	8,920	6,279	260	581	6,079	691
J-60	2297	5,626	2,808	650	1,169	14,040	1132
J-70	827	5,688	10,643	650	1,737	43,214	1930
J-80	4189	7,534	4,225	650	982	12,464	636
J-90	6082	6,082	6,082	1300	1,300	24,700	0
J-100	716	1,915	743	650	810	12,468	294
J-110	4642	6,014	6,975	650	1,044	20,491	562
J-120	4949	5,040	4,949	260	273	4,940	19
J-130	5170	5,599	5,184	260	392	4,984	196
J-140	5248	5,738	5,488	260	336	5,894	109
J-150	4330	4,571	4,588	260	326	5,891	52
J-160	1487	3,960	1,520	1040	1,282	19,846	437
J-170	1901	1,901	2,182	260	260	5,895	0

For Disaster Scenario 2, Flow Distribution predicted that Junctions 60, 70, 80, 90, and 160 would be the top five nodes that would affect the most demand in the distribution system. After the failure scenarios were analyzed, the top five most critical nodes were junctions 60, 70, 80, 90, and 160 (Table 11). This method correctly predicted all five nodes that would affect the most demand. Flow Distribution was not as successful in selecting the top nodes to affect population, as it predicted junctions 60, 50, 80, 140, and 160, and the actual nodes that affected the most population were junctions 40, 50, 60, 90, and 160. Only three of the five critical nodes were successfully predicted.

Table 11: Results from Disaster Scenario 2

Junction	Population	Expected Population Effect	Actual Population Effect	Demand (gpm)	Expected Demand Effect (gpm)	Demand Effect (gpm)	Outflow
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
J-20	3069	3,069	3,097	650	650	12,434	0
J-30	1421	5,923	1,571	260	593	5,386	611
J-40	6100	6,100	6,131	260	260	5,038	0
J-50	5953	6,486	6,025	260	310	5,186	84
J-60	2297	14,510	18,504	650	2588	64,993	3115
J-70	827	1,851	902	650	860	12,580	405
J-80	4189	6,499	4,249	650	840	12,534	380
J-90	6082	6,082	6,087	1300	1300	24,714	0
J-100	716	1,640	754	650	818	12,459	302
J-110	4642	5,149	4,676	650	746	12,446	305
J-120	4949	4,949	4,949	260	260	4,940	0
J-130	5170	6,194	5,260	260	458	5,196	547
J-140	5248	6,707	5,334	260	454	5,222	336
J-150	4330	5,419	4,413	260	539	5,217	433
J-160	1487	19,844	14,779	1040	3146	59,716	3515
J-170	1901	2,009	1,973	260	273	5,168	27

For both scenarios, the values for the expected demand affected and the actual demand effect were not equivalent because the expected demand effect was calculated for only one hour and the actual was the calculated for the entire 24-hour period. It was assumed that the nodes that affected the most demand and population in the hour chosen (tenth hour of simulation) would be the same nodes that would affect the most demand and population during the rest of the simulation. This assumption was checked by running Flow Distribution analysis for every hour of simulation for Disaster Scenario 1. The results were then summed to get the total expected demand and population effect for the 24-hour simulation period. Table 12 documents the results for run 1, ninety percent of the nodes that were predicted to be the critical nodes for peak hour 10 were the same when Flow Distribution was analyzed for every hour of simulation. Since the results varied little between the analyzing only the peak hour versus the entire simulation, the assumption previously stated was deemed valid.

Table 12: Population Effect for Peak Hour 10 versus 24hr Period for Run 1

Junction	Population Effectuated for 24hr Period (ppl)	Population Effect for Peak Hour 10 (ppl)	Population Effectuated for 24hr Period (gpm)	Population Effect for Peak Hour 10 (gpm)
J-20	571979	22811	78682	3910
J-30	240446	8622	23573	1017
J-40	169075	7089	7668	372
J-50	221146	8914	12481	582
J-60	146082	5620	23728	1170
J-70	192568	5646	41701	1738
J-80	176145	7520	19161	982
J-90	150313	6164	25210	1312
J-100	59875	1873	17161	808
J-110	159245	6008	22774	1044
J-120	125890	5039	6012	273
J-130	127327	5597	6960	391
J-140	145811	5729	7772	335
J-150	118315	4518	8142	312
J-160	131768	3951	25712	1282
J-170	43873	1901	4800	260

Although there are several ways to improve Flow Distribution's accuracy (discussed in Chapter 5: Conclusion), it predicted the critical nodes correctly 70% of the time. Of all the research conducted, only Jowitt & Chengchao (1993) solved for the critical nodes in the distribution system, and verified their results. Jowitt's method predicted the critical nodes 70% of the time. Intuition may suggest that the most critical node would be the one with the most outflow or demand. It seems plausible to believe that the node with the most outflow supplies the most water to the system or disabling the node that supplies the largest demand will globally affect the demand of the system the most. In a redundant system flow can be rerouted when the node with the most outflow is disabled rendering that node to not be critical. The node with the most demand may not have any outflow and nodes with less demand may have more outflow so when disabled it will affect more demand throughout the system. The result tables (Table 10 and Table 11) support this because the outflow and demand for each node are shown and the most critical nodes were not only the nodes with the highest outflow or demand. Using outflow to

predict the most critical nodes, it would have correctly selected the critical node 55% of the time. Selecting the nodes with the highest demand or population would have correctly predicted the critical nodes 60% of the time. Considering this, the accuracy of Flow Distribution can be improved and its accuracy is comparable or better than the methods just mentioned provides evidence that this method is reasonably effective and accurate.

CHAPTER 5: CONCLUSION

The objectives for this research were to develop a method that identified critical nodes and/ or pipes without analyzing every failure scenario, was flexible for application to different WDS, capable of incorporating critical infrastructure, and the results were verifiable. The primary advantage of using Flow Distribution is it can identify the critical nodes without analyzing any failure scenarios and analyzing only the normal conditions of the disaster scenarios, and for this study, it predicted the critical nodes with 70% accuracy. Flow Distribution is not a complicated method and is an adaptation of the gravity model, widely used in transportation engineering studies, applied to WDS. Even though critical infrastructure was not implemented in this analysis, Flow Distribution allows for incorporation of critical infrastructure in the analysis. The last objective was met because the accuracy was verified by applying two different disaster scenarios and analyzing each failure scenario then comparing the predicted nodes to the actual critical nodes.

The purpose of Flow Distribution is to be used as part of a vulnerability assessment to determine weak aspects in the system and it is not meant to be an all-inclusive method covering every necessary aspect of a vulnerability assessment. However, this newly developed method provides a simple quantitative method for vulnerability assessment as opposed to the complicated quantitative and qualitative methods used in practice.

5.1. Improvement

Despite the overall success of Flow Distribution, there were several ways it could be improved including calibrating and solving for a more appropriate number of critical nodes.

Calibration is an important part of the gravity model because it correlates the theoretical outflows to the actual or modeled outflows. As stated in the Methodology chapter the calibration factor, alpha, in the Flow Distribution equation was assigned the standard factor of two in place of calibration for the reasons previously stated. If calibration were performed for this analysis, it

would be expected that the predicted values would be closer to the simulated values. If Flow Distribution were to be applied to a real system, calibration would be required. Several different calibration methods exist for calibrating the gravity model, and can be applied to Flow Distribution and the accuracy should be vastly improved.

The accuracy of Flow Distribution could also be improved by adding a gradient term or factor to the Flow Distribution equation. The current equation only accounts for the influences that friction has on the path water takes in a distribution system. However, the head difference between nodes is another contributing factor because water is more likely to travel to nodes with a positive head difference. Information necessary for a gradient factor can be determined from the schematic information of the distribution system and should be easy to implement with Flow Distribution.

During the development of the Flow Distribution experiment, choosing to predict the top five critical nodes was an arbitrary decision. After performing the analysis, two or three nodes significantly affected the distribution system more than the rest of the nodes. Flow Distribution correctly predicted the top three critical nodes 83% of the time and the top two critical nodes with 100% accuracy. Predicting the top four and five nodes was more difficult for Flow Distribution because the population and demand effect values were relatively close (within 10%) with the remaining junctions. It was unreasonable to think that an uncalibrated Flow Distribution program would distinguish between several nodes with such subtle differences. Using Flow Distribution to predict the top two or three nodes would have yielded better results and been more appropriate for this model. Flow Distribution works best in identifying outliers or nodes that if disabled would affect the system significantly.

Anytown is also a highly redundant system and the effects of disabled nodes are not as prevalent as they would be in a less redundant system. The table below (Table 13) supports this statement because it shows the demand effects to the rest of the system not including the demand of the node disabled. The junctions that caused the most problems were the ones that supplied

water to the system from either a reservoir or tank. With high redundancy, water is easily rerouted so it can be delivered to the nodes by a different route when a node is disabled. It is possible with this level of redundancy, Anytown only has a few critical nodes, and the rest have minimal effect on the system.

Table 13: Demand Effect to the Rest of the System for Disaster Run 1 & 2

Junction	Run 1			Run 2		
	Demand Effect (gpm)	Total Demand at node (gpm)	Demand Effect to rest of system (gpm)	Demand Effect (gpm)	Total Demand at node (gpm)	Demand Effect to rest of system (gpm)
J-20	140,579	12,350	128,229	12,434	12,350	84
J-30	32,285	4,940	27,345	5,386	4,940	446
J-40	5,028	4,940	88	5,038	4,940	98
J-50	6,079	4,940	1,139	5,186	4,940	246
J-60	14,040	12,350	1,690	64,993	12,350	52,643
J-70	39,593	12,350	27,243	12,580	12,350	230
J-80	12,464	12,350	114	12,534	12,350	184
J-90	24,700	24,700	0	24,714	24,700	14
J-100	12,468	12,350	118	12,459	12,350	109
J-110	20,491	12,350	8,141	12,446	12,350	96
J-120	4,940	4,940	0	4,940	4,940	0
J-130	4,984	4,940	44	5,196	4,940	256
J-140	5,894	4,940	954	5,222	4,940	282
J-150	5,891	4,940	951	5,217	4,940	277
J-160	19,846	19,760	86	59,716	19,760	39,956
J-170	5,895	4,940	955	5,168	4,940	228

5.2. Limitations

The application of Flow Distribution for vulnerability assessments has limitations. First, the normal operating scenario must resemble the disaster scenario in terms of the major water sources. If the same normal operating scenario had been used for the both disaster scenarios, the same five nodes would have been predicted to be the most critical, but as we saw, the critical nodes were different for the two disaster scenarios. This means a different disaster scenario must be created every time the water sources are changed for Flow Distribution to be effective.

Another limitation to this method is it will only analyze the detrimental effects of one disabled node or a group of nodes skeletonized to one node. It is conceivable for a disaster event to disable more than one demand node or multiple skeletonized groups at a time. The most detrimental node combination may not necessarily be the most critical nodes that were calculated

using the Flow Distribution method. This method does not consider the possible interactions that may occur if multiple nodes are disabled at a time. This method already assumes the nodes that supply the most demand or population to its direct consumers and to the downstream nodes in the system during normal operating conditions will affect the most demand or population when disabled. This assumption was correct 70% when one node was disabled, and the accuracy would most likely decrease exponentially if it were to be used to predict a combination of disabled nodes.

This program is also limited because only one time step is used for the analysis. To analyze the entire simulation, each time step must be analyzed separately. In theory, the critical nodes calculated by the program may change depending on which time step is used for the analysis. This method assumes that the critical nodes calculated by the method for the hour chosen, peak in this case, are the same for all other time steps.

5.3. Future Work

Although Flow Distribution produced fairly accurate results, additional research can be utilized to expand on this method including calibrating, application to a real system, and use with other methods to complete a vulnerability assessment. As stated previously, several approaches can be used to calibrate the gravity model and additional research could be utilized to determine which approaches, if any, yield the most accurate results for Flow Distribution. Applying Flow Distribution to a real system would add complications to the analysis including a connectivity analysis, skeletonization, and data management, and would test one of this research's objectives of creating a method that could be applied to any system. This research could be taken a step further by not only applying it to a real system, but using it as part of a vulnerability assessment to determine the feasibility of using Flow Distribution as part of a vulnerability assessment. One of the objectives of this research was to develop a method that allowed critical infrastructure to be incorporated. Critical infrastructure was not incorporated in this research, and future work could

determine the most effective and efficient method of incorporating critical infrastructure in the Flow Distribution analysis.

In the field of vulnerability assessments for water distribution systems, future work is needed. The literature review shows that an agreed upon method does not exist. It would be advantageous if the numerous methods were consolidated to form an agreed upon assessment program that covered all the required components of a vulnerability assessment stated by the EPA. Currently, each community performs a vulnerability assessment with different methodology making it impossible to compare results. A standard assessment would allow vulnerability comparison among various WDS, as well as, laws to be passed allowing only a certain amount of system vulnerability within a WDS.

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Appendix A: Matlab Code

```

%Flow Distribution

clc
clear

n = 18; %Number of nodes (includes pumps, reservoir, valves)
Pn = 34; %Number of pipes in system

Filename = 'Anytown_MatlabFile.xlsx';
ImportSheet = 'Run4';
ExportFile = 'Anytown_MatlabFile.xlsx';
ExportSheet = 'Run4_Results';

SN = zeros(Pn,1); %Start Node matrix
EN = zeros(Pn,1); %End Node matrix

R = zeros(1,Pn); %Pipe resistance matrix
DSp = zeros(n,n); %Intermediate Step
Y = zeros(n,n); %Intermediate Step
T = zeros(n,n); %Flow distribution matrix
PopEff = zeros(n,n); %Population Distribution matrix
DemEff = zeros(n,n); %Demand Distribution matrix

% Pipe Matrix imported from excel
% (Length, C-Factor, Diameter, Start Node, End Node, Start Node ML, End Node
ML)
P = xlsread(Filename, ImportSheet, 'C3:I36');

% Junction Matrix imported from excel
% (Demand, Production, Inflow, Population)
J = xlsread(Filename, ImportSheet, 'N3:Q20');

%Individual Pipe Impedance (k-factor)
%Equation = (phi*Length/(C-factor^1.85*Diameter^4.87)
for i=1:Pn
    R(i) = (P(i,1)*4.33)/((P(i,2)^1.85)*(P(i,3)/12)^4.87);
end
%display (R)

for i=1:Pn
    SN(i) = P(i,6);
end

for i=1:Pn
    EN(i) = P(i,7);
end

%Path of least resistance
%DG = sparse(start nodes, end nodes, resistance in each pipe, the size of
%the matrix, which equals the number of pipes
%SP equals the shortest path from one node to the rest of the nodes in the
%system
DG = sparse(SN, EN, R,n,n);
UG = tril(DG + DG');
view(biograph(UG,[], 'ShowArrows', 'off', 'ShowWeights', 'on'));

```

```

ShortPath = graphallshortestpaths(UG,'directed',false);

%display(ShortPath)

%Solves for DSp (column E)
for i=1:n
    for j=1:n
        DSp(i,j) = J(i,1)/((ShortPath(i,j))^2);
    end
end

% Infinity values exist in the DSp function because the DSp for loop divides
% by zero for the matrix diagonal
for i = 1:n
    for j = 1:n
        if i == j
            DSp(i,j) = 0;
        end
    end
end

%display(DSp)

% We need the row sums of matrix DSp, so we transpose matrix then sum the
% matrix columns
SumDSp = sum(DSp);

for i=1:n
    for j=1:n
        Y(i,j) = DSp(i,j)/SumDSp(j);
        T(i,j) = J(j,2)*Y(i,j);
    end
    Tsum(i) = sum(T(j));
end
%display(SumDSp)
%display(Y)
%display(sum(Y))
%display(T)
%display(sum(T))

for i=1:n
    for j=1:n
        DemEff(i,j) = T(i,j)/J(i,3)*J(i,1);
    end
end

for i = 1:n
    for j = 1:n
        if i == j
            DemEff(i,j) = J(i,1);
        end
    end
end

for i = 1:n

```

```

        for j = 1:n
            if DemEff(i,j) == inf
                DemEff(i,j) = 0;
            end
        end
    end
end

for i=1:n
    for j=1:n
        PopEff(i,j) = T(i,j)*J(i,4)/J(i,3);
    end
end

for i = 1:n
    for j = 1:n
        if i == j
            PopEff(i,j) = J(i,4);
        end
    end
end

for i = 1:n
    for j = 1:n
        if PopEff(i,j) == inf
            PopEff(i,j) = 0;
        end
    end
end

xlswrite(ExportFile, PopEff, ExportSheet, 'B2');
xlswrite(ExportFile, DemEff, ExportSheet, 'B28');
%xlswrite(ExportFile, R, ExportSheet, 'B58');
%xlswrite(ExportFile, ShortPath, 'Check', 'B3');

```


Appendix B: Tank Sizing

Appendix C: Disaster Scenario 1

Normal Operating Conditions

Failure Scenario 'J-20 Out'

Failure Scenario 'J-30 Out'

Failure Scenario 'J-40 Out'

Failure Scenario 'J-50 Out'

Failure Scenario 'J-60 Out'

Failure Scenario 'J-70 Out'

Failure Scenario 'J-80 Out'

Failure Scenario 'J-90 Out'

Failure Scenario 'J-100 Out'

Failure Scenario 'J-100 Out'

Failure Scenario 'J-110 Out'

Failure Scenario 'J-120 Out'

Failure Scenario 'J-130 Out'

Failure Scenario 'J-140 Out'

Failure Scenario 'J-150 Out'

Failure Scenario 'J-160 Out'

Failure Scenario 'J-170 Out'

