Infrastructure Vulnerability Assessment Model (I-VAM)

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1. Abstract

Quantifying vulnerability to critical infrastructure has not been adequately addressed in the literature. Thus, the purpose of this paper is to present a model that quantifies vulnerability. Vulnerability is defined as a measure of system susceptibility to threat scenarios. This paper asserts that vulnerability is a condition of the system and it can be quantified using the Infrastructure Vulnerability Assessment Model (I-VAM). The model is presented and then applied to a medium-sized clean water system. The model requires subject matter experts to establish value functions, weights and to assess protection measures of the system. Simulation is used to account for uncertainty in measurement, aggregate expert assessment, and to yield a vulnerability (Ω) density function. Results demonstrate that I-VAM is useful to decision-makers who prefer quantification to qualitative treatment of vulnerability. I-VAM can be used to quantify vulnerability to other infrastructures, Supervisory Control and Data Acquisition Systems (SCADA), and Distributed Control Systems (DCS).

Keywords: quantify vulnerability, vulnerability assessment, vulnerability definition

2. Introduction

Military and civilian leaders have the responsibility to protect our Nation's critical infrastructure, communities, and symbols of American power from terrorists, home and abroad, as well as from natural disasters. Central to protection is the ability to assess vulnerability. It is commonplace for vulnerability studies to identify weak points in the system, yet they are without quantifiable rigor. The author has seen first hand the frustration of military leaders who needed a way to quantify vulnerability to help make better force protection decisions. Sousa-Poza (2003) agrees making the point explicit in his socio-technical systems course that decision-makers prefer quantification.

The paper is organized into four sections. The introduction section of the paper documents the confusion of terms and definitions of terms such as vulnerability, risk, hazard, risk or vulnerability assessment, threat assessments, etc. and concludes with an operational definition of vulnerability that is used thought the remainder of the paper. The model section presents an overview of the Critical Infrastructure Vulnerability Assessment Model (I-VAM). The demonstration section applies the model to a medium-sized clean water system. The paper concludes by summarizing main points and suggesting that I-VAM is suited to other critical infrastructures.

Background

Vulnerability means different things to different people and the term is often confused with risk. Buckel (2000) contends that work must be done to clear up the definition of vulnerability with respect to risk. For example, Emergency Management Australia (1998) defines vulnerability as the degree of susceptibility and resilience of the community and environment to hazards. Likewise, the Emergency Management Australia (1998) glossary of terms interchanges the terms vulnerability analysis with hazard *analysis* or vulnerability *assessment.* National Water Resources Association (NWRA) (2002) defines a vulnerability assessment as the identification of weaknesses in security, focusing on defined threats that could compromise its ability to provide a service. Blaike et al. (p. 4, 1994) defines vulnerability as "the characteristics of a person or group in terms of their capacity to anticipate, cope with, resist, and recover from the impact of a natural hazard". The National Oceanic and Atmospheric Administration (2002) views vulnerability as: "susceptibility of resources to negative impacts from hazard events". Nilsson et al. (2001) contend that vulnerability is the collective result of risks and the ability of a society, local municipal authority, company or organization to deal with and survive external and internal emergency situations. Gheorghe (2001) defines vulnerability as the susceptibility and resilience/survivability of the community / system and its environment to hazards. Vulnerability is a function of susceptibility, resilience and the environment. International Strategy for Disaster Reduction (2002) defines vulnerability to disasters is "a status resulting from human action. It describes the degree to which a society is either threatened by or protected from the impact of natural hazards". NSTAC- National Security Telecommunications Advisory Committee (1997) states that vulnerability is a function of access and exposure. Buckle (2000) says that vulnerability is a broad measure of the susceptibility to suffer loss or damage. The higher the resilience, the less likely damage may be, and the faster and more effective recovery is likely to be. Conversely, the higher the vulnerability, the more exposure there is to loss and damage. Hierarchical Holographic Modeling (Haimes 1981) identifies sources of risk and indirectly implies systems vulnerabilities (Ezell, Haimes and Lambert 2000). The Infrastructure Risk Analysis Model (IRAM) introduced by Ezell, Farr, and Wiese (2000a) models vulnerability as simply a function of access and exposure. The IRAM approach is a functional decomposition where access and exposure is subjectively scored. The result is a rank ordering of vulnerability.