Normal Operating Conditions

Pipe Information Imported into Matlab from WaterCAD

No.	Pipe	Length (ft)	C-Factor	Dia. (in.)	Start Node	Stop Node	Start Node	Stop Node	Flow (gpm)
1	P-2	12000	70	16	J-20	J-70	1	6	2,568
2	P-4	12000	120	12	J-20	J-30	1	2	2,064
3	P-6	12000	70	12	J-20	J-110	1	10	1,224
4	P-8	9000	70	12	J-30	J-70	2	6	40
5	P-10	600	70	12	J-70	J-100	6	9	922
6	P-12	600	70	10	J-70	J-90	6	8	578
7	P-14	600	70	12	J-70	J-60	6	5	458
8	P-16	600	70	10	J-60	J-90	5	8	488
9	P-18	600	70	12	J-60	J-80	5	7	714
10	P-20	600	70	10	J-80	J-90	7	8	187
11	P-22	600	70	10	J-90	J-150	8	14	26
12	P-24	600	70	10	J-100	J-90	9	8	73
13	P-26	600	70	12	J-100	J-150	9	14	128
14	P-28	600	70	10	J-80	J-150	7	14	189
15	P-30	600	120	10	J-30	J-60	2	5	527
16	P-32	600	120	10	J-30	J-40	2	3	572
17	P-34	600	120	10	J-30	J-50	2	4	665
18	P-36	600	120	10	J-40	J-50	3	4	312
19	P-38	600	120	10	J-50	J-80	4	7	637
20	P-40	600	120	10	J-80	J-140	7	13	324
21	P-42	600	120	8	J-150	J-140	14	13	2
22	P-44	600	120	8	J-150	J-160	14	15	81
23	P-46	600	120	8	J-100	J-160	9	15	114
24	P-48	600	70	8	J-110	J-100	10	9	43
25	P-50	600	120	10	J-110	J-160	10	15	249
26	P-52	600	120	8	J-110	J-120	10	11	282
27	P-56	600	120	8	J-120	J-130	11	12	22
28	P-58	600	120	10	J-160	J-130	15	12	432
29	P-60	600	120	8	J-130	J-170	12	16	194
30	P-62	600	120	8	J-140	J-160	13	15	81
31	P-64	12000	120	8	J-140	J-170	13	16	66
32	P-66	12000	120	8	J-50	J-140	4	13	80
33	P-78	100	120	12	T-65	J-60	17	5	867
34	P-80	100	120	12	T-165	J-160	18	15	947
35	P-100	1	130	6	PMP-3	J-20	22	1	0
36	P-101	1	130	6	PMP-3	R-1	22	19	0
37	P-102	1	130	6	R-1	PMP-2	19	21	3,253
38	P-103	1	130	6	R-1	PMP-1	19	20	3,253
39	P-104	1	130	6	PMP-1	J-20	20	1	3,253
40	P-105	1	130	6	PMP-2	J-20	21	1	3,253

Junction Information Imported into Matlab

Junc.	Matlab ID	Demand (gpm)	Node Outflow	Inflow (gpm)	Pop
J-20	1	650	5856	6506	3069
J-30	2	260	1804	2064	1421
J-40	3	260	312	572	6100
J-50	4	260	717	977	5953
J-60	5	650	1202	1852	2297
J-70	6	650	1958	2608	827
J-80	7	650	700	1351	4189
J-90	8	1,300	26	1326	6082
J-100	9	650	315	965	716
J-110	10	650	574	1224	4642
J-120	11	260	22	282	4949
J-130	12	260	194	454	5170
J-140	13	260	147	406	5248
J-150	14	260	83	343	4330
J-160	15	1,040	432	1472	1487
J-170	16	260	0	260	1901
T-65	17	0	867	0	0
T-165	18	0	947	0	0
R-1	19	0	6506	0	0
PMP-1	20	0	3253	3253	0
PMP-2	21	0	3253	3253	0
PMP-3	22	0	0	0	0
		Matlab Input			

Node inflow and outflow were calculated using the ‘Sumif’ command in Excel. For each junction, only the flows that had start and stop nodes equal to the junction in question were summed to solve for the outflow and inflow.

Flow Distribution Results: Demand Affected

	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
J-20	650	1	0	0	1	3	0	0	0	0	0	0	0	0	0	0
J-30	27	260	9	14	21	9	3	0	1	0	0	0	0	0	0	0
J-40	76	122	260	50	19	14	12	0	2	1	0	0	1	0	1	0
J-50	44	72	19	260	11	8	29	0	1	1	0	0	2	0	1	0
J-60	248	236	16	24	650	215	76	0	11	3	0	1	6	2	3	0
J-70	255	37	5	7	82	650	13	0	30	3	0	1	2	3	3	0
J-80	249	81	22	132	158	74	650	0	6	5	0	2	35	4	7	0
J-90	883	94	16	38	107	200	70	1300	39	12	1	4	10	15	13	0
J-100	477	43	7	10	55	413	16	0	650	12	1	4	3	30	17	0
J-110	147	7	2	4	6	16	6	0	5	650	3	11	2	2	119	0
J-120	62	3	1	1	2	4	2	0	1	12	260	4	1	0	5	0
J-130	63	3	1	2	3	7	2	0	2	16	1	260	1	1	51	0
J-140	105	19	5	18	24	19	69	0	2	5	0	1	260	2	7	0
J-150	169	12	3	7	12	50	12	0	39	6	0	2	3	260	8	0
J-160	381	21	6	13	18	52	19	0	19	314	4	98	9	7	1040	0
J-170	67	3	1	1	2	5	2	0	1	5	1	4	1	0	6	260
Total	3,905	1,016	372	581	1,169	1,737	982	1,300	810	1,044	273	392	336	326	1,282	260

Flow Distribution Results: Population Affected

	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
J-20	3069	5	1	2	4	12	2	0	2	1	0	0	0	0	1	0
J-30	147	1421	50	76	113	47	18	0	4	2	0	0	2	1	2	0
J-40	1780	2872	6100	1171	436	335	286	0	36	24	2	8	34	11	27	0
J-50	1017	1641	446	5953	249	192	654	0	20	19	2	6	44	10	22	0
J-60	878	835	57	85	2297	760	267	0	37	9	1	3	20	6	11	0
J-70	325	48	6	9	104	827	17	0	38	3	0	1	2	4	4	0
J-80	1607	522	142	851	1019	475	4189	0	41	35	3	11	224	24	44	0
J-90	4133	440	74	179	501	934	329	6082	183	56	5	17	47	68	63	0
J-100	525	48	8	11	61	455	18	0	716	13	1	4	3	33	19	0
J-110	1049	53	14	29	42	112	41	0	36	4642	24	82	17	13	849	0
J-120	1185	48	13	24	35	83	30	0	22	222	4949	69	11	8	100	0
J-130	1260	63	17	35	50	135	50	0	43	317	29	5170	21	16	1020	0
J-140	2111	389	106	357	475	380	1394	0	47	92	6	29	5248	33	132	0
J-150	2814	194	45	108	198	832	198	0	653	96	6	30	45	4330	138	0
J-160	545	31	8	18	26	74	28	0	28	449	6	140	13	10	1487	0
J-170	494	20	5	10	15	34	12	0	9	33	5	29	4	3	42	1901
Total	22,937	8,629	7,091	8,920	5,626	5,688	7,534	6,082	1,915	6,014	5,040	5,599	5,738	4,571	3,960	1,901

Demand during Normal Operating Conditions

J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
350	140	140	140	350	350	350	700	350	350	140	140	140	140	560	140
350	140	140	140	350	350	350	700	350	350	140	140	140	140	560	140
350	140	140	140	350	350	350	700	350	350	140	140	140	140	560	140
300	120	120	120	300	300	300	600	300	300	120	120	120	120	480	120
300	120	120	120	300	300	300	600	300	300	120	120	120	120	480	120
300	120	120	120	300	300	300	600	300	300	120	120	120	120	480	120
600	240	240	240	600	600	600	1200	600	600	240	240	240	240	960	240
600	240	240	240	600	600	600	1200	600	600	240	240	240	240	960	240
600	240	240	240	600	600	600	1200	600	600	240	240	240	240	960	240
650	260	260	260	650	650	650	1300	650	650	260	260	260	260	1040	260
650	260	260	260	650	650	650	1300	650	650	260	260	260	260	1040	260
650	260	260	260	650	650	650	1300	650	650	260	260	260	260	1040	260
600	240	240	240	600	600	600	1200	600	600	240	240	240	240	960	240
600	240	240	240	600	600	600	1200	600	600	240	240	240	240	960	240
600	240	240	240	600	600	600	1200	600	600	240	240	240	240	960	240
550	220	220	220	550	550	550	1100	550	550	220	220	220	220	880	220
550	220	220	220	550	550	550	1100	550	550	220	220	220	220	880	220
550	220	220	220	550	550	550	1100	550	550	220	220	220	220	880	220
500	200	200	200	500	500	500	1000	500	500	200	200	200	200	800	200
500	200	200	200	500	500	500	1000	500	500	200	200	200	200	800	200
500	200	200	200	500	500	500	1000	500	500	200	200	200	200	800	200
450	180	180	180	450	450	450	900	450	450	180	180	180	180	720	180
450	180	180	180	450	450	450	900	450	450	180	180	180	180	720	180
450	180	180	180	450	450	450	900	450	450	180	180	180	180	720	180
350	140	140	140	350	350	350	700	350	350	140	140	140	140	560	140
12,350	4,940	4,940	4,940	12,350	12,350	12,350	24,700	12,350	12,350	4,940	4,940	4,940	4,940	19,760	4,940

Failure Scenario 'J-20 Out'

Demand Supplied

Time (hrs)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	0	140	500	140	350	350	350	700	350	350	1140	500	140	140	560	140
1	0	140	500	140	350	350	350	700	350	350	1130	500	140	140	560	140
2	0	140	500	140	350	350	350	700	350	350	1107	495	140	140	560	139
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	0	420	1500	420	1050	1050	1050	2100	1050	1050	3377	1495	420	420	1680	419

‘J-20 Out’ Results

Node	Demand Supplied		Demand Effectuated	Population Served		
	Normal Conditions	Failure Scenario J-20 Out		Normal Conditions	Failure Scenario J-20 Out	Population Effectuated
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	0	12350	3069	0	3069
J-30	4940	420	4520	1421	121	1301
J-40	4940	1500	3440	6100	1852	4248
J-50	4940	420	4520	5953	506	5447
J-60	12350	1050	11300	2297	195	2102
J-70	12350	1050	11300	827	70	757
J-80	12350	1050	11300	4189	356	3832
J-90	24700	2100	22600	6082	517	5565
J-100	12350	1050	11300	716	61	655
J-110	12350	1050	11300	4642	395	4247
J-120	4940	3377	1563	4949	3383	1566
J-130	4940	1495	3445	5170	1565	3605
J-140	4940	420	4520	5248	446	4802
J-150	4940	420	4520	4330	368	3962
J-160	19760	1680	18080	1487	126	1360
J-170	4940	419	4521	1901	161	1740

The equations below were used for every failure scenario.

Column 4 = Column(2) – Column(3)

Column 6 = [Column(3)/ Column(2)]*Column 5

Column 7 = Column(5) – Column (6)

Failure Scenario ‘J-30 Out’

Demand Supplied

Time (hrs)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	350	0.00	500	140	350	350	350	700	350	350	1140	500	140	140	560	140
1	350	0.00	500	140	350	350	350	700	350	350	1140	500	140	140	560	140
2	350	0.00	500	140	350	350	350	700	350	350	1140	500	140	140	560	140
3	300	0.00	500	120	300	300	300	600	300	300	1120	500	120	120	480	120
4	300	0.00	500	120	300	300	300	600	300	300	1120	500	120	120	480	120
5	300	0.00	500	120	300	300	300	600	300	300	1120	500	120	120	480	120
6	600	0.00	500	240	600	600	600	1200	600	600	1240	500	240	240	960	240
7	600	0.00	500	240	600	600	600	1200	600	600	1240	500	240	240	960	240
8	600	0.00	322	156	402	435	394	796	401	403	786	320	157	158	628	153
9	650	0.00	304	159	413	450	403	816	411	414	755	302	161	162	643	157
10	650	0.00	304	159	413	450	403	816	411	414	755	302	161	162	643	157
11	650	0.00	304	159	413	450	403	816	411	414	755	302	161	162	643	157
12	600	0.00	322	156	402	435	394	796	401	403	786	320	157	158	628	153
13	600	0.00	322	156	402	435	394	796	401	403	786	320	157	158	628	153
14	600	0.00	322	156	402	435	394	796	401	403	786	320	157	158	628	153
15	550	0.00	342	151	390	418	383	773	389	391	820	340	153	154	611	149
16	550	0.00	342	151	390	418	383	773	389	391	820	340	153	154	611	149
17	550	0.00	342	151	390	418	383	773	389	391	820	340	153	154	611	149
18	500	0.00	364	146	376	400	370	747	375	376	858	361	148	148	590	144
19	500	0.00	364	146	376	400	370	747	375	376	858	361	148	148	590	144
20	500	0.00	364	147	376	400	370	747	375	376	858	361	148	148	590	144
21	450	0.00	388	141	361	381	355	716	359	360	900	385	142	142	567	139
22	450	0.00	388	141	361	381	355	716	359	360	900	385	142	142	567	139
23	450	0.00	388	141	361	381	355	716	359	360	900	385	142	142	567	139
24	350	0.00	446	126	321	334	317	638	320	320	999	443	127	127	506	124
Total	12350	0	9,928	3,802	9,699	10,171	9,576	19,278	9,676	9,705	23,402	9,887	3,827	3,837	15,291	3,763

'J-30 Out' Results

Node	Demand Supplied		Demand Effectd	Population Served		
	Normal Conditions	Failure Scenario J-30 Out		Normal Conditions	Failure Scenario J-30 Out	Population Effectd
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	12350	0	3069	3069	0
J-30	4940	0	4940	1421	0	1421
J-40	4940	9928	-4988	6100	12259	-6159
J-50	4940	3802	1138	5953	4582	1371
J-60	12350	9699	2651	2297	1804	493
J-70	12350	10171	2179	827	681	146
J-80	12350	9576	2774	4189	3248	941
J-90	24700	19278	5422	6082	4747	1335
J-100	12350	9676	2674	716	561	155
J-110	12350	9705	2645	4642	3648	994
J-120	4940	23402	-18462	4949	23445	-18496
J-130	4940	9887	-4947	5170	10347	-5177
J-140	4940	3827	1113	5248	4066	1182
J-150	4940	3837	1103	4330	3363	967
J-160	19760	15291	4469	1487	1151	336
J-170	4940	3763	1177	1901	1448	453

Failure Scenario 'J-40 Out'

Demand Supplied

Time (hours)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	350	140	0	140	350	350	350	700	350	350	1140	500	140	140	560	140
1	350	140	0	140	350	350	350	700	350	350	1140	500	140	140	560	140
2	350	140	0	140	350	350	350	700	350	350	1140	500	140	140	560	140
3	300	120	0	120	300	300	300	600	300	300	1120	500	120	120	480	120
4	300	120	0	120	300	300	300	600	300	300	1120	500	120	120	480	120
5	300	120	0	120	300	300	300	600	300	300	1120	500	120	120	480	120
6	600	240	0	240	600	600	600	1200	600	600	1240	500	240	240	960	240
7	600	240	0	240	600	600	600	1200	600	600	1240	500	240	240	960	240
8	600	240	0	240	600	600	600	1200	600	600	1240	500	240	240	960	240
9	650	260	0	260	650	650	650	1300	650	650	1260	500	260	260	1040	260
10	650	260	0	260	650	650	650	1300	650	650	1260	500	260	260	1040	260
11	650	260	0	260	650	650	650	1300	650	650	1260	500	260	260	1040	260
12	600	240	0	240	600	600	600	1200	600	600	1240	500	240	240	960	240
13	600	240	0	240	600	600	600	1200	600	600	1240	500	240	240	960	240
14	600	240	0	240	600	600	600	1200	600	600	1240	500	240	240	960	240
15	550	220	0	220	550	550	550	1100	550	550	1220	500	220	220	880	220
16	550	220	0	220	550	550	550	1098	548	542	1151	478	218	219	861	210
17	550	220	0	220	550	550	550	1098	548	542	1151	478	218	219	861	210
18	500	200	0	200	500	500	500	1000	500	500	1200	500	200	200	800	200
19	500	200	0	200	500	500	500	1000	500	500	1200	500	200	200	800	200
20	500	200	0	200	500	500	500	1000	500	500	1200	500	200	200	800	200
21	450	180	0	180	450	450	450	900	450	450	1180	500	180	180	720	180
22	450	180	0	180	450	450	450	900	450	450	1180	500	180	180	720	180
23	450	180	0	180	450	450	450	900	450	450	1180	500	180	180	720	180
24	350	140	0	140	350	350	350	700	350	350	1140	500	140	140	560	140
Total	12,350	4,940	0	4,940	12,350	12,350	12,350	24,696	12,346	12,334	29,802	12,456	4,936	4,938	19,722	4,920

'J-40 Out' Results

Node	Demand Supplied		Demand Effectuated	Population Served		
	Normal Conditions	Failure Scenario J-40 Out		Normal Conditions	Failure Scenario J-40 Out	Population Effectuated
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	12350	0	3069	3069	0
J-30	4940	4940	0	1421	1421	0
J-40	4940	0	4940	6100	0	6100
J-50	4940	4940	0	5953	5953	0
J-60	12350	12350	0	2297	2297	0
J-70	12350	12350	0	827	827	0
J-80	12350	12350	0	4189	4189	0
J-90	24700	24696	4	6082	6081	1
J-100	12350	12346	4	716	716	0
J-110	12350	12334	16	4642	4636	6
J-120	4940	29802	-24862	4949	29857	-24908
J-130	4940	12456	-7516	5170	13035	-7865
J-140	4940	4936	4	5248	5244	4
J-150	4940	4938	2	4330	4329	2
J-160	19760	19722	38	1487	1484	3
J-170	4940	4920	20	1901	1894	8

Failure Scenario 'J-50' Out

Demand Supplied

Time (hours)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	350	140	500	0	350	350	350	700	350	350	1140	500	140	140	560	140
1	350	140	500	0	350	350	350	700	350	350	1140	500	140	140	560	140
2	350	140	500	0	350	350	350	700	350	350	1140	500	140	140	560	140
3	300	120	500	0	300	300	300	600	300	300	1120	500	120	120	480	120
4	300	120	500	0	300	300	300	600	300	300	1120	500	120	120	480	120
5	300	120	500	0	300	300	300	600	300	300	1120	500	120	120	480	120
6	600	240	500	0	600	600	600	1200	600	600	1240	500	240	240	960	240
7	600	240	500	0	600	600	600	1200	600	600	1240	500	240	240	960	240
8	600	240	500	0	600	600	600	1200	600	600	1240	500	240	240	960	240
9	650	260	500	0	650	650	650	1300	650	650	1260	500	260	260	1040	260
10	650	260	500	0	650	650	650	1300	650	650	1260	500	260	260	1040	260
11	650	260	500	0	650	650	650	1300	650	650	1260	500	260	260	1040	260
12	600	240	500	0	600	600	600	1200	600	600	1240	500	240	240	960	240
13	600	240	500	0	600	600	600	1200	600	600	1240	500	240	240	960	240
14	600	240	498	0	567	577	546	1093	546	540	1065	435	217	217	856	209
15	550	220	500	0	546	550	528	1057	528	522	1108	461	210	210	829	203
16	550	220	500	0	546	550	528	1057	528	522	1108	461	210	210	829	203
17	550	220	500	0	546	550	528	1057	528	522	1108	461	210	210	829	203
18	500	200	500	0	500	500	500	1000	500	500	1171	494	200	200	800	198
19	500	200	500	0	500	500	500	1000	500	500	1171	494	200	200	800	198
20	500	200	500	0	500	500	500	1000	500	500	1171	494	200	200	800	198
21	450	180	500	0	450	450	450	900	450	450	1180	500	180	180	720	180
22	450	180	500	0	450	450	450	900	450	450	1180	500	180	180	720	180
23	450	180	500	0	450	450	450	900	450	450	1180	500	180	180	720	180
24	350	140	500	0	350	350	350	700	350	350	1140	500	140	140	560	140
Total	12350	4,940	12,498	0	12,305	12,327	12,230	24,464	12,230	12,206	29,342	12,300	4,887	4,887	19,503	4,852

'J-50 Out' Results

Node	Demand Supplied		Demand Effectd	Population Served		
	Normal Conditions	Failure Scenario J-50 Out		Normal Conditions	Failure Scenario J-50 Out	Population Effectd
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	12350	0	3069	3069	0
J-30	4940	4940	0	1421	1421	0
J-40	4940	12498	-7558	6100	15432	-9332
J-50	4940	0	4940	5953	0	5953
J-60	12350	12305	45	2297	2288	8
J-70	12350	12327	23	827	826	2
J-80	12350	12230	120	4189	4148	41
J-90	24700	24464	236	6082	6024	58
J-100	12350	12230	120	716	709	7
J-110	12350	12206	144	4642	4588	54
J-120	4940	29342	-24402	4949	29397	-24447
J-130	4940	12300	-7360	5170	12872	-7702
J-140	4940	4887	53	5248	5192	56
J-150	4940	4887	53	4330	4284	46
J-160	19760	19503	257	1487	1468	19
J-170	4940	4852	88	1901	1868	34

Failure Scenario 'J-60 Out'

Demand Supplied

Time (hours)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	350	140	500	140	0	350	350	700	350	350	1140	500	140	140	560	140
1	350	140	500	140	0	350	350	700	350	350	1140	500	140	140	560	140
2	350	140	500	140	0	350	350	700	350	350	1140	500	140	140	560	140
3	300	120	500	120	0	300	300	600	300	300	1120	500	120	120	480	120
4	300	120	500	120	0	300	300	600	300	300	1120	500	120	120	480	120
5	300	120	500	120	0	300	300	600	300	300	1120	500	120	120	480	120
6	600	240	500	240	0	600	600	1200	600	600	1240	500	240	240	960	240
7	600	240	500	240	0	600	600	1200	600	600	1240	500	240	240	960	240
8	600	240	500	240	0	600	600	1200	600	600	1240	500	240	240	960	240
9	650	260	500	260	0	650	650	1300	650	650	1260	500	260	260	1040	260
10	650	260	500	260	0	650	650	1300	650	650	1260	500	260	260	1040	260
11	650	255	477	246	0	633	584	1165	584	577	1065	429	232	232	914	223
12	600	240	497	237	0	600	566	1129	565	559	1103	451	225	225	887	216
13	600	240	497	237	0	600	566	1129	565	559	1103	451	225	225	887	216
14	600	240	497	237	0	600	566	1129	565	559	1103	451	225	225	887	216
15	550	220	500	220	0	550	548	1094	547	541	1149	477	218	218	860	210
16	550	220	500	220	0	550	548	1094	547	541	1149	477	218	218	860	210
17	550	220	500	220	0	550	548	1094	547	541	1149	477	218	218	860	210
18	500	200	500	200	0	500	500	1000	500	500	1200	500	200	200	800	200
19	500	200	500	200	0	500	500	1000	500	500	1200	500	200	200	800	200
20	500	200	500	200	0	500	500	1000	500	500	1200	500	200	200	800	200
21	450	180	500	180	0	450	450	900	450	450	1180	500	180	180	720	180
22	450	180	500	180	0	450	450	900	450	450	1180	500	180	180	720	180
23	450	180	500	180	0	450	450	900	450	450	1180	500	180	180	720	180
24	350	140	500	140	0	350	350	700	350	350	1140	500	140	140	560	140
Total	12350	4,935	12,468	4,917	0	12,333	12,176	24,334	12,170	12,127	29,121	12,213	4,861	4,861	19,355	4,801

'J-60 Out' Results

Node	Demand Supplied		Demand Effectd	Population Served		
	Normal Conditions	Failure Scenario J-60 Out		Normal Conditio ns	Failure Scenario J-60 Out	Population Effectd
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	12350	0	3069	3069	0
J-30	4940	4935	5	1421	1420	1
J-40	4940	12468	-7528	6100	15395	-9295
J-50	4940	4917	23	5953	5926	28
J-60	12350	0	12350	2297	0	2297
J-70	12350	12333	17	827	826	1
J-80	12350	12176	174	4189	4130	59
J-90	24700	24334	366	6082	5992	90
J-100	12350	12170	180	716	706	10
J-110	12350	12127	223	4642	4558	84
J-120	4940	29121	-24181	4949	29175	-24226
J-130	4940	12213	-7273	5170	12781	-7611
J-140	4940	4861	79	5248	5164	84
J-150	4940	4861	79	4330	4261	69
J-160	19760	19355	405	1487	1456	30
J-170	4940	4801	139	1901	1848	54

Failure Scenario 'J-70 Out'

Demand Supplied

Time (hours)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	350	140	500	140	350	0	350	700	350	350	1140	500	140	140	560	140
1	350	140	500	140	350	0	350	700	350	350	1140	500	140	140	560	140
2	350	140	500	140	350	0	350	700	350	350	1140	500	140	140	560	140
3	300	120	500	120	300	0	300	600	300	300	1120	500	120	120	480	120
4	300	120	500	120	300	0	300	600	300	300	1120	500	120	120	480	120
5	300	120	500	120	300	0	300	600	300	300	1120	500	120	120	480	120
6	600	240	500	240	600	0	600	1200	600	600	1240	500	240	240	960	240
7	600	240	500	240	600	0	600	1200	600	600	1240	500	240	240	960	240
8	600	163	330	157	375	0	369	722	360	371	721	293	145	144	575	141
9	650	169	315	162	385	0	378	739	369	381	692	277	149	148	589	144
10	650	169	315	162	385	0	378	739	369	381	692	277	149	148	589	144
11	650	169	315	162	385	0	378	739	369	381	692	277	149	148	589	144
12	600	163	330	157	375	0	369	722	360	371	721	293	145	144	575	141
13	600	163	330	157	375	0	369	722	360	371	721	293	145	144	575	141
14	600	163	330	157	375	0	369	722	360	371	721	293	145	144	575	141
15	550	157	346	151	363	0	358	703	351	360	753	312	141	141	560	137
16	550	157	346	151	363	0	358	703	351	360	753	312	141	141	560	137
17	550	157	346	151	363	0	358	703	351	360	753	312	141	141	560	137
18	500	150	365	145	350	0	346	680	340	347	789	332	137	136	542	133
19	500	150	365	145	350	0	346	680	340	347	789	332	137	136	542	133
20	500	150	365	145	350	0	346	680	340	347	789	332	137	136	542	133
21	450	142	386	138	335	0	332	654	327	332	829	355	131	131	521	128
22	450	142	386	138	335	0	332	654	327	332	829	355	131	131	521	128
23	450	142	386	138	335	0	332	654	327	332	829	355	131	131	521	128
24	350	124	436	122	298	0	296	586	293	296	923	409	118	117	467	115
Total	12350	3,890	9,992	3,798	9,247	0	9,164	18,102	9,044	9,190	22,256	9,409	3,632	3,621	14,443	3,565

'J-70 Out' Results

Node	Demand Supplied		Demand Effectuated	Population Served		
	Normal Conditions	Failure Scenario J-70 Out		Normal Conditions	Failure Scenario J-70 Out	Population Effectuated
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	12350	0	3069	3069	0
J-30	4940	3890	1050	1421	1119	302
J-40	4940	9992	-5052	6100	12338	-6238
J-50	4940	3798	1142	5953	4577	1376
J-60	12350	9247	3103	2297	1720	577
J-70	12350	0	12350	827	0	827
J-80	12350	9164	3186	4189	3108	1081
J-90	24700	18102	6598	6082	4458	1625
J-100	12350	9044	3306	716	524	192
J-110	12350	9190	3160	4642	3454	1188
J-120	4940	22256	-17316	4949	22297	-17348
J-130	4940	9409	-4469	5170	9846	-4677
J-140	4940	3632	1308	5248	3859	1390
J-150	4940	3621	1319	4330	3174	1156
J-160	19760	14443	5317	1487	1087	400
J-170	4940	3565	1375	1901	1372	529

Failure Scenario ‘J-80 Out’

Demand Supplied

Time (hours)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	350	140	500	140	350	350	0	700	350	350	1140	500	140	140	560	140
1	350	140	500	140	350	350	0	700	350	350	1140	500	140	140	560	140
2	350	140	500	140	350	350	0	700	350	350	1140	500	140	140	560	140
3	300	120	500	120	300	300	0	600	300	300	1120	500	120	120	480	120
4	300	120	500	120	300	300	0	600	300	300	1120	500	120	120	480	120
5	300	120	500	120	300	300	0	600	300	300	1120	500	120	120	480	120
6	600	240	500	240	600	600	0	1200	600	600	1240	500	240	240	960	240
7	600	240	500	240	600	600	0	1200	600	600	1240	500	240	240	960	240
8	600	240	500	240	600	600	0	1200	600	600	1240	500	240	240	960	240
9	650	260	500	260	650	650	0	1300	650	650	1260	500	260	260	1040	260
10	650	260	500	260	650	650	0	1300	650	650	1260	500	260	260	1040	260
11	650	260	500	260	650	650	0	1300	650	650	1260	500	260	260	1040	260
12	600	240	500	240	600	600	0	1200	600	600	1240	500	240	240	960	240
13	600	240	500	240	600	600	0	1200	600	600	1240	500	240	240	960	240
14	600	240	500	240	600	600	0	1200	600	600	1240	500	240	240	960	240
15	550	220	500	220	550	550	0	1100	550	550	1220	500	220	220	880	220
16	550	220	500	220	550	550	0	1100	548	539	1143	475	215	217	855	209
17	550	220	500	220	550	550	0	1100	548	539	1143	475	215	217	855	209
18	500	200	500	200	500	500	0	1000	500	500	1200	500	200	200	800	200
19	500	200	500	200	500	500	0	1000	500	500	1200	500	200	200	800	200
20	500	200	500	200	500	500	0	1000	500	500	1200	500	200	200	800	200
21	450	180	500	180	450	450	0	900	450	450	1180	500	180	180	720	180
22	450	180	500	180	450	450	0	900	450	450	1180	500	180	180	720	180
23	450	180	500	180	450	450	0	900	450	450	1180	500	180	180	720	180
24	350	140	500	140	350	350	0	700	350	350	1140	500	140	140	560	140
Total	12,350	4,940	12,500	4,940	12,350	12,350	0	24,700	12,346	12,328	29,786	12,450	4,930	4,934	19,710	4,918

'J-80 Out' Results

Node	Demand Supplied		Demand Effectuated	Population Served		
	Normal Conditions	Failure Scenario J-80 Out		Normal Conditions	Failure Scenario J-80 Out	Population Effectuated
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	12350	0	3069	3069	0
J-30	4940	4940	0	1421	1421	0
J-40	4940	12500	-7560	6100	15435	-9335
J-50	4940	4940	0	5953	5953	0
J-60	12350	12350	0	2297	2297	0
J-70	12350	12350	0	827	827	0
J-80	12350	0	12350	4189	0	4189
J-90	24700	24700	0	6082	6082	0
J-100	12350	12346	4	716	716	0
J-110	12350	12328	22	4642	4634	8
J-120	4940	29786	-24846	4949	29841	-24892
J-130	4940	12450	-7510	5170	13029	-7859
J-140	4940	4930	10	5248	5238	11
J-150	4940	4934	6	4330	4325	5
J-160	19760	19710	50	1487	1483	4
J-170	4940	4918	22	1901	1893	8

Failure Scenario 'J-90 Out'

Demand Supplied

Time (hours)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	350	140	500	140	350	350	350	0	350	350	1140	500	140	140	560	140
1	350	140	500	140	350	350	350	0	350	350	1140	500	140	140	560	140
2	350	140	500	140	350	350	350	0	350	350	1140	500	140	140	560	140
3	300	120	500	120	300	300	300	0	300	300	1120	500	120	120	480	120
4	300	120	500	120	300	300	300	0	300	300	1120	500	120	120	480	120
5	300	120	500	120	300	300	300	0	300	300	1120	500	120	120	480	120
6	600	240	500	240	600	600	600	0	600	600	1240	500	240	240	960	240
7	600	240	500	240	600	600	600	0	600	600	1240	500	240	240	960	240
8	600	240	500	240	600	600	600	0	600	600	1240	500	240	240	960	240
9	650	260	500	260	650	650	650	0	650	650	1260	500	260	260	1040	260
10	650	260	500	260	650	650	650	0	650	650	1260	500	260	260	1040	260
11	650	260	500	260	650	650	650	0	650	650	1260	500	260	260	1040	260
12	600	240	500	240	600	600	600	0	600	600	1240	500	240	240	960	240
13	600	240	500	240	600	600	600	0	600	600	1240	500	240	240	960	240
14	600	240	500	240	600	600	600	0	600	600	1240	500	240	240	960	240
15	550	220	500	220	550	550	550	0	550	550	1220	500	220	220	880	220
16	550	220	500	220	550	550	550	0	550	550	1220	500	220	220	880	220
17	550	220	500	220	550	550	550	0	550	550	1220	500	220	220	880	220
18	500	200	500	200	500	500	500	0	500	500	1200	500	200	200	800	200
19	500	200	500	200	500	500	500	0	500	500	1200	500	200	200	800	200
20	500	200	500	200	500	500	500	0	500	500	1200	500	200	200	800	200
21	450	180	500	180	450	450	450	0	450	450	1180	500	180	180	720	180
22	450	180	500	180	450	450	450	0	450	450	1180	500	180	180	720	180
23	450	180	500	180	450	450	450	0	450	450	1180	500	180	180	720	180
24	350	140	500	140	350	350	350	0	350	350	1140	500	140	140	560	140
Total	12350	4,940	12,500	4,940	12,350	12,350	12,350	0	12,350	12,350	29,940	12,500	4,940	4,940	19,760	4,940

'J-90 Out' Results

Node	Demand Supplied		Demand Effectuated	Population Served		
	Normal Conditions	Failure Scenario J-90 Out		Normal Conditions	Failure Scenario J-90 Out	Population Effectuated
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	12350	0	3069	3069	0
J-30	4940	4940	0	1421	1421	0
J-40	4940	12500	-7560	6100	15435	-9335
J-50	4940	4940	0	5953	5953	0
J-60	12350	12350	0	2297	2297	0
J-70	12350	12350	0	827	827	0
J-80	12350	12350	0	4189	4189	0
J-90	24700	0	24700	6082	0	6082
J-100	12350	12350	0	716	716	0
J-110	12350	12350	0	4642	4642	0
J-120	4940	29940	-25000	4949	29996	-25046
J-130	4940	12500	-7560	5170	13081	-7912
J-140	4940	4940	0	5248	5248	0
J-150	4940	4940	0	4330	4330	0
J-160	19760	19760	0	1487	1487	0
J-170	4940	4940	0	1901	1901	0

Failure Scenario 'J-100 Out'