Seven references: Buckle (2000), Dictionary.com (2000), Emergency Management of Australia (1998), Gheorghe (2001), International Strategy for Disaster Reduction (2002), National Oceanic and Atmospheric Administration (2002), and the National Security Telecommunications Advisory Committee (1997) use the adjective "susceptibility to…" to define vulnerability. Four references: Blaike et al. (1994), Nilsson et al. (2001), Nilsson, Magnusson, Hallin, and Lenntorp (2000), and the National Waterworks for Rural America (2002) use the adjectives cope and deal with to define vulnerability. Two definitions provided by Nilsson et al. (2001) and Nilsson, Magnusson, Hallin, and Lenntorp (2000) view vulnerability as a collection of risks. From the literature a theme begins to emerge in the attributes that describe vulnerability: susceptibility to "what"; weakness in the system; a target with respect to a threat or risk; exposure to hazard.

The Relationship between Risk and Vulnerability

Risk assessment methodologies are often employed to help understand what can go wrong, estimate the likelihood and the consequences, and to develop risk mitigation strategies to counter risk. One critical component of risk assessment methodology is determining the vulnerability of a system (Ezell et al. 2000a, 200b). Blaike (1994), Buckle (200a,b), NOAA(2002) indicate a link the concept of vulnerability and risk.

Foundational definitions such as Lowrance's (1976), defines risk as a measure of the probability and severity of adverse effects whereas Blaike (1994), Buckle (2000a, 2000b), NOAA (2002) suggests vulnerability is *susceptibility* to risk. Kaplan (1997) define risk as a triplet of scenario, likelihood, and consequences. The difference between Lowrance (1976) and Kaplan (1997) is the notion of scenario(s) as a euphemism for "what can go wrong". NSTAC (1997) argues that vulnerable systems are systems that are exposed, accessible and therefore susceptible (NOAA 2002) to natural hazards as well as willful intrusion, tampering, or terrorism. Therefore, a relationship emerges from the literature between vulnerability and risk. Vulnerability highlights the notion of susceptibility to a scenario whereas risk focuses on the severity of consequences to a scenario.

Critical Infrastructure

This paper focuses on the medium-sized water systems as the critical infrastructure to demonstrate I-VAM. To understand the magnitude of this critical infrastructure, consider the number of utilities and customers per infrastructure sector. There are 168,000 public water systems in the United States ranging in size serving 25 Americans to eight million Americans (CDI 2002). Figure I provides a sense of the scope of water systems as an extraordinarily large critical infrastructure. A water system can be decomposed into two distinct systems, clean water and sanitary sewer systems. A clean water system has seven main functions in the process flow (AWWA 2002b): 1) water arrives from a source; 2) pumped from a well, river, etc. to a treatment plant; 3) treatment plant removes impurities; 4) clean water is stored in tank; 5) distribution mains carry clean water to industry and service lines; 6) service lines carry water to homes; and

7) from industry and homes, water enters the sanitary sewer system.

3. Model Overview

The Infrastructure Vulnerability Assessment Model (I-VAM) is built upon the mathematics of multi-attribute value theory and is structured as a value model. Value model development was guided by the work of Keeney, R.L. (1992), Keeney, R.L. and Raiffa, H. (1993), and Parnell, G.S., Jackson, J.A., Jones, B.L., Lehmkuhl, L.J., Conley, H.W., and Andrew, J.M., (1998). Model decomposition is inspired by systems theory, guided by the research of Sage and Armstrong (2000), Haimes (1998) and Gibson (1991). The model is targeted to a medium sized clean water system as a large-scale complex system (Ezell 2000a). Taken as an entire system, functional decomposition of a clean water system is guided by the research of AWWA (2002b) and shown in Table I. This decomposition serves as the structure of value model. In addition to I-VAM, the process flow for the vulnerability assessment is 1) SME elicitation; 2) SME aggregation simulation; and 3) I-VAM simulation.

At the lowest levels of I-VAM, deterrence (d_1), detection (d_2), delay (d_3) and response (r) are used to measure protection for component in the system. Deterrence (d_1) is defined by Garcia (2001) as those measures implemented that are perceived by adversaries as too difficult to defeat. Detection (d_2) is defined as the probability of determining that an unauthorized action has occurred or is occurring including: sensing, communicating alarm to control center, and assessing the alarm. Delay (d_3) is defined as the time, measured in minutes that an element of a physical protection system designed to impede adversary penetration into or exit from the protected area (Garcia 2001). Response (r) is defined as time (minutes) to respond to a threat (Garcia 2001).