Demand Supplied

Time (hours)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	350	140	500	140	350	350	350	700	0	350	1140	500	140	140	560	140
1	350	140	500	140	350	350	350	700	0	350	1140	500	140	140	560	140
2	350	140	500	140	350	350	350	700	0	350	1140	500	140	140	560	140
3	300	120	500	120	300	300	300	600	0	300	1120	500	120	120	480	120
4	300	120	500	120	300	300	300	600	0	300	1120	500	120	120	480	120
5	300	120	500	120	300	300	300	600	0	300	1120	500	120	120	480	120
6	600	240	500	240	600	600	600	1200	0	600	1240	500	240	240	960	240
7	600	240	500	240	600	600	600	1200	0	600	1240	500	240	240	960	240
8	600	240	500	240	600	600	600	1200	0	600	1240	500	240	240	960	240
9	650	260	500	260	650	650	650	1300	0	650	1260	500	260	260	1040	260
10	650	260	500	260	650	650	650	1300	0	650	1260	500	260	260	1040	260
11	650	260	500	260	650	650	650	1300	0	650	1260	500	260	260	1040	260
12	600	240	500	240	600	600	600	1200	0	600	1240	500	240	240	960	240
13	600	240	500	240	600	600	600	1200	0	600	1240	500	240	240	960	240
14	600	240	500	240	600	600	600	1200	0	600	1240	500	240	240	960	240
15	550	220	500	220	550	550	550	1100	0	550	1220	500	220	220	880	220
16	550	220	500	220	550	550	550	1100	0	533	1134	472	220	220	850	208
17	550	220	500	220	550	550	550	1100	0	533	1134	472	220	220	850	208
18	500	200	500	200	500	500	500	1000	0	500	1200	500	200	200	800	200
19	500	200	500	200	500	500	500	1000	0	500	1200	500	200	200	800	200
20	500	200	500	200	500	500	500	1000	0	500	1200	500	200	200	800	200
21	450	180	500	180	450	450	450	900	0	450	1180	500	180	180	720	180
22	450	180	500	180	450	450	450	900	0	450	1180	500	180	180	720	180
23	450	180	500	180	450	450	450	900	0	450	1180	500	180	180	720	180
24	350	140	500	140	350	350	350	700	0	350	1140	500	140	140	560	140
Total	12,350	4,940	12,500	4,940	12,350	12,350	12,350	24,700	0	12,316	29,768	12,444	4,940	4,940	19,700	4,916

'J-100 Out' Results

Node	Demand Supplied		Demand Effectuated	Population Served		
	Normal Conditions	Failure Scenario J-100 Out		Normal Conditions	Failure Scenario J-100 Out	Population Effectuated
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	12350	0	3069	3069	0
J-30	4940	4940	0	1421	1421	0
J-40	4940	12500	-7560	6100	15435	-9335
J-50	4940	4940	0	5953	5953	0
J-60	12350	12350	0	2297	2297	0
J-70	12350	12350	0	827	827	0
J-80	12350	12350	0	4189	4189	0
J-90	24700	24700	0	6082	6082	0
J-100	12350	0	12350	716	0	716
J-110	12350	12316	34	4642	4629	13
J-120	4940	29768	-24828	4949	29823	-24874
J-130	4940	12444	-7504	5170	13023	-7853
J-140	4940	4940	0	5248	5248	0
J-150	4940	4940	0	4330	4330	0
J-160	19760	19700	60	1487	1482	5
J-170	4940	4916	24	1901	1892	9

Failure Scenario 'J-110 Out'

Demand Supplied

Time (hours)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	350	140	500	140	350	350	350	700	350	0	1140	500	140	140	560	140
1	350	140	500	140	350	350	350	700	350	0	1140	500	140	140	560	140
2	350	140	500	140	350	350	350	700	350	0	1140	500	140	140	560	140
3	300	120	500	120	300	300	300	600	300	0	1120	500	120	120	480	120
4	300	120	500	120	300	300	300	600	300	0	1120	500	120	120	480	120
5	300	120	500	120	300	300	300	600	300	0	1120	500	120	120	480	120
6	600	240	500	240	600	600	600	1200	600	0	1240	500	240	240	960	240
7	600	240	500	240	600	600	600	1200	600	0	1240	500	240	240	960	240
8	600	240	500	240	600	600	600	1200	600	0	1240	500	240	240	960	240
9	650	260	500	260	650	650	650	1300	650	0	1260	500	260	260	1040	260
10	650	260	500	260	650	650	650	1300	650	0	1260	500	260	260	1040	260
11	650	218	409	212	527	544	513	1021	508	0	792	348	201	202	767	181
12	600	210	428	205	510	524	497	991	493	0	828	369	195	196	748	177
13	600	210	428	205	510	524	497	991	493	0	828	369	195	196	748	177
14	600	210	428	205	510	524	497	991	493	0	828	369	195	196	748	177
15	550	201	449	197	491	503	480	957	476	0	867	391	189	190	726	172
16	550	201	449	197	491	503	480	957	476	0	867	391	189	190	726	172
17	550	201	449	197	491	503	480	957	476	0	867	391	189	190	726	172
18	500	192	472	188	469	480	460	918	457	0	909	415	181	182	699	166
19	500	192	472	188	469	480	460	918	457	0	909	415	181	182	699	166
20	500	192	472	188	469	480	460	918	457	0	909	415	181	182	699	166
21	450	180	497	178	446	450	438	874	435	0	955	442	173	173	669	159
22	450	180	497	178	446	450	438	874	435	0	955	442	173	173	669	159
23	450	180	497	178	446	450	438	874	435	0	955	442	173	173	669	159
24	350	140	500	140	350	350	350	700	350	0	1140	500	140	140	560	140
Total	12350	4,727	11,947	4,676	11,675	11,815	11,538	23,041	11,491	0	25,629	11,199	4,575	4,585	17,933	4,363

'J-110 Out' Results

Node	Demand Supplied		Demand Effectuated	Population Served		
	Normal Conditions	Failure Scenario J-110 Out		Normal Conditions	Failure Scenario J-110 Out	Population Effectuated
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	12350	0	3069	3069	0
J-30	4940	4727	213	1421	1360	61
J-40	4940	11947	-7007	6100	14752	-8652
J-50	4940	4676	264	5953	5635	318
J-60	12350	11675	675	2297	2171	126
J-70	12350	11815	535	827	792	36
J-80	12350	11538	812	4189	3913	275
J-90	24700	23041	1659	6082	5674	409
J-100	12350	11491	859	716	666	50
J-110	12350	0	12350	4642	0	4642
J-120	4940	25629	-20689	4949	25677	-20727
J-130	4940	11199	-6259	5170	11720	-6550
J-140	4940	4575	365	5248	4861	388
J-150	4940	4585	355	4330	4019	311
J-160	19760	17933	1827	1487	1349	137
J-170	4940	4363	577	1901	1679	222

Failure Scenario 'J-120 Out'

Demand Supplied

Time (hours)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	350	140	500	140	350	350	350	700	350	350	0	500	140	140	560	140
1	350	140	500	140	350	350	350	700	350	350	0	500	140	140	560	140
2	350	140	500	140	350	350	350	700	350	350	0	500	140	140	560	140
3	300	120	500	120	300	300	300	600	300	300	0	500	120	120	480	120
4	300	120	500	120	300	300	300	600	300	300	0	500	120	120	480	120
5	300	120	500	120	300	300	300	600	300	300	0	500	120	120	480	120
6	600	240	500	240	600	600	600	1200	600	600	0	500	240	240	960	240
7	600	240	500	240	600	600	600	1200	600	600	0	500	240	240	960	240
8	600	240	500	240	600	600	600	1200	600	600	0	500	240	240	960	240
9	650	260	500	260	650	650	650	1300	650	650	0	500	260	260	1040	260
10	650	260	500	260	650	650	650	1300	650	650	0	500	260	260	1040	260
11	650	260	500	260	650	650	650	1300	650	650	0	500	260	260	1040	260
12	600	240	500	240	600	600	600	1200	600	600	0	500	240	240	960	240
13	600	240	500	240	600	600	600	1200	600	600	0	500	240	240	960	240
14	600	240	500	240	600	600	600	1200	600	600	0	500	240	240	960	240
15	550	220	500	220	550	550	550	1100	550	550	0	500	220	220	880	220
16	550	220	500	220	550	550	550	1100	550	550	0	500	220	220	880	220
17	550	220	500	220	550	550	550	1100	550	550	0	500	220	220	880	220
18	500	200	500	200	500	500	500	1000	500	500	0	500	200	200	800	200
19	500	200	500	200	500	500	500	1000	500	500	0	500	200	200	800	200
20	500	200	500	200	500	500	500	1000	500	500	0	500	200	200	800	200
21	450	180	500	180	450	450	450	900	450	450	0	500	180	180	720	180
22	450	180	500	180	450	450	450	900	450	450	0	500	180	180	720	180
23	450	180	500	180	450	450	450	900	450	450	0	500	180	180	720	180
24	350	140	500	140	350	350	350	700	350	350	0	500	140	140	560	140
Total	12350	4,940	12,500	4,940	12,350	12,350	12,350	24,700	12,350	12,350	0	12,500	4,940	4,940	19,760	4,940

‘J-120 Out’ Results

Node	Demand Supplied		Demand Effectuated	Population Served		
	Normal Conditions	Failure Scenario J-120 Out		Normal Conditions	Failure Scenario J-120 Out	Population Effectuated
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	12350	0	3069	3069	0
J-30	4940	4940	0	1421	1421	0
J-40	4940	12500	-7560	6100	15435	-9335
J-50	4940	4940	0	5953	5953	0
J-60	12350	12350	0	2297	2297	0
J-70	12350	12350	0	827	827	0
J-80	12350	12350	0	4189	4189	0
J-90	24700	24700	0	6082	6082	0
J-100	12350	12350	0	716	716	0
J-110	12350	12350	0	4642	4642	0
J-120	4940	0	4940	4949	0	4949
J-130	4940	12500	-7560	5170	13081	-7912
J-140	4940	4940	0	5248	5248	0
J-150	4940	4940	0	4330	4330	0
J-160	19760	19760	0	1487	1487	0
J-170	4940	4940	0	1901	1901	0

Failure Scenario 'J-130 Out'

Demand Supplied'

Time (hours)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	350	140	500	140	350	350	350	700	350	350	1140	0	140	140	560	140
1	350	140	500	140	350	350	350	700	350	350	1140	0	140	140	560	140
2	350	140	500	140	350	350	350	700	350	350	1140	0	140	140	560	140
3	300	120	500	120	300	300	300	600	300	300	1120	0	120	120	480	120
4	300	120	500	120	300	300	300	600	300	300	1120	0	120	120	480	120
5	300	120	500	120	300	300	300	600	300	300	1120	0	120	120	480	120
6	600	240	500	240	600	600	600	1200	600	600	1240	0	240	240	960	240
7	600	240	500	240	600	600	600	1200	600	600	1240	0	240	240	960	240
8	600	240	500	240	600	600	600	1200	600	600	1240	0	240	240	960	240
9	650	260	500	260	650	650	650	1300	650	650	1260	0	260	260	1040	260
10	650	260	500	260	650	650	650	1300	650	650	1260	0	260	260	1040	260
11	650	260	500	260	650	650	650	1300	650	650	1260	0	260	260	1040	260
12	600	240	500	240	600	600	600	1200	600	600	1240	0	240	240	960	240
13	600	240	500	240	600	600	600	1200	600	600	1240	0	240	240	960	240
14	600	240	500	240	600	600	600	1200	600	600	1240	0	240	240	960	240
15	550	220	500	220	550	550	550	1100	550	550	1220	0	220	220	880	220
16	550	220	500	220	550	550	550	1100	550	548	1108	0	220	220	876	204
17	550	220	500	220	550	550	550	1100	550	548	1108	0	220	220	876	204
18	500	200	500	200	500	500	500	1000	500	500	1200	0	200	200	800	200
19	500	200	500	200	500	500	500	1000	500	500	1200	0	200	200	800	200
20	500	200	500	200	500	500	500	1000	500	500	1200	0	200	200	800	200
21	450	180	500	180	450	450	450	900	450	450	1180	0	180	180	720	180
22	450	180	500	180	450	450	450	900	450	450	1180	0	180	180	720	180
23	450	180	500	180	450	450	450	900	450	450	1180	0	180	180	720	180
24	350	140	500	140	350	350	350	700	350	350	1140	0	140	140	560	140
Total	12350	4,940	12,500	4,940	12,350	12,350	12,350	24,700	12,350	12,346	29,716	0	4,940	4,940	19,752	4,908

'J-130 Out' Results

Node	Demand Supplied		Demand Effectuated	Population Served		
	Normal Conditions	Failure Scenario J-130 Out		Normal Conditions	Failure Scenario J-130 Out	Population Effectuated
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	12350	0	3069	3069	0
J-30	4940	4940	0	1421	1421	0
J-40	4940	12500	-7560	6100	15435	-9335
J-50	4940	4940	0	5953	5953	0
J-60	12350	12350	0	2297	2297	0
J-70	12350	12350	0	827	827	0
J-80	12350	12350	0	4189	4189	0
J-90	24700	24700	0	6082	6082	0
J-100	12350	12350	0	716	716	0
J-110	12350	12346	4	4642	4641	2
J-120	4940	29716	-24776	4949	29771	-24822
J-130	4940	0	4940	5170	0	5170
J-140	4940	4940	0	5248	5248	0
J-150	4940	4940	0	4330	4330	0
J-160	19760	19752	8	1487	1486	1
J-170	4940	4908	32	1901	1889	12

Failure Scenario 'J-140 Out'

Demand Supplied

Time (hours)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	350	140	500	140	350	350	350	700	350	350	1140	500	0	140	560	140
1	350	140	500	140	350	350	350	700	350	350	1140	500	0	140	560	140
2	350	140	500	140	350	350	350	700	350	350	1140	500	0	140	560	140
3	300	120	500	120	300	300	300	600	300	300	1120	500	0	120	480	120
4	300	120	500	120	300	300	300	600	300	300	1120	500	0	120	480	120
5	300	120	500	120	300	300	300	600	300	300	1120	500	0	120	480	120
6	600	240	500	240	600	600	600	1200	600	600	1240	500	0	240	960	240
7	600	240	500	240	600	600	600	1200	600	600	1240	500	0	240	960	240
8	600	240	500	240	600	600	600	1200	600	600	1240	500	0	240	960	240
9	650	260	500	260	650	650	650	1300	650	650	1260	500	0	260	1040	260
10	650	260	500	260	650	650	650	1300	650	650	1260	500	0	260	1040	260
11	650	260	500	260	650	650	650	1300	650	650	1260	500	0	260	1040	260
12	600	240	500	240	600	600	600	1200	600	600	1240	500	0	240	960	240
13	600	240	500	240	600	600	600	1200	600	600	1240	500	0	240	960	240
14	600	232	478	229	569	580	563	1113	553	541	1063	434	0	221	856	207
15	550	220	500	220	547	550	542	1073	533	522	1103	457	0	213	827	200
16	550	220	500	220	547	550	542	1073	533	522	1103	457	0	213	827	200
17	550	220	500	220	547	550	542	1073	533	522	1103	457	0	213	827	200
18	500	200	500	200	500	500	500	1000	500	500	1174	495	0	200	800	197
19	500	200	500	200	500	500	500	1000	500	500	1174	495	0	200	800	197
20	500	200	500	200	500	500	500	1000	500	500	1174	495	0	200	800	197
21	450	180	500	180	450	450	450	900	450	450	1180	500	0	180	720	180
22	450	180	500	180	450	450	450	900	450	450	1180	500	0	180	720	180
23	450	180	500	180	450	450	450	900	450	450	1180	500	0	180	720	180
24	350	140	500	140	350	350	350	700	350	350	1140	500	0	140	560	140
Total	12,350	4,932	12,478	4,929	12,310	12,330	12,289	24,532	12,252	12,207	29,334	12,290	0	4,900	19,497	4,838

'J-140 Out' Results

Node	Demand Supplied		Demand Effectuated	Population Served		
	Normal Conditions	Failure Scenario J-140 Out		Normal Conditions	Failure Scenario J-140 Out	Population Effectuated
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	12350	0	3069	3069	0
J-30	4940	4932	8	1421	1419	2
J-40	4940	12478	-7538	6100	15407	-9308
J-50	4940	4929	11	5953	5940	13
J-60	12350	12310	40	2297	2289	7
J-70	12350	12330	20	827	826	1
J-80	12350	12289	61	4189	4168	21
J-90	24700	24532	168	6082	6041	41
J-100	12350	12252	98	716	710	6
J-110	12350	12207	143	4642	4588	54
J-120	4940	29334	-24394	4949	29389	-24439
J-130	4940	12290	-7350	5170	12861	-7692
J-140	4940	0	4940	5248	0	5248
J-150	4940	4900	40	4330	4295	35
J-160	19760	19497	263	1487	1467	20
J-170	4940	4838	102	1901	1862	39

Failure Scenario 'J-150 Out'

Demand Supplied

Time (hours)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	350	140	500	140	350	350	350	700	350	350	1140	500	140	0	560	140
1	350	140	500	140	350	350	350	700	350	350	1140	500	140	0	560	140
2	350	140	500	140	350	350	350	700	350	350	1140	500	140	0	560	140
3	300	120	500	120	300	300	300	600	300	300	1120	500	120	0	480	120
4	300	120	500	120	300	300	300	600	300	300	1120	500	120	0	480	120
5	300	120	500	120	300	300	300	600	300	300	1120	500	120	0	480	120
6	600	240	500	240	600	600	600	1200	600	600	1240	500	240	0	960	240
7	600	240	500	240	600	600	600	1200	600	600	1240	500	240	0	960	240
8	600	240	500	240	600	600	600	1200	600	600	1240	500	240	0	960	240
9	650	260	500	260	650	650	650	1300	650	650	1260	500	260	0	1040	260
10	650	260	500	260	650	650	650	1300	650	650	1260	500	260	0	1040	260
11	650	260	500	260	650	650	650	1300	650	650	1260	500	260	0	1040	260
12	600	240	500	240	600	600	600	1200	600	600	1240	500	240	0	960	240
13	600	240	500	240	600	600	600	1200	600	600	1240	500	240	0	960	240
14	600	231	474	227	566	578	558	1114	555	543	1071	438	220	0	859	210
15	550	220	497	218	545	550	538	1073	534	524	1111	461	212	0	830	203
16	550	220	497	218	545	550	538	1073	534	524	1111	461	212	0	830	203
17	550	220	497	218	545	550	538	1073	534	524	1111	461	212	0	830	203
18	500	200	500	200	500	500	500	1000	500	500	1180	498	200	0	800	199
19	500	200	500	200	500	500	500	1000	500	500	1180	498	200	0	800	199
20	500	200	500	200	500	500	500	1000	500	500	1180	498	200	0	800	199
21	450	180	500	180	450	450	450	900	450	450	1180	500	180	0	720	180
22	450	180	500	180	450	450	450	900	450	450	1180	500	180	0	720	180
23	450	180	500	180	450	450	450	900	450	450	1180	500	180	0	720	180
24	350	140	500	140	350	350	350	700	350	350	1140	500	140	0	560	140
Total	12350	4,931	12,465	4,921	12,301	12,328	12,272	24,533	12,257	12,215	29,384	12,315	4,896	0	19,509	4,856

'J-150 Out' Results

Node	Demand Supplied		Demand Effectd	Population Served		
	Normal Conditions	Failure Scenario J-150 Out		Normal Conditions	Failure Scenario J-150 Out	Population Effectd
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	12350	0	3069	3069	0
J-30	4940	4931	9	1421	1419	3
J-40	4940	12465	-7525	6100	15391	-9292
J-50	4940	4921	19	5953	5931	23
J-60	12350	12301	49	2297	2288	9
J-70	12350	12328	22	827	826	1
J-80	12350	12272	78	4189	4162	26
J-90	24700	24533	167	6082	6041	41
J-100	12350	12257	93	716	711	5
J-110	12350	12215	135	4642	4591	51
J-120	4940	29384	-24444	4949	29439	-24489
J-130	4940	12315	-7375	5170	12888	-7718
J-140	4940	4896	44	5248	5202	47
J-150	4940	0	4940	4330	0	4330
J-160	19760	19509	251	1487	1468	19
J-170	4940	4856	84	1901	1869	32

Failure Scenario 'J-160 Out'

Demand Supplied

Time (hours)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	350	140	500	140	350	350	350	700	350	350	1140	500	140	140	0	140
1	350	140	500	140	350	350	350	700	350	350	1140	500	140	140	0	140
2	350	140	500	140	350	350	350	700	350	350	1140	500	140	140	0	140
3	300	120	500	120	300	300	300	600	300	300	1120	500	120	120	0	120
4	300	120	500	120	300	300	300	600	300	300	1120	500	120	120	0	120
5	300	120	500	120	300	300	300	600	300	300	1120	500	120	120	0	120
6	600	240	500	240	600	600	600	1200	600	600	1240	500	240	240	0	240
7	600	240	500	240	600	600	600	1200	600	600	1240	500	240	240	0	240
8	600	240	500	240	600	600	600	1200	600	600	1240	500	240	240	0	240
9	650	260	500	260	650	650	650	1300	650	650	1260	500	260	260	0	260
10	650	260	500	260	650	650	650	1300	650	650	1260	500	260	260	0	260
11	650	260	500	260	650	650	650	1300	650	650	1260	500	260	260	0	260
12	600	240	500	240	600	600	600	1200	600	600	1240	500	240	240	0	240
13	600	240	500	240	600	600	600	1200	600	600	1240	500	240	240	0	240
14	600	240	500	240	600	600	600	1200	600	595	1064	424	240	240	0	204
15	550	220	500	220	550	550	550	1100	550	550	1144	464	220	220	0	205
16	550	220	500	220	550	550	550	1100	550	550	1144	464	220	220	0	205
17	550	220	500	220	550	550	550	1100	550	550	1144	464	220	220	0	205
18	500	200	500	200	500	500	500	1000	500	500	1200	500	200	200	0	200
19	500	200	500	200	500	500	500	1000	500	500	1200	500	200	200	0	200
20	500	200	500	200	500	500	500	1000	500	500	1200	500	200	200	0	200
21	450	180	500	180	450	450	450	900	450	450	1180	500	180	180	0	180
22	450	180	500	180	450	450	450	900	450	450	1180	500	180	180	0	180
23	450	180	500	180	450	450	450	900	450	450	1180	500	180	180	0	180
24	350	140	500	140	350	350	350	700	350	350	1140	500	140	140	0	140
Total	12350	4,940	12,500	4,940	12,350	12,350	12,350	24,700	12,350	12,345	29,536	12,316	4,940	4,940	0	4,859

'J-160 Out' Results

Node	Demand Supplied		Demand Effectd	Population Served		
	Normal Conditions	Failure Scenario J-160 Out		Normal Conditions	Failure Scenario J-160 Out	Population Effectd
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	12350	0	3069	3069	0
J-30	4940	4940	0	1421	1421	0
J-40	4940	12500	-7560	6100	15435	-9335
J-50	4940	4940	0	5953	5953	0
J-60	12350	12350	0	2297	2297	0
J-70	12350	12350	0	827	827	0
J-80	12350	12350	0	4189	4189	0
J-90	24700	24700	0	6082	6082	0
J-100	12350	12350	0	716	716	0
J-110	12350	12345	5	4642	4640	2
J-120	4940	29536	-24596	4949	29591	-24642
J-130	4940	12316	-7376	5170	12889	-7719
J-140	4940	4940	0	5248	5248	0
J-150	4940	4940	0	4330	4330	0
J-160	19760	0	19760	1487	0	1487
J-170	4940	4859	81	1901	1870	31

Failure Scenario 'J-170 Out'

Demand Supplied

Time (hours)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	350	140	500	140	350	350	350	700	350	350	1140	500	140	140	560	0
1	350	140	500	140	350	350	350	700	350	350	1140	500	140	140	560	0
2	350	140	500	140	350	350	350	700	350	350	1140	500	140	140	560	0
3	300	120	500	120	300	300	300	600	300	300	1120	500	120	120	480	0
4	300	120	500	120	300	300	300	600	300	300	1120	500	120	120	480	0
5	300	120	500	120	300	300	300	600	300	300	1120	500	120	120	480	0
6	600	240	500	240	600	600	600	1200	600	600	1240	500	240	240	960	0
7	600	240	500	240	600	600	600	1200	600	600	1240	500	240	240	960	0
8	600	240	500	240	600	600	600	1200	600	600	1240	500	240	240	960	0
9	650	260	500	260	650	650	650	1300	650	650	1260	500	260	260	1040	0
10	650	260	500	260	650	650	650	1300	650	650	1260	500	260	260	1040	0
11	650	260	500	260	650	650	650	1300	650	650	1260	500	260	260	1040	0
12	600	240	500	240	600	600	600	1200	600	600	1240	500	240	240	960	0
13	600	240	500	240	600	600	600	1200	600	600	1240	500	240	240	960	0
14	600	230	471	226	563	574	554	1104	551	547	1082	443	220	220	868	0
15	550	220	494	217	541	550	534	1064	531	527	1121	466	212	212	838	0
16	550	220	494	217	541	550	534	1064	531	527	1121	466	212	212	838	0
17	550	220	494	217	541	550	534	1064	531	527	1121	466	212	212	838	0
18	500	200	500	200	500	500	500	1000	500	500	1190	500	200	200	800	0
19	500	200	500	200	500	500	500	1000	500	500	1190	500	200	200	800	0
20	500	200	500	200	500	500	500	1000	500	500	1190	500	200	200	800	0
21	450	180	500	180	450	450	450	900	450	450	1180	500	180	180	720	0
22	450	180	500	180	450	450	450	900	450	450	1180	500	180	180	720	0
23	450	180	500	180	450	450	450	900	450	450	1180	500	180	180	720	0
24	350	140	500	140	350	350	350	700	350	350	1140	500	140	140	560	0
Total	12,350	4,930	12,453	4,917	12,286	12,324	12,256	24,496	12,244	12,228	29,455	12,341	4,896	4,896	19,542	0

'J-170 Out' Results

Node	Demand Supplied		Demand Effectd	Population Served		
	Normal Conditions	Failure Scenario J-170 Out		Normal Conditions	Failure Scenario J-170 Out	Population Effectd
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	12350	0	3069	3069	0
J-30	4940	4930	10	1421	1419	3
J-40	4940	12453	-7513	6100	15377	-9277
J-50	4940	4917	23	5953	5926	28
J-60	12350	12286	64	2297	2285	12
J-70	12350	12324	26	827	826	2
J-80	12350	12256	94	4189	4157	32
J-90	24700	24496	204	6082	6032	50
J-100	12350	12244	106	716	710	6
J-110	12350	12228	122	4642	4596	46
J-120	4940	29455	-24515	4949	29510	-24561
J-130	4940	12341	-7401	5170	12915	-7745
J-140	4940	4896	44	5248	5202	47
J-150	4940	4896	44	4330	4292	39
J-160	19760	19542	218	1487	1471	16
J-170	4940	0	4940	1901	0	1901

Appendix D: Disaster Scenario 2

Normal Operating Conditions

Failure Scenario 'J-20 Out'

Failure Scenario 'J-30 Out'

Failure Scenario 'J-40 Out'

Failure Scenario 'J-50 Out'

Failure Scenario 'J-60 Out'

Failure Scenario 'J-70 Out'

Failure Scenario 'J-80 Out'

Failure Scenario 'J-90 Out'

Failure Scenario 'J-100 Out'

Failure Scenario 'J-100 Out'

Failure Scenario 'J-110 Out'

Failure Scenario 'J-120 Out'

Failure Scenario 'J-130 Out'

Failure Scenario 'J-140 Out'

Failure Scenario 'J-150 Out'

Failure Scenario 'J-160 Out'

Failure Scenario 'J-170 Out'

Normal Operating Conditions

Pipe Information Imported into Matlab from WaterCAD

No.	Pipe	Length (ft)	C- Factor	Dia. (in.)	Start Node	Stop Node	Start Node	Stop Node	Flow (gpm)
1	P-2	12,000	70	16	J-70	J-20	6	1	263
2	P-4	12,000	120	12	J-30	J-20	2	1	230
3	P-6	12,000	70	12	J-110	J-20	10	1	157
4	P-8	9,000	70	12	J-30	J-70	2	6	55
5	P-10	600	70	12	J-100	J-70	9	6	134
6	P-12	600	70	10	J-70	J-90	6	8	142
7	P-14	600	70	12	J-60	J-70	5	6	865
8	P-16	600	70	10	J-60	J-90	5	8	560
9	P-18	600	70	12	J-60	J-80	5	7	818
10	P-20	600	70	10	J-80	J-90	7	8	215
11	P-22	600	70	10	J-150	J-90	14	8	216
12	P-24	600	70	10	J-100	J-90	9	8	168
13	P-26	600	70	12	J-150	J-100	14	9	204
14	P-28	600	70	10	J-150	J-80	14	7	13
15	P-30	600	120	10	J-60	J-30	5	2	872
16	P-32	600	120	10	J-30	J-40	2	3	176
17	P-34	600	120	10	J-30	J-50	2	4	150
18	P-36	600	120	10	J-50	J-40	4	3	84
19	P-38	600	120	10	J-80	J-50	7	4	165
20	P-40	600	120	10	J-140	J-80	13	7	198
21	P-42	600	120	8	J-140	J-150	13	14	109
22	P-44	600	120	8	J-160	J-150	15	14	583
23	P-46	600	120	8	J-160	J-100	15	9	600
24	P-48	600	70	8	J-110	J-100	10	9	148
25	P-50	600	120	10	J-160	J-110	15	10	955
26	P-52	600	120	8	J-120	J-110	11	10	0
27	P-56	600	120	8	J-130	J-120	12	11	260
28	P-58	600	120	10	J-160	J-130	15	12	808
29	P-60	600	120	8	J-130	J-170	12	16	287
30	P-62	600	120	8	J-160	J-140	15	13	569
31	P-64	12,000	120	8	J-170	J-140	16	13	27
32	P-66	12,000	120	8	J-140	J-50	13	4	29
33	P-78	100	120	12	T-65	J-60	17	5	3,765
34	P-80	100	120	12	T-165	J-160	18	15	4,555

Junction Information Imported into Matlab

Junction	Matlab ID	Demand (gpm)	Node Outflow (gpm)	Inflow (gpm)	Population
J-20	1	650	0	650	3069
J-30	2	260	611	872	1421
J-40	3	260	0	260	6100
J-50	4	260	84	344	5953
J-60	5	650	3115	3765	2297
J-70	6	650	405	1054	827
J-80	7	650	380	1029	4189
J-90	8	1300	0	1301	6082
J-100	9	650	302	952	716
J-110	10	650	305	955	4642
J-120	11	260	0	260	4949
J-130	12	260	547	808	5170
J-140	13	260	336	596	5248
J-150	14	260	433	692	4330
J-160	15	1040	3515	4555	1487
J-170	16	260	27	287	1901
T-65	17	0	3765	0	0
T-165	18	0	4555	0	0
Matlab Input					

Flow Distribution Results: Demand Affected

	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
J-20	650	4	0	0	24	5	2	0	3	1	0	2	2	4	20	0
J-30	0	260	0	4	126	4	4	0	2	0	0	1	2	1	6	0
J-40	0	91	260	13	106	7	15	0	3	1	0	2	7	4	20	0
J-50	0	69	0	260	80	5	44	0	2	1	0	2	12	5	22	0
J-60	0	39	0	1	650	22	20	0	5	1	0	1	6	3	12	0
J-70	0	31	0	2	525	650	18	0	71	4	0	6	10	28	67	1
J-80	0	36	0	20	538	20	650	0	8	4	0	6	103	19	73	1
J-90	0	33	0	5	288	43	40	1300	39	7	0	11	24	61	113	2
J-100	0	15	0	1	145	87	9	0	650	6	0	11	7	124	142	1
J-110	0	3	0	1	20	4	4	0	6	650	0	41	7	10	1240	2
J-120	0	1	0	0	5	1	1	0	1	7	260	11	1	2	46	1
J-130	0	1	0	0	4	1	1	0	1	5	0	260	1	2	234	1
J-140	0	4	0	1	41	3	25	0	2	2	0	3	260	4	36	0
J-150	0	2	0	0	14	5	3	0	17	1	0	2	3	260	31	0
J-160	0	2	0	0	15	3	3	0	6	54	0	89	7	9	1040	2
J-170	0	1	0	0	5	1	1	0	1	2	0	10	1	2	42	260
Total	650	593	260	310	2,588	860	840	1,300	818	746	260	458	454	539	3,146	273

Flow Distribution Results: Population Affected

	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
J-20	3069	19	0	2	115	25	12	0	15	6	0	10	10	18	94	2
J-30	0	1421	0	21	691	23	24	0	9	2	0	3	12	8	33	1
J-40	0	2140	6100	302	2487	153	342	0	75	29	0	47	170	95	480	8
J-50	0	1579	0	5953	1835	113	1008	0	55	29	0	47	282	113	512	7
J-60	0	139	0	5	2297	77	71	0	18	2	0	4	22	12	43	1
J-70	0	40	0	3	669	827	23	0	91	4	0	7	12	36	86	1
J-80	0	232	0	131	3468	129	4189	0	52	24	0	40	664	125	472	5
J-90	0	155	0	22	1349	201	185	6082	183	31	0	51	111	287	529	8
J-100	0	16	0	1	160	95	10	0	716	7	0	12	7	136	156	1
J-110	0	23	0	4	139	30	29	0	44	4642	0	296	50	70	8853	17
J-120	0	18	0	3	99	19	18	0	23	128	4949	211	26	36	882	18
J-130	0	12	0	2	73	16	15	0	23	95	0	5170	27	37	4661	25
J-140	0	89	0	28	834	53	513	0	30	33	0	55	5248	90	730	6
J-150	0	30	0	6	237	79	50	0	289	24	0	39	46	4330	519	4
J-160	0	3	0	1	21	5	5	0	9	77	0	127	10	13	1487	3
J-170	0	6	0	1	34	6	6	0	8	16	0	74	9	12	307	1901
Total	3,069	5,923	6,100	6,486	14,510	1,851	6,499	6,082	1,640	5,149	4,949	6,194	6,707	5,419	19,844	2,009

Normal Operating Condition

Time (hours)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	350	140	140	140	350	350	350	700	350	350	140	140	140	140	560	140
1	350	140	140	140	350	350	350	700	350	350	140	140	140	140	560	140
2	350	140	140	140	350	350	350	700	350	350	140	140	140	140	560	140
3	300	120	120	120	300	300	300	600	300	300	120	120	120	120	480	120
4	300	120	120	120	300	300	300	600	300	300	120	120	120	120	480	120
5	300	120	120	120	300	300	300	600	300	300	120	120	120	120	480	120
6	600	240	240	240	600	600	600	1200	600	600	240	240	240	240	960	240
7	600	240	240	240	600	600	600	1200	600	600	240	240	240	240	960	240
8	600	240	240	240	600	600	600	1200	600	600	240	240	240	240	960	240
9	650	260	260	260	650	650	650	1300	650	650	260	260	260	260	1040	260
10	650	260	260	260	650	650	650	1300	650	650	260	260	260	260	1040	260
11	650	260	260	260	650	650	650	1300	650	650	260	260	260	260	1040	260
12	600	240	240	240	600	600	600	1200	600	600	240	240	240	240	960	240
13	600	240	240	240	600	600	600	1200	600	600	240	240	240	240	960	240
14	600	240	240	240	600	600	600	1200	600	600	240	240	240	240	960	240
15	550	220	220	220	550	550	550	1100	550	550	220	220	220	220	880	220
16	550	220	220	220	550	550	550	1100	550	550	220	220	220	220	880	220
17	550	220	220	220	550	550	550	1100	550	550	220	220	220	220	880	220
18	500	200	200	200	500	500	500	1000	500	500	200	200	200	200	800	200
19	500	200	200	200	500	500	500	1000	500	500	200	200	200	200	800	200
20	500	200	200	200	500	500	500	1000	500	500	200	200	200	200	800	200
21	450	180	180	180	450	450	450	900	450	450	180	180	180	180	720	180
22	450	180	180	180	450	450	450	900	450	450	180	180	180	180	720	180
23	450	180	180	180	450	450	450	900	450	450	180	180	180	180	720	180
24	350	140	140	140	350	350	350	700	350	350	140	140	140	140	560	140
Total	12,350	4,940	4,940	4,940	12,350	12,350	12,350	24,700	12,350	12,350	4,940	4,940	4,940	4,940	19,760	4,940