I-VAM Value Functions

Four value functions are developed to measure of protection of each component in the value model. The definitions of the measures are guided by the research of Garcia (2001), Sandia (2000) and AWWA (2002b). Figure II shows an example of the deterrence protection measure value function. Garcia (2001) defines deterrence as measures implemented that are perceived by adversaries as too difficult to defeat. In Figure II, the deter value function x-axis has a description for each on an ordinal scale of one to five. On the V(x) axis, the subject-matter expert decided that for a given subsystem, the value he placed on the level of increasing deterrence. Interested readers can review all 14 sets (56 individually) of the actual value functions in Ezell (2004).

Raw data and weights, represented by the scores and relative importance of elements were assigned by subject-matter experts. I-VAM is an additive preference model in that it assigns value to each attribute measurement on a scale 0-100, using value assignment methodology. Value functions were built through subject-matter expertise assignment and have the following form:

$$V(x) = \sum_{m=1}^{n} w_m v_m (x_m)$$

Equation 1. Additive Value Form

where *m* is the evaluation measure, x_m is the level of the *m*th measure, $v_m(x_m)$ is the value of the value function at level x_m, and w_m is the product of the weights for each level up the hierarchy (Parnell, Conley, Jackson, Lehmkuhl, and Andrew, 1998).
In the adjacent columns, component, subsystem and system show the remaining levels from lowest to the top of the model. The numbering system also indicates the location in

the system. For example, 1.1.1 indicates the River component, whereas 1.1 indicates the Source subsystem within the model. Figure III shows how each measure maps to the lowest portion of the model. Calculations for the model are in the form $V(x) = \sum_{m=1}^{n} w_m v_m(x_m)$. For example, to calculate component value and vulnerability for the river component, the weight of each protection measure is multiplied by the corresponding value of x from the value functions and summed together for the river component.

$$v_{1.1.1}(x_{1.1.1}) = w_{1.1.1.1} * v_{1.1.1.1}(x_{1.1.1.1}) + w_{1.1.1.2} * v_{1.1.1.2}(x_{1.1.1.2}) + \\ w_{1.1.1.3} * v_{1.1.1.3}(x_{1.1.1.3}) + w_{1.1.1.4} * v_{1.1.1.4}(x_{1.1.1.4})$$

Equation 2. River Component Value (1.1.1)

River component (1.1.1) vulnerability would be the ideal v^* or max possible value score, v*(x) minus the assessed value score, v(x). The difference becomes river component vulnerability: $\Omega_{(1.1.1)}$.

$$\Omega_{1.1.1} = v^*{}_{1.1.1}(x) - v_{1.1.1}(x)$$

Equation 3. River Component Vulnerability (1.1.1)

Subsystem value score is the sum product of all component value scores and their associated weight. For the case of the source subsystem (1.1) the value score is given by equation 4.

$$v_{1.1}(x) = w_{1.1.1} * v_{1.1.1}(x) + w_{1.1.2} * v_{1.1.2}(x)$$

Equation 4. Source Subsystem Value (1.1)

Vulnerability of the source (1.1) subsystem is the difference of the ideal or maximum possible value score for the subsystem and the assessed value score given in equation 5.

$$\Omega_{1.1} = v^{*}{}_{1.1}(x) - v_{1.1}(x)$$

Equation 5. Source Subsystem Vulnerability (1.1)

Overall system value score is the product sum of all subsystems given in equation 6.

$$\begin{aligned}&V(X) = w_{1.1} * v_{1.1}(x) + w_{1.2} * v_{1.2}(x) + w_{1.3} * v_{1.3}(x) + w_{1.4} * v_{1.4}(x)\\&w_{1.5} * v_{1.5}(x) + w_{1.6} * v_{1.6}(x)\end{aligned}$$

Equation 6. Overall Clean Water System Value Assessment

Overall vulnerability, Ω is the max value (100) minus the overall assessed value given in equation 6, above.

4. Applying I-VAM to a Clean Water System

In this section I-VAM is applied to a medium-sized clean water system. A brief description of the water system is provided. For interested readers of the full system description, see Ezell (2004). In addition to quantifying vulnerability, sensitivity analysis in presented as well a discussion on model validity.