Failure Scenario 'J-20 Out'

Demand Supplied

Time (hours)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	0	140	500	140	350	350	350	700	350	350	1140	500	140	140	560	140
1	0	140	500	140	350	350	350	700	350	350	1140	500	140	140	560	140
2	0	140	500	140	350	350	350	700	350	350	1140	500	140	140	560	140
3	0	120	500	120	300	300	300	600	300	300	1120	500	120	120	480	120
4	0	120	500	120	300	300	300	600	300	300	1120	500	120	120	480	120
5	0	120	500	120	300	300	300	600	300	300	1120	500	120	120	480	120
6	0	240	500	240	600	600	600	1200	600	600	1240	500	240	240	960	240
7	0	240	500	240	600	600	600	1200	600	600	1240	500	240	240	960	240
8	0	240	500	240	600	600	600	1200	600	600	1240	500	240	240	960	240
9	0	260	500	260	650	650	650	1300	650	650	1260	500	260	260	1040	260
10	0	260	500	260	650	650	650	1300	650	650	1260	500	260	260	1040	260
11	0	260	500	260	650	650	650	1300	650	650	1260	500	260	260	1040	260
12	0	240	500	240	600	600	600	1200	600	600	1240	500	240	240	960	240
13	0	240	500	240	600	600	600	1200	600	600	1240	500	240	240	960	240
14	0	240	500	240	600	600	600	1200	600	600	1240	500	240	240	960	240
15	0	220	500	220	550	550	550	1100	550	550	1220	500	220	220	880	220
16	0	220	500	220	550	550	550	1100	550	550	1220	500	220	220	880	220
17	0	220	500	220	550	550	550	1100	550	550	1211	500	220	220	880	220
18	0	200	500	200	500	500	500	1000	500	500	1186	500	200	200	800	200
19	0	200	500	200	500	500	500	1000	500	500	1175	500	200	200	800	200
20	0	200	500	200	500	500	500	1000	500	500	1165	496	200	200	800	198
21	0	180	500	180	450	450	450	900	450	449	1141	494	180	180	720	178
22	0	180	500	180	450	450	450	900	450	445	1132	490	180	180	720	176
23	0	179	496	179	450	447	447	892	446	441	1123	486	179	179	718	175
24	0	139	496	139	350	348	347	694	347	343	1086	485	139	139	557	136
Total	0	4,938	12,492	4,938	12,350	12,345	12,344	24,686	12,343	12,328	29,659	12,451	4,938	4,938	19,755	4,923

'J-20 Out' Results

Node	Demand Supplied		Demand Effectuated	Population Served		
	Normal Conditions	Failure Scenario J-20 Out		Normal Conditions	Failure Scenario J-20 Out	Population Effectuated
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	0	12350	3069	0	3069
J-30	4940	4938	2	1421	1421	1
J-40	4940	12492	-7552	6100	15425	-9325
J-50	4940	4938	2	5953	5951	2
J-60	12350	12350	0	2297	2297	0
J-70	12350	12345	5	827	827	0
J-80	12350	12344	6	4189	4187	2
J-90	24700	24686	14	6082	6079	3
J-100	12350	12343	7	716	716	0
J-110	12350	12328	22	4642	4634	8
J-120	4940	29659	-24719	4949	29714	-24765
J-130	4940	12451	-7511	5170	13030	-7860
J-140	4940	4938	2	5248	5246	2
J-150	4940	4938	2	4330	4329	2
J-160	19760	19755	5	1487	1487	0
J-170	4940	4923	17	1901	1895	7

Failure Scenario 'J-30 Out'

Demand Supplied

Time (hours)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	350	0	500	140	350	350	350	700	350	350	1140	500	140	140	560	140
1	350	0	500	140	350	350	350	700	350	350	1140	500	140	140	560	140
2	350	0	500	140	350	350	350	700	350	350	1140	500	140	140	560	140
3	300	0	500	120	300	300	300	600	300	300	1120	500	120	120	480	120
4	300	0	500	120	300	300	300	600	300	300	1120	500	120	120	480	120
5	300	0	500	120	300	300	300	600	300	300	1120	500	120	120	480	120
6	600	0	500	240	600	600	600	1200	600	600	1240	500	240	240	960	240
7	600	0	500	240	600	600	600	1200	600	600	1240	500	240	240	960	240
8	600	0	500	240	600	600	600	1200	600	600	1240	500	240	240	960	240
9	650	0	500	260	650	650	650	1300	650	650	1260	500	260	260	1040	260
10	650	0	500	260	650	650	650	1300	650	650	1260	500	260	260	1040	260
11	650	0	500	260	650	650	650	1300	650	650	1260	500	260	260	1040	260
12	600	0	500	240	600	600	600	1200	600	600	1240	500	240	240	960	240
13	600	0	500	240	600	600	600	1200	600	600	1240	500	240	240	960	240
14	600	0	500	240	600	600	600	1200	600	600	1237	500	240	240	960	240
15	550	0	500	220	550	550	550	1100	550	550	1213	500	220	220	880	220
16	550	0	500	220	550	550	550	1100	550	550	1201	500	220	220	880	220
17	546	0	500	220	550	550	550	1100	550	550	1189	499	220	220	880	219
18	496	0	499	200	500	500	500	1000	500	500	1165	497	200	200	800	199
19	491	0	494	199	500	500	500	1000	500	495	1154	492	200	200	800	197
20	487	0	490	197	500	498	498	995	497	491	1144	488	199	199	800	195
21	438	0	488	177	450	447	446	892	446	440	1121	485	178	178	718	175
22	434	0	484	175	450	443	442	885	442	437	1112	481	177	177	712	173
23	431	0	480	174	450	439	439	877	439	433	1102	477	175	175	706	172
24	337	0	481	136	350	342	342	683	341	337	1067	477	137	137	548	134
Total	12,260	0	12,416	4,918	12,350	12,319	12,317	24,632	12,315	12,283	29,465	12,396	4,926	4,926	19,724	4,904

'J-30 Out' Results

Node	Demand Supplied		Demand Effectd	Population Served		
	Normal Conditions	Failure Scenario J-30 Out		Normal Conditions	Failure Scenario J-30 Out	Population Effectd
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	12260	90	3069	3047	22
J-30	4940	0	4940	1421	0	1421
J-40	4940	12416	-7476	6100	15331	-9231
J-50	4940	4918	22	5953	5927	27
J-60	12350	12350	0	2297	2297	0
J-70	12350	12319	31	827	825	2
J-80	12350	12317	33	4189	4177	11
J-90	24700	24632	68	6082	6066	17
J-100	12350	12315	35	716	714	2
J-110	12350	12283	67	4642	4617	25
J-120	4940	29465	-24525	4949	29520	-24571
J-130	4940	12396	-7456	5170	12972	-7803
J-140	4940	4926	14	5248	5234	15
J-150	4940	4926	14	4330	4318	12
J-160	19760	19724	36	1487	1484	3
J-170	4940	4904	36	1901	1888	14

Failure Scenario 'J-40 Out'

Demand Supplied

Time (hours)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	350	140	0	140	350	350	350	700	350	350	1140	500	140	140	560	140
1	350	140	0	140	350	350	350	700	350	350	1140	500	140	140	560	140
2	350	140	0	140	350	350	350	700	350	350	1140	500	140	140	560	140
3	300	120	0	120	300	300	300	600	300	300	1120	500	120	120	480	120
4	300	120	0	120	300	300	300	600	300	300	1120	500	120	120	480	120
5	300	120	0	120	300	300	300	600	300	300	1120	500	120	120	480	120
6	600	240	0	240	600	600	600	1200	600	600	1240	500	240	240	960	240
7	600	240	0	240	600	600	600	1200	600	600	1240	500	240	240	960	240
8	600	240	0	240	600	600	600	1200	600	600	1240	500	240	240	960	240
9	650	260	0	260	650	650	650	1300	650	650	1260	500	260	260	1040	260
10	650	260	0	260	650	650	650	1300	650	650	1260	500	260	260	1040	260
11	650	260	0	260	650	650	650	1300	650	650	1260	500	260	260	1040	260
12	600	240	0	240	600	600	600	1200	600	600	1240	500	240	240	960	240
13	600	240	0	240	600	600	600	1200	600	600	1240	500	240	240	960	240
14	600	240	0	240	600	600	600	1200	600	600	1240	500	240	240	960	240
15	550	220	0	220	550	550	550	1100	550	550	1220	500	220	220	880	220
16	550	220	0	220	550	550	550	1100	550	550	1220	500	220	220	880	220
17	550	220	0	220	550	550	550	1100	550	550	1210	500	220	220	880	220
18	500	200	0	200	500	500	500	1000	500	500	1186	500	200	200	800	200
19	500	200	0	200	500	500	500	1000	500	500	1175	500	200	200	800	200
20	500	200	0	200	500	500	500	1000	500	500	1165	496	200	200	800	198
21	450	180	0	180	450	450	450	900	450	449	1142	494	180	180	720	178
22	446	180	0	180	450	450	450	900	450	445	1133	490	180	180	720	176
23	442	179	0	179	450	446	447	892	446	442	1123	486	179	179	719	175
24	345	139	0	139	350	347	348	695	347	344	1087	486	139	139	557	136
Total	12,333	4,938	0	4,938	12,350	12,343	12,345	24,687	12,343	12,330	29,661	12,452	4,938	4,938	19,756	4,923

'J-40 Out' Results

Node	Demand Supplied		Demand Effectuated	Population Served		
	Normal Conditions	Failure Scenario J-40 Out		Normal Conditions	Failure Scenario J-40 Out	Population Effectuated
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	12333	17	3069	3065	4
J-30	4940	4938	2	1421	1421	1
J-40	4940	0	4940	6100	0	6100
J-50	4940	4938	2	5953	5951	2
J-60	12350	12350	0	2297	2297	0
J-70	12350	12343	7	827	827	0
J-80	12350	12345	5	4189	4187	2
J-90	24700	24687	13	6082	6079	3
J-100	12350	12343	7	716	716	0
J-110	12350	12330	20	4642	4635	8
J-120	4940	29661	-24721	4949	29716	-24767
J-130	4940	12452	-7512	5170	13031	-7861
J-140	4940	4938	2	5248	5246	2
J-150	4940	4938	2	4330	4329	2
J-160	19760	19756	4	1487	1487	0
J-170	4940	4923	17	1901	1895	7

Failure Scenario 'J-50 Out'

Demand Supplied

Time (hours)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	350	140	500	0	350	350	350	700	350	350	1140	500	140	140	560	140
1	350	140	500	0	350	350	350	700	350	350	1140	500	140	140	560	140
2	350	140	500	0	350	350	350	700	350	350	1140	500	140	140	560	140
3	300	120	500	0	300	300	300	600	300	300	1120	500	120	120	480	120
4	300	120	500	0	300	300	300	600	300	300	1120	500	120	120	480	120
5	300	120	500	0	300	300	300	600	300	300	1120	500	120	120	480	120
6	600	240	500	0	600	600	600	1200	600	600	1240	500	240	240	960	240
7	600	240	500	0	600	600	600	1200	600	600	1240	500	240	240	960	240
8	600	240	500	0	600	600	600	1200	600	600	1240	500	240	240	960	240
9	650	260	500	0	650	650	650	1300	650	650	1260	500	260	260	1040	260
10	650	260	500	0	650	650	650	1300	650	650	1260	500	260	260	1040	260
11	650	260	500	0	650	650	650	1300	650	650	1260	500	260	260	1040	260
12	600	240	500	0	600	600	600	1200	600	600	1240	500	240	240	960	240
13	600	240	500	0	600	600	600	1200	600	600	1240	500	240	240	960	240
14	600	240	500	0	600	600	600	1200	600	600	1240	500	240	240	960	240
15	550	220	500	0	550	550	550	1100	550	550	1220	500	220	220	880	220
16	550	220	500	0	550	550	550	1100	550	550	1213	500	220	220	880	220
17	550	220	500	0	550	550	550	1100	550	550	1201	500	220	220	880	220
18	500	200	500	0	500	500	500	1000	500	500	1177	500	200	200	800	200
19	500	200	500	0	500	500	500	1000	500	500	1166	497	200	200	800	199
20	496	200	499	0	500	500	500	1000	500	496	1155	492	200	200	800	197
21	445	180	496	0	450	449	450	898	449	445	1132	490	180	180	720	176
22	441	178	492	0	450	446	446	891	445	441	1122	486	178	178	718	175
23	437	177	488	0	450	442	443	883	442	437	1113	482	177	177	712	173
24	341	137	488	0	349	344	344	687	343	340	1077	481	138	137	552	135
Total	12,310	4,932	12,463	0	12,349	12,331	12,333	24,659	12,329	12,309	29,576	12,428	4,933	4,932	19,742	4,915

'J-50 Out' Results

Node	Demand Supplied		Demand Effectuated	Population Served		
	Normal Conditions	Failure Scenario J-50 Out		Normal Conditions	Failure Scenario J-50 Out	Population Effectuated
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	12310	40	3069	3059	10
J-30	4940	4932	8	1421	1419	2
J-40	4940	12463	-7523	6100	15389	-9289
J-50	4940	0	4940	5953	0	5953
J-60	12350	12349	1	2297	2297	0
J-70	12350	12331	19	827	826	1
J-80	12350	12333	17	4189	4183	6
J-90	24700	24659	41	6082	6072	10
J-100	12350	12329	21	716	715	1
J-110	12350	12309	41	4642	4627	15
J-120	4940	29576	-24636	4949	29631	-24682
J-130	4940	12428	-7488	5170	13006	-7836
J-140	4940	4933	7	5248	5241	7
J-150	4940	4932	8	4330	4323	7
J-160	19760	19742	18	1487	1486	1
J-170	4940	4915	25	1901	1892	10

Failure Scenario 'J-60 Out'

Demand Supplied

Time (hours)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	350	140	500	140	0	350	350	700	350	350	1140	500	140	140	560	140
1	350	140	500	140	0	350	350	700	350	350	1140	500	140	140	560	140
2	350	140	500	140	0	350	350	700	350	350	1140	500	140	140	560	140
3	300	120	500	120	0	300	300	600	300	300	1120	500	120	120	480	120
4	300	120	500	120	0	300	300	600	300	300	1120	500	120	120	480	120
5	300	120	500	120	0	300	300	600	300	300	1120	500	120	120	480	120
6	557	223	464	223	0	563	565	1127	575	599	1213	500	231	230	960	240
7	548	219	456	220	0	554	556	1108	565	589	1193	499	227	227	960	237
8	539	216	449	216	0	544	547	1090	556	579	1173	491	223	223	960	233
9	561	224	431	225	0	567	569	1135	581	609	1157	478	233	233	1040	245
10	551	220	423	221	0	557	559	1114	570	598	1136	469	229	228	1032	241
11	540	216	415	217	0	546	549	1094	560	587	1116	461	225	224	1013	236
12	501	200	417	201	0	506	508	1014	517	539	1091	457	208	207	924	217
13	492	197	410	197	0	497	499	995	508	529	1072	449	204	203	908	213
14	483	193	402	194	0	488	490	977	499	519	1052	440	200	200	891	209
15	445	178	404	178	0	449	450	898	457	473	1028	437	184	183	807	190
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	7,167	2,866	7,271	2,872	0	7,221	7,242	14,452	7,338	7,571	18,011	7,681	2,944	2,938	12,615	3,041

'J-60 Out' Results

Node	Demand Supplied		Demand Effectuated	Population Served		
	Normal Conditions	Failure Scenario J-60 Out		Normal Conditions	Failure Scenario J-60 Out	Population Effectuated
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	7167	5183	3069	1781	1288
J-30	4940	2866	2074	1421	825	597
J-40	4940	7271	-2331	6100	8978	-2878
J-50	4940	2872	2068	5953	3461	2492
J-60	12350	0	12350	2297	0	2297
J-70	12350	7221	5129	827	484	344
J-80	12350	7242	5108	4189	2456	1732
J-90	24700	14452	10248	6082	3559	2524
J-100	12350	7338	5012	716	426	291
J-110	12350	7571	4779	4642	2846	1796
J-120	4940	18011	-13071	4949	18044	-13095
J-130	4940	7681	-2741	5170	8038	-2868
J-140	4940	2944	1996	5248	3128	2121
J-150	4940	2938	2002	4330	2575	1755
J-160	19760	12615	7145	1487	949	538
J-170	4940	3041	1899	1901	1170	731

Failure Scenario 'J-70 Out'

Demand Supplied

Time (hours)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	350	140	500	140	350	0	350	700	350	350	1140	500	140	140	560	140
1	350	140	500	140	350	0	350	700	350	350	1140	500	140	140	560	140
2	350	140	500	140	350	0	350	700	350	350	1140	500	140	140	560	140
3	300	120	500	120	300	0	300	600	300	300	1120	500	120	120	480	120
4	300	120	500	120	300	0	300	600	300	300	1120	500	120	120	480	120
5	300	120	500	120	300	0	300	600	300	300	1120	500	120	120	480	120
6	600	240	500	240	600	0	600	1200	600	600	1240	500	240	240	960	240
7	600	240	500	240	600	0	600	1200	600	600	1240	500	240	240	960	240
8	600	240	500	240	600	0	600	1200	600	600	1240	500	240	240	960	240
9	650	260	500	260	650	0	650	1300	650	650	1260	500	260	260	1040	260
10	650	260	500	260	650	0	650	1300	650	650	1260	500	260	260	1040	260
11	650	260	500	260	650	0	650	1300	650	650	1260	500	260	260	1040	260
12	600	240	500	240	600	0	600	1200	600	600	1240	500	240	240	960	240
13	600	240	500	240	600	0	600	1200	600	600	1240	500	240	240	960	240
14	600	240	500	240	600	0	600	1200	600	600	1240	500	240	240	960	240
15	550	220	500	220	550	0	550	1100	550	550	1220	500	220	220	880	220
16	550	220	500	220	550	0	550	1100	550	550	1209	500	220	220	880	220
17	548	220	500	220	550	0	550	1100	550	550	1198	500	220	220	880	220
18	499	200	500	200	500	0	500	1000	500	500	1174	500	200	200	800	200
19	494	200	500	200	500	0	500	1000	500	499	1164	496	200	200	800	198
20	490	200	500	200	500	0	500	1000	500	495	1153	492	200	200	800	197
21	441	180	500	180	450	0	450	900	450	444	1131	490	180	180	720	176
22	437	180	498	179	450	0	448	894	446	440	1121	486	179	179	719	175
23	434	178	494	178	450	0	445	886	443	437	1112	482	178	177	713	173
24	340	139	494	138	350	0	346	690	344	340	1077	482	138	138	553	135
Total	12,283	4,937	12,486	4,935	12,350	0	12,339	24,670	12,333	12,305	29,559	12,428	4,935	4,934	19,745	4,914

'J-70 Out' Results

Node	Demand Supplied		Demand Effectuated	Population Served		
	Normal Conditions	Failure Scenario J-70 Out		Normal Conditions	Failure Scenario J-70 Out	Population Effectuated
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	12283	67	3069	3052	17
J-30	4940	4937	3	1421	1421	1
J-40	4940	12486	-7546	6100	15417	-9318
J-50	4940	4935	5	5953	5947	6
J-60	12350	12350	0	2297	2297	0
J-70	12350	0	12350	827	0	827
J-80	12350	12339	11	4189	4185	4
J-90	24700	24670	30	6082	6075	7
J-100	12350	12333	17	716	715	1
J-110	12350	12305	45	4642	4625	17
J-120	4940	29559	-24619	4949	29614	-24665
J-130	4940	12428	-7488	5170	13006	-7836
J-140	4940	4935	5	5248	5243	5
J-150	4940	4934	6	4330	4325	5
J-160	19760	19745	15	1487	1486	1
J-170	4940	4914	26	1901	1891	10

Failure Scenario 'J-80 Out'

Demand Supplied

Time (hours)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	350	140	500	140	350	350	0	700	350	350	1140	500	140	140	560	140
1	350	140	500	140	350	350	0	700	350	350	1140	500	140	140	560	140
2	350	140	500	140	350	350	0	700	350	350	1140	500	140	140	560	140
3	300	120	500	120	300	300	0	600	300	300	1120	500	120	120	480	120
4	300	120	500	120	300	300	0	600	300	300	1120	500	120	120	480	120
5	300	120	500	120	300	300	0	600	300	300	1120	500	120	120	480	120
6	600	240	500	240	600	600	0	1200	600	600	1240	500	240	240	960	240
7	600	240	500	240	600	600	0	1200	600	600	1240	500	240	240	960	240
8	600	240	500	240	600	600	0	1200	600	600	1240	500	240	240	960	240
9	650	260	500	260	650	650	0	1300	650	650	1260	500	260	260	1040	260
10	650	260	500	260	650	650	0	1300	650	650	1260	500	260	260	1040	260
11	650	260	500	260	650	650	0	1300	650	650	1260	500	260	260	1040	260
12	600	240	500	240	600	600	0	1200	600	600	1240	500	240	240	960	240
13	600	240	500	240	600	600	0	1200	600	600	1240	500	240	240	960	240
14	600	240	500	240	600	600	0	1200	600	600	1240	500	240	240	960	240
15	550	220	500	220	550	550	0	1100	550	550	1220	500	220	220	880	220
16	550	220	500	220	550	550	0	1100	550	550	1213	500	220	220	880	220
17	550	220	500	220	550	550	0	1100	550	550	1201	500	220	220	880	220
18	500	200	500	200	500	500	0	1000	500	500	1177	500	200	200	800	200
19	500	200	500	200	500	500	0	1000	500	500	1167	497	200	200	800	199
20	497	200	500	200	500	500	0	1000	500	497	1157	493	200	200	800	197
21	447	180	500	180	450	450	0	900	450	446	1134	490	180	180	720	176
22	443	179	497	179	450	448	0	894	447	442	1124	486	179	179	719	175
23	439	178	493	177	450	444	0	886	443	439	1115	482	177	177	713	174
24	343	138	493	138	350	346	0	690	345	342	1079	482	138	138	553	135
Total	12,319	4,935	12,483	4,934	12,350	12,338	0	24,670	12,335	12,316	29,587	12,430	4,934	4,934	19,745	4,916

'J-80 Out' Results

Node	Demand Supplied		Demand Effectuated	Population Served		
	Normal Conditions	Failure Scenario J-80 Out		Normal Conditions	Failure Scenario J-80 Out	Population Effectuated
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	12319	12350	3069	3061	8
J-30	4940	4935	4520	1421	1420	1
J-40	4940	12483	3440	6100	15414	-9314
J-50	4940	4934	4520	5953	5946	7
J-60	12350	12350	11300	2297	2297	0
J-70	12350	12338	11300	827	827	1
J-80	12350	0	11300	4189	0	4189
J-90	24700	24670	22600	6082	6075	7
J-100	12350	12335	11300	716	715	1
J-110	12350	12316	11300	4642	4629	13
J-120	4940	29587	1563	4949	29642	-24693
J-130	4940	12430	3445	5170	13008	-7838
J-140	4940	4934	4520	5248	5242	6
J-150	4940	4934	4520	4330	4325	5
J-160	19760	19745	18080	1487	1486	1
J-170	4940	4916	4521	1901	1892	9

Failure Scenario 'J-90 Out'

Demand Supplied

Time (hours)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	350	140	500	140	350	350	350	0	350	350	1140	500	140	140	560	140
1	350	140	500	140	350	350	350	0	350	350	1140	500	140	140	560	140
2	350	140	500	140	350	350	350	0	350	350	1140	500	140	140	560	140
3	300	120	500	120	300	300	300	0	300	300	1120	500	120	120	480	120
4	300	120	500	120	300	300	300	0	300	300	1120	500	120	120	480	120
5	300	120	500	120	300	300	300	0	300	300	1120	500	120	120	480	120
6	600	240	500	240	600	600	600	0	600	600	1240	500	240	240	960	240
7	600	240	500	240	600	600	600	0	600	600	1240	500	240	240	960	240
8	600	240	500	240	600	600	600	0	600	600	1240	500	240	240	960	240
9	650	260	500	260	650	650	650	0	650	650	1260	500	260	260	1040	260
10	650	260	500	260	650	650	650	0	650	650	1260	500	260	260	1040	260
11	650	260	500	260	650	650	650	0	650	650	1260	500	260	260	1040	260
12	600	240	500	240	600	600	600	0	600	600	1240	500	240	240	960	240
13	600	240	500	240	600	600	600	0	600	600	1240	500	240	240	960	240
14	600	240	500	240	600	600	600	0	600	600	1240	500	240	240	960	240
15	550	220	500	220	550	550	550	0	550	550	1220	500	220	220	880	220
16	550	220	500	220	550	550	550	0	550	550	1220	500	220	220	880	220
17	550	220	500	220	550	550	550	0	550	550	1220	500	220	220	880	220
18	500	200	500	200	500	500	500	0	500	500	1198	500	200	200	800	200
19	500	200	500	200	500	500	500	0	500	500	1188	500	200	200	800	200
20	500	200	500	200	500	500	500	0	500	500	1179	500	200	200	800	200
21	450	180	500	180	450	450	450	0	450	450	1155	500	180	180	720	180
22	450	180	500	180	450	450	450	0	450	450	1146	496	180	180	720	178
23	448	180	500	180	450	450	450	0	450	447	1138	492	180	180	720	177
24	350	140	500	140	350	350	350	0	350	348	1101	492	140	140	560	138
Total	12,348	4,940	12,500	4,940	12,350	12,350	12,350	0	12,350	12,345	29,765	12,480	4,940	4,940	19,760	4,933

'J-90 Out' Results

Node	Demand Supplied		Demand Effectuated	Population Served		
	Normal Conditions	Failure Scenario J-90 Out		Normal Conditions	Failure Scenario J-90 Out	Population Effectuated
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	12348	2	3069	3068	0
J-30	4940	4940	0	1421	1421	0
J-40	4940	12500	-7560	6100	15435	-9335
J-50	4940	4940	0	5953	5953	0
J-60	12350	12350	0	2297	2297	0
J-70	12350	12350	0	827	827	0
J-80	12350	12350	0	4189	4189	0
J-90	24700	0	24700	6082	0	6082
J-100	12350	12350	0	716	716	0
J-110	12350	12345	5	4642	4640	2
J-120	4940	29765	-24825	4949	29820	-24871
J-130	4940	12480	-7540	5170	13060	-7891
J-140	4940	4940	0	5248	5248	0
J-150	4940	4940	0	4330	4330	0
J-160	19760	19760	0	1487	1487	0
J-170	4940	4933	7	1901	1899	3

Failure Scenario 'J-100 Out'

Demand Supplied

Time (hours)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	350	140	500	140	350	350	350	700	0	350	1140	500	140	140	560	140
1	350	140	500	140	350	350	350	700	0	350	1140	500	140	140	560	140
2	350	140	500	140	350	350	350	700	0	350	1140	500	140	140	560	140
3	300	120	500	120	300	300	300	600	0	300	1120	500	120	120	480	120
4	300	120	500	120	300	300	300	600	0	300	1120	500	120	120	480	120
5	300	120	500	120	300	300	300	600	0	300	1120	500	120	120	480	120
6	600	240	500	240	600	600	600	1200	0	600	1240	500	240	240	960	240
7	600	240	500	240	600	600	600	1200	0	600	1240	500	240	240	960	240
8	600	240	500	240	600	600	600	1200	0	600	1240	500	240	240	960	240
9	650	260	500	260	650	650	650	1300	0	650	1260	500	260	260	1040	260
10	650	260	500	260	650	650	650	1300	0	650	1260	500	260	260	1040	260
11	650	260	500	260	650	650	650	1300	0	650	1260	500	260	260	1040	260
12	600	240	500	240	600	600	600	1200	0	600	1240	500	240	240	960	240
13	600	240	500	240	600	600	600	1200	0	600	1240	500	240	240	960	240
14	600	240	500	240	600	600	600	1200	0	600	1240	500	240	240	960	240
15	550	220	500	220	550	550	550	1100	0	550	1220	500	220	220	880	220
16	550	220	500	220	550	550	550	1100	0	550	1220	500	220	220	880	220
17	550	220	500	220	550	550	550	1100	0	550	1209	500	220	220	880	220
18	500	200	500	200	500	500	500	1000	0	500	1184	500	200	200	800	200
19	500	200	500	200	500	500	500	1000	0	500	1174	500	200	200	800	200
20	499	200	500	200	500	500	500	1000	0	499	1164	497	200	200	800	199
21	448	180	500	180	450	450	450	900	0	447	1140	494	180	180	720	178
22	445	180	499	180	450	450	450	899	0	444	1131	490	180	180	720	176
23	441	178	495	178	450	446	446	891	0	440	1122	486	179	179	720	175
24	344	139	495	139	350	347	347	694	0	342	1085	486	139	139	558	136
Total	12,327	4,937	12,489	4,937	12,350	12,343	12,343	24,684	0	12,322	29,649	12,453	4,938	4,938	19,758	4,924

'J-100 Out' Results

Node	Demand Supplied		Demand Effectuated	Population Served		
	Normal Conditions	Failure Scenario J-100 Out		Normal Conditions	Failure Scenario J-100 Out	Population Effectuated
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	12327	23	3069	3063	6
J-30	4940	4937	3	1421	1421	1
J-40	4940	12489	-7549	6100	15421	-9321
J-50	4940	4937	3	5953	5950	4
J-60	12350	12350	0	2297	2297	0
J-70	12350	12343	7	827	827	0
J-80	12350	12343	7	4189	4186	2
J-90	24700	24684	16	6082	6078	4
J-100	12350	0	12350	716	0	716
J-110	12350	12322	28	4642	4632	11
J-120	4940	29649	-24709	4949	29704	-24755
J-130	4940	12453	-7513	5170	13032	-7862
J-140	4940	4938	2	5248	5246	2
J-150	4940	4938	2	4330	4329	2
J-160	19760	19758	2	1487	1487	0
J-170	4940	4924	16	1901	1895	6

Failure Scenario 'J-110 Out'

Demand Supplied

Time (hours)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	350	140	500	140	350	350	350	700	350	0	1140	500	140	140	560	140
1	350	140	500	140	350	350	350	700	350	0	1140	500	140	140	560	140
2	350	140	500	140	350	350	350	700	350	0	1140	500	140	140	560	140
3	300	120	500	120	300	300	300	600	300	0	1120	500	120	120	480	120
4	300	120	500	120	300	300	300	600	300	0	1120	500	120	120	480	120
5	300	120	500	120	300	300	300	600	300	0	1120	500	120	120	480	120
6	600	240	500	240	600	600	600	1200	600	0	1233	500	240	240	960	240
7	600	240	500	240	600	600	600	1200	600	0	1222	500	240	240	960	240
8	600	240	500	240	600	600	600	1200	600	0	1212	500	240	240	960	240
9	650	260	500	260	650	650	650	1300	650	0	1212	500	260	260	1040	260
10	650	260	500	260	650	650	650	1300	650	0	1201	500	260	260	1040	260
11	650	260	500	260	650	650	650	1300	650	0	1189	500	260	260	1040	260
12	600	240	500	240	600	600	600	1200	600	0	1168	500	240	240	960	240
13	600	240	500	240	600	600	600	1200	600	0	1157	500	240	240	960	240
14	600	240	500	240	600	600	600	1200	600	0	1146	500	240	240	960	240
15	550	220	500	220	550	550	550	1100	550	0	1125	500	220	220	880	220
16	550	220	500	220	550	550	550	1100	550	0	1114	500	220	220	880	220
17	550	220	500	220	550	550	550	1100	550	0	1104	496	220	220	880	218
18	500	200	500	200	500	500	500	1000	500	0	1084	494	200	200	800	198
19	500	200	500	200	500	500	500	1000	500	0	1075	490	200	200	800	196
20	500	200	500	200	500	500	500	1000	500	0	1066	486	200	200	800	194
21	450	180	500	180	450	450	450	900	450	0	1046	484	180	180	720	174
22	446	180	499	180	450	450	450	900	450	0	1037	480	180	180	720	173
23	442	179	495	178	450	447	447	893	447	0	1029	476	179	179	720	171
24	345	139	495	139	350	348	348	695	348	0	999	476	139	139	560	133
Total	12,333	4,938	12,489	4,937	12,350	12,345	12,345	24,688	12,345	0	28,199	12,382	4,938	4,938	19,760	4,897

'J-110 Out' Results

Node	Demand Supplied		Demand Effectd	Population Served		
	Normal Conditions	Failure Scenario J-110 Out		Normal Conditions	Failure Scenario J-110 Out	Population Effectd
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	12333	17	3069	3065	4
J-30	4940	4938	2	1421	1421	1
J-40	4940	12489	-7549	6100	15421	-9321
J-50	4940	4937	3	5953	5950	4
J-60	12350	12350	0	2297	2297	0
J-70	12350	12345	5	827	827	0
J-80	12350	12345	5	4189	4187	2
J-90	24700	24688	12	6082	6079	3
J-100	12350	12345	5	716	716	0
J-110	12350	0	12350	4642	0	4642
J-120	4940	28199	-23259	4949	28251	-23302
J-130	4940	12382	-7442	5170	12958	-7788
J-140	4940	4938	2	5248	5246	2
J-150	4940	4938	2	4330	4329	2
J-160	19760	19760	0	1487	1487	0
J-170	4940	4897	43	1901	1885	17

Failure Scenario 'J-120 Out'

Demand Supplied

Time (hours)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	350	140	500	140	350	350	350	700	350	350	0	500	140	140	560	140
1	350	140	500	140	350	350	350	700	350	350	0	500	140	140	560	140
2	350	140	500	140	350	350	350	700	350	350	0	500	140	140	560	140
3	300	120	500	120	300	300	300	600	300	300	0	500	120	120	480	120
4	300	120	500	120	300	300	300	600	300	300	0	500	120	120	480	120
5	300	120	500	120	300	300	300	600	300	300	0	500	120	120	480	120
6	600	240	500	240	600	600	600	1200	600	600	0	500	240	240	960	240
7	600	240	500	240	600	600	600	1200	600	600	0	500	240	240	960	240
8	600	240	500	240	600	600	600	1200	600	600	0	500	240	240	960	240
9	650	260	500	260	650	650	650	1300	650	650	0	500	260	260	1040	260
10	650	260	500	260	650	650	650	1300	650	650	0	500	260	260	1040	260
11	650	260	500	260	650	650	650	1300	650	650	0	500	260	260	1040	260
12	600	240	500	240	600	600	600	1200	600	600	0	500	240	240	960	240
13	600	240	500	240	600	600	600	1200	600	600	0	500	240	240	960	240
14	600	240	500	240	600	600	600	1200	600	600	0	500	240	240	960	240
15	550	220	500	220	550	550	550	1100	550	550	0	500	220	220	880	220
16	550	220	500	220	550	550	550	1100	550	550	0	500	220	220	880	220
17	550	220	500	220	550	550	550	1100	550	550	0	500	220	220	880	220
18	500	200	500	200	500	500	500	1000	500	500	0	500	200	200	800	200
19	500	200	500	200	500	500	500	1000	500	500	0	500	200	200	800	200
20	500	200	500	200	500	500	500	1000	500	500	0	500	200	200	800	200
21	450	180	500	180	450	450	450	900	450	450	0	500	180	180	720	180
22	450	180	500	180	450	450	450	900	450	450	0	500	180	180	720	180
23	450	180	500	180	450	450	450	900	450	450	0	500	180	180	720	180
24	350	140	500	140	350	350	350	700	350	350	0	500	140	140	560	140
Total	12,350	4,940	12,500	4,940	12,350	12,350	12,350	24,700	12,350	12,350	0	12,500	4,940	4,940	19,760	4,940

'J-120 Out' Results

Node	Demand Supplied		Demand Effectuated	Population Served		
	Normal Conditions	Failure Scenario J-120 Out		Normal Conditions	Failure Scenario J-120 Out	Population Effectuated
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	12350	0	3069	3069	0
J-30	4940	4940	0	1421	1421	0
J-40	4940	12500	-7560	6100	15435	-9335
J-50	4940	4940	0	5953	5953	0
J-60	12350	12350	0	2297	2297	0
J-70	12350	12350	0	827	827	0
J-80	12350	12350	0	4189	4189	0
J-90	24700	24700	0	6082	6082	0
J-100	12350	12350	0	716	716	0
J-110	12350	12350	0	4642	4642	0
J-120	4940	0	4940	4949	0	4949
J-130	4940	12500	-7560	5170	13081	-7912
J-140	4940	4940	0	5248	5248	0
J-150	4940	4940	0	4330	4330	0
J-160	19760	19760	0	1487	1487	0
J-170	4940	4940	0	1901	1901	0

Failure Scenario 'J-130 Out'

Demand Supplied

Time (hours)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	350	140	500	140	350	350	350	700	350	350	1140	0	140	140	560	140
1	350	140	500	140	350	350	350	700	350	350	1140	0	140	140	560	140
2	350	140	500	140	350	350	350	700	350	350	1140	0	140	140	560	140
3	300	120	500	120	300	300	300	600	300	300	1120	0	120	120	480	120
4	300	120	500	120	300	300	300	600	300	300	1120	0	120	120	480	120
5	300	120	500	120	300	300	300	600	300	300	1120	0	120	120	480	120
6	600	240	500	240	600	600	600	1200	600	600	1240	0	240	240	960	240
7	600	240	500	240	600	600	600	1200	600	600	1240	0	240	240	960	240
8	600	240	500	240	600	600	600	1200	600	600	1236	0	240	240	960	240
9	650	260	500	260	650	650	650	1300	650	650	1233	0	260	260	1040	258
10	650	260	500	260	650	650	650	1300	650	650	1222	0	260	260	1040	255
11	650	260	500	260	650	650	650	1300	650	650	1210	0	260	260	1040	253
12	600	240	500	240	600	600	600	1200	600	600	1190	0	240	240	960	235
13	600	240	500	240	600	600	600	1200	600	600	1179	0	240	240	960	233
14	600	240	500	240	600	600	600	1200	600	600	1168	0	240	240	960	231
15	550	220	500	220	550	550	550	1100	550	550	1148	0	220	220	880	214
16	550	220	500	220	550	550	550	1100	550	550	1138	0	220	220	880	212
17	550	220	500	220	550	550	550	1100	550	550	1127	0	220	220	880	210
18	500	200	500	200	500	500	500	1000	500	500	1108	0	200	200	800	192
19	500	200	500	200	500	500	500	1000	500	500	1099	0	200	200	800	191
20	497	200	500	200	500	500	500	1000	500	496	1089	0	200	200	800	189
21	447	180	500	180	450	450	450	900	450	446	1071	0	180	180	720	171
22	443	179	497	179	450	448	449	896	448	442	1062	0	180	180	720	170
23	440	178	493	178	450	445	445	889	445	438	1054	0	178	178	720	169
24	343	139	494	139	350	346	347	693	346	342	1026	0	139	139	560	134
Total	12,320	4,936	12,484	4,936	12,350	12,339	12,341	24,678	12,339	12,314	28,620	0	4,937	4,937	19,760	4,817

'J-130 Out' Results

Node	Demand Supplied		Demand Effectd	Population Served		
	Normal Conditions	Failure Scenario J-130 Out		Normal Conditions	Failure Scenario J- 130 Out	Population Effectd
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	12320	30	3069	3062	7
J-30	4940	4936	4	1421	1420	1
J-40	4940	12484	-7544	6100	15415	-9315
J-50	4940	4936	4	5953	5949	5
J-60	12350	12350	0	2297	2297	0
J-70	12350	12339	11	827	827	1
J-80	12350	12341	9	4189	4186	3
J-90	24700	24678	22	6082	6077	5
J-100	12350	12339	11	716	715	1
J-110	12350	12314	36	4642	4629	14
J-120	4940	28620	-23680	4949	28673	-23724
J-130	4940	0	4940	5170	0	5170
J-140	4940	4937	3	5248	5245	3
J-150	4940	4937	3	4330	4328	3
J-160	19760	19760	0	1487	1487	0
J-170	4940	4817	123	1901	1854	47

Failure Scenario 'J-140 Out'

Demand Supplied

Time (hours)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	350	140	500	140	350	350	350	700	350	350	1140	500	0	140	560	140
1	350	140	500	140	350	350	350	700	350	350	1140	500	0	140	560	140
2	350	140	500	140	350	350	350	700	350	350	1140	500	0	140	560	140
3	300	120	500	120	300	300	300	600	300	300	1120	500	0	120	480	120
4	300	120	500	120	300	300	300	600	300	300	1120	500	0	120	480	120
5	300	120	500	120	300	300	300	600	300	300	1120	500	0	120	480	120
6	600	240	500	240	600	600	600	1200	600	600	1240	500	0	240	960	240
7	600	240	500	240	600	600	600	1200	600	600	1240	500	0	240	960	240
8	600	240	500	240	600	600	600	1200	600	600	1240	500	0	240	960	240
9	650	260	500	260	650	650	650	1300	650	650	1260	500	0	260	1040	260
10	650	260	500	260	650	650	650	1300	650	650	1260	500	0	260	1040	260
11	650	260	500	260	650	650	650	1300	650	650	1260	500	0	260	1040	260
12	600	240	500	240	600	600	600	1200	600	600	1240	500	0	240	960	240
13	600	240	500	240	600	600	600	1200	600	600	1240	500	0	240	960	240
14	600	240	500	240	600	600	600	1200	600	600	1240	500	0	240	960	240
15	550	220	500	220	550	550	550	1100	550	550	1220	500	0	220	880	220
16	550	220	500	220	550	550	550	1100	550	550	1212	500	0	220	880	220
17	550	220	500	220	550	550	550	1100	550	550	1200	500	0	220	880	220
18	500	200	500	200	500	500	500	1000	500	500	1176	500	0	200	800	199
19	500	200	500	200	500	500	500	1000	500	500	1165	496	0	200	800	198
20	495	200	500	200	500	500	500	997	499	496	1154	491	0	200	800	196
21	444	180	498	179	450	449	449	895	447	445	1131	489	0	179	720	176
22	441	178	493	178	450	445	445	887	444	441	1121	485	0	178	720	174
23	437	176	489	176	450	441	441	880	440	437	1112	481	0	176	714	173
24	341	137	489	137	348	343	344	685	343	341	1076	480	0	137	553	134
Total	12,308	4,931	12,469	4,930	12,348	12,328	12,329	24,644	12,323	12,310	29,567	12,422	0	4,930	19,747	4,910

'J-140 Out' Results

Node	Demand Supplied		Demand Effectuated	Population Served		
	Normal Conditions	Failure Scenario J-140 Out		Normal Conditions	Failure Scenario J-140 Out	Population Effectuated
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	12308	42	3069	3059	10
J-30	4940	4931	9	1421	1419	3
J-40	4940	12469	-7529	6100	15396	-9297
J-50	4940	4930	10	5953	5941	12
J-60	12350	12348	2	2297	2296	0
J-70	12350	12328	22	827	826	1
J-80	12350	12329	21	4189	4181	7
J-90	24700	24644	56	6082	6068	14
J-100	12350	12323	27	716	715	2
J-110	12350	12310	40	4642	4627	15
J-120	4940	29567	-24627	4949	29622	-24673
J-130	4940	12422	-7482	5170	13000	-7830
J-140	4940	0	4940	5248	0	5248
J-150	4940	4930	10	4330	4322	9
J-160	19760	19747	13	1487	1486	1
J-170	4940	4910	30	1901	1890	12

Failure Scenario ‘J-150 Out’

Demand Supplied

Time (hours)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	350	140	500	140	350	350	350	700	350	350	1140	500	140	0	560	140
1	350	140	500	140	350	350	350	700	350	350	1140	500	140	0	560	140
2	350	140	500	140	350	350	350	700	350	350	1140	500	140	0	560	140
3	300	120	500	120	300	300	300	600	300	300	1120	500	120	0	480	120
4	300	120	500	120	300	300	300	600	300	300	1120	500	120	0	480	120
5	300	120	500	120	300	300	300	600	300	300	1120	500	120	0	480	120
6	600	240	500	240	600	600	600	1200	600	600	1240	500	240	0	960	240
7	600	240	500	240	600	600	600	1200	600	600	1240	500	240	0	960	240
8	600	240	500	240	600	600	600	1200	600	600	1240	500	240	0	960	240
9	650	260	500	260	650	650	650	1300	650	650	1260	500	260	0	1040	260
10	650	260	500	260	650	650	650	1300	650	650	1260	500	260	0	1040	260
11	650	260	500	260	650	650	650	1300	650	650	1260	500	260	0	1040	260
12	600	240	500	240	600	600	600	1200	600	600	1240	500	240	0	960	240
13	600	240	500	240	600	600	600	1200	600	600	1240	500	240	0	960	240
14	600	240	500	240	600	600	600	1200	600	600	1240	500	240	0	960	240
15	550	220	500	220	550	550	550	1100	550	550	1220	500	220	0	880	220
16	550	220	500	220	550	550	550	1100	550	550	1214	500	220	0	880	220
17	550	220	500	220	550	550	550	1100	550	550	1202	500	220	0	880	220
18	500	200	500	200	500	500	500	1000	500	500	1178	500	200	0	800	200
19	500	200	500	200	500	500	500	1000	500	500	1167	498	200	0	800	199
20	495	200	500	200	500	499	500	997	499	496	1157	493	200	0	800	197
21	444	180	498	179	450	448	449	895	447	445	1133	491	180	0	720	177
22	441	178	493	178	450	444	445	887	444	441	1124	487	178	0	720	175
23	437	176	489	176	449	440	442	880	440	437	1114	483	177	0	715	174
24	341	137	489	137	348	343	343	685	343	341	1078	482	137	0	553	135
Total	12,308	4,931	12,469	4,930	12,347	12,324	12,329	24,644	12,323	12,310	29,587	12,434	4,932	0	19,748	4,917

'J-150 Out' Results

Node	Demand Supplied		Demand Effectd	Population Served		
	Normal Conditions	Failure Scenario J-150 Out		Normal Conditions	Failure Scenario J-150 Out	Population Effectd
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	12308	42	3069	3059	10
J-30	4940	4931	9	1421	1419	3
J-40	4940	12469	-7529	6100	15396	-9297
J-50	4940	4930	10	5953	5941	12
J-60	12350	12347	3	2297	2296	1
J-70	12350	12324	26	827	826	2
J-80	12350	12329	21	4189	4181	7
J-90	24700	24644	56	6082	6068	14
J-100	12350	12323	27	716	715	2
J-110	12350	12310	40	4642	4627	15
J-120	4940	29587	-24647	4949	29642	-24693
J-130	4940	12434	-7494	5170	13012	-7842
J-140	4940	4932	8	5248	5240	8
J-150	4940	0	4940	4330	0	4330
J-160	19760	19748	12	1487	1486	1
J-170	4940	4917	23	1901	1893	9

Failure Scenario 'J-160 Out'

Demand Supplied

Time (hours)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	350	140	500	140	350	350	350	700	350	338	990	433	140	140	0	122
1	350	140	500	140	350	350	350	700	350	334	980	429	140	140	0	121
2	350	140	500	140	350	350	350	700	350	331	970	424	140	140	0	120
3	300	120	500	120	300	300	300	600	300	287	968	431	120	120	0	104
4	300	120	500	120	300	300	300	600	300	284	959	427	120	120	0	103
5	300	120	500	120	300	300	300	600	300	282	949	423	120	120	0	102
6	575	240	500	240	600	600	600	1200	594	476	870	350	239	239	0	169
7	566	240	497	239	600	593	596	1182	585	468	856	344	236	236	0	167
8	558	237	490	235	600	584	587	1164	576	461	843	339	232	232	0	164
9	585	249	476	248	650	615	619	1225	606	478	817	323	244	244	0	170
10	575	245	469	244	650	605	609	1205	596	471	804	318	241	240	0	167
11	566	241	461	240	650	595	599	1186	586	463	790	313	237	236	0	164
12	523	222	459	221	595	548	551	1092	541	432	789	317	218	218	0	154
13	515	218	452	217	585	539	542	1075	532	425	776	312	215	214	0	151
14	507	215	445	214	576	531	533	1058	523	418	763	307	211	211	0	149
15	465	196	443	195	522	485	487	967	479	387	761	311	193	193	0	138
16	458	193	436	192	514	478	480	952	471	381	749	306	190	190	0	136
17	450	190	429	189	506	470	472	937	464	375	736	301	187	187	0	134
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	8,293	3,466	8,557	3,454	8,998	8,593	8,625	17,143	8,503	7,091	15,370	6,408	3,423	3,420	0	2,535

'J-160 Out' Results

Node	Demand Supplied		Demand Effectuated	Population Served		
	Normal Conditions	Failure Scenario J-160 Out		Normal Conditions	Failure Scenario J-160 Out	Population Effectuated
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	8293	4057	3069	2061	1008
J-30	4940	3466	1474	1421	997	424
J-40	4940	8557	-3617	6100	10566	-4466
J-50	4940	3454	1486	5953	4163	1791
J-60	12350	8998	3352	2297	1673	623
J-70	12350	8593	3757	827	576	252
J-80	12350	8625	3725	4189	2925	1263
J-90	24700	17143	7557	6082	4221	1861
J-100	12350	8503	3847	716	493	223
J-110	12350	7091	5259	4642	2665	1977
J-120	4940	15370	-10430	4949	15399	-10449
J-130	4940	6408	-1468	5170	6706	-1536
J-140	4940	3423	1517	5248	3637	1612
J-150	4940	3420	1520	4330	2998	1332
J-160	19760	0	19760	1487	0	1487
J-170	4940	2535	2405	1901	976	926

Failure Scenario 'J-170 Out'

Demand Supplied

Time (hours)	J-20	J-30	J-40	J-50	J-60	J-70	J-80	J-90	J-100	J-110	J-120	J-130	J-140	J-150	J-160	J-170
0	350	140	500	140	350	350	350	700	350	350	1140	500	140	140	560	0
1	350	140	500	140	350	350	350	700	350	350	1140	500	140	140	560	0
2	350	140	500	140	350	350	350	700	350	350	1140	500	140	140	560	0
3	300	120	500	120	300	300	300	600	300	300	1120	500	120	120	480	0
4	300	120	500	120	300	300	300	600	300	300	1120	500	120	120	480	0
5	300	120	500	120	300	300	300	600	300	300	1120	500	120	120	480	0
6	600	240	500	240	600	600	600	1200	600	600	1240	500	240	240	960	0
7	600	240	500	240	600	600	600	1200	600	600	1240	500	240	240	960	0
8	600	240	500	240	600	600	600	1200	600	600	1240	500	240	240	960	0
9	650	260	500	260	650	650	650	1300	650	650	1260	500	260	260	1040	0
10	650	260	500	260	650	650	650	1300	650	650	1260	500	260	260	1040	0
11	650	260	500	260	650	650	650	1300	650	650	1260	500	260	260	1040	0
12	600	240	500	240	600	600	600	1200	600	600	1240	500	240	240	960	0
13	600	240	500	240	600	600	600	1200	600	600	1240	500	240	240	960	0
14	600	240	500	240	600	600	600	1200	600	600	1240	500	240	240	960	0
15	550	220	500	220	550	550	550	1100	550	550	1220	500	220	220	880	0
16	550	220	500	220	550	550	550	1100	550	550	1216	500	220	220	880	0
17	550	220	500	220	550	550	550	1100	550	550	1204	500	220	220	880	0
18	500	200	500	200	500	500	500	1000	500	500	1179	500	200	200	800	0
19	500	200	500	200	500	500	500	1000	500	500	1169	499	200	200	800	0
20	496	200	500	200	500	500	500	1000	500	496	1158	494	200	200	800	0
21	445	180	498	180	450	449	450	898	449	445	1134	491	180	180	720	0
22	441	178	494	178	450	445	446	890	445	441	1124	487	178	178	719	0
23	438	177	490	177	450	442	442	883	441	438	1115	483	177	177	713	0
24	341	137	490	137	349	344	344	687	343	341	1078	482	138	137	552	0
Total	12,311	4,932	12,472	4,932	12,349	12,330	12,332	24,658	12,328	12,311	29,597	12,436	4,933	4,932	19,744	0

'J-170 Out' Results

Node	Demand Supplied		Demand Effectd	Population Served		
	Normal Conditions	Failure Scenario J-170 Out		Normal Conditions	Failure Scenario J-170 Out	Population Effectd
(1)	(2)	(3)	(4)	(5)	(6)	(7)
J-20	12350	12311	39	3069	3059	10
J-30	4940	4932	8	1421	1419	2
J-40	4940	12472	-7532	6100	15400	-9300
J-50	4940	4932	8	5953	5944	10
J-60	12350	12349	1	2297	2297	0
J-70	12350	12330	20	827	826	1
J-80	12350	12332	18	4189	4182	6
J-90	24700	24658	42	6082	6072	10
J-100	12350	12328	22	716	715	1
J-110	12350	12311	39	4642	4627	15
J-120	4940	29597	-24657	4949	29652	-24703
J-130	4940	12436	-7496	5170	13014	-7845
J-140	4940	4933	7	5248	5241	7
J-150	4940	4932	8	4330	4323	7
J-160	19760	19744	16	1487	1486	1
J-170	4940	0	4940	1901	0	1901