Eliciting Relative Importance

Subject matter expert one (SME-I) was asked to rate the relative importance of each subsystem and component within the clean water system. Table IIa and IIb summarize the assessment of relative importance. At the protection measure level, the relative importance of measures varied little. SME-I noted that these measures were always important regardless of the component being assessed. At the component level of the system, relative importance became more evident. At the subsystem level, the greatest differences in importance were observed. The subject matter expert assessed the importance of the source and control subsystems very low, 1/3 the importance of the transmission and treatment system, reasoning that the source is larger and more robust.

Assessing the Clean Water System

SME-I and SME-II scored the notional clean water system described below using a scoring matrix. The deterrence measure was discrete and detect, delay and response measures were assessed with uncertainty modeled with the triangle distribution following the expert elicitation work of Chytka (2003). The notional city and corresponding water system was an amalgamation of previous work from Ezell (1998); Ezell, Farr and Wiese (2000b); and Ezell, Haimes, and Lambert (2001). The City was a medium-sized municipality comprised of 10,000 customers. It has a water treatment and distribution system that supplies approximately 2 million gallons per day (MGD). The community is mainly residential with some light industrial facilities.

SME-III was interviewed to assess the level of expertise of subject matter experts one and two. The weighted inner loop aggregation simulation was applied and the resulting distributions were used as inputs into I-VAM. Next, I-VAM simulation was executed. In addition, output graphs comparing an ideal system performance with the performance of the notional system as scored by the subject matter experts. Last, sensitivity analysis is discussed and the implication of the sensitivity of the model is examined.

Aggregation of Scores

SME-III was interviewed to determine the weighting factors for SME-II and SME-II. Using expert criteria- 1) years of experience and 2) education, SME-III concluded that SME-I should receive 0.6 of the total weight and SME-II should receive 0.4 weight. The major contributing factor was experience in water. SME-III judged SME-I experience as more direct and precise, where each had similar educational experiences. Using the weighted inner loop aggregation simulation technique advocated by the research of Chytka (2003), SME-I and SME-II scores were combined for use in I-VAM. A sample of that aggregation from 150,000 trials is presented in Figure IV. Figure IV depicts the assessments of SME-I and SME-II, modeled as a triangle distribution with a minimum score, most likely score and maximum score. Crystal Ball ™ ran 150,000 trials multiplying a weight of 0.6 times SME-I random variable plus 0.4 times SME-II random variable. Each random variable was generated with respect to each SME triangle distribution. The combined result was a beta distribution with parameters: 6.73 min, 62.16 max, 5.49 alpha and beta of 6.39. Once the aggregation was completed, all input data was supplied to I-VAM. Tables IIIa and IIIb provide a recap of all input data for columns: measure local wt., x assessment, component local wt., and subsystem local wt. Output is italicized by columns measuring v(x), component v(x), component omega value, subsystem v(x) and omega value, and system V(x) and corresponding omega value. Figures IX-XI are bar graphs from the model that provide a pictorial representation of the system's vulnerability.

Figure VI is a bar graph of overall system value score. The graph shows the ideal score and each subsystem's contribution to the ideal score. The bar to the right is the system's actual value score. Each slice in the bar represents each subsystem's contribution to the score achieved. The difference in the bar graph height is the omega vulnerability value for the system; $\Omega = V^*(X) - V(X) = 100 - 68.12 = 31.88$. Figure XII is different from Figures IX-XI in that it shows the a vulnerability distribution as result of 150,000 trials.

Model Sensitivity

Model sensitivity was accomplished by evaluating the influence of each assumption within the model to the model's output (Decisioneering 1996). In Crystal Ball ® (Decisioneering 2004, Version 5.0), the influence of each assumption was accomplished by analyzing each assumption's contribution to variance and by measuring the relative importance of each assumption to the model's output. A positive coefficient indicates that an increase in an assumption is associated with an increase in the model's output. A negative coefficient implies the reverse. The larger the absolute value of the coefficient, the stronger the relationship. In addition, the Monte Carlo simulation (more random number generation) was run at 15,000 trials and 150,000 trials to observe if there was change in the output. Also, Latin-Hypercube (more even random number sample) runs were simulated to observe output at 15,000 and 150,000 trials (Chytka 2003; Decisioneering 2004).

Sensitivity Analysis

Sensitivity of the model was assessed in two ways. The first was to look at the type of simulation: Monte Carlo and Latin Hyper-cube. For each simulation, the mean, median, mode and standard deviation were very close, within $1/100^{th}$ of one percent as.

However, the Gamma distribution was slightly better fit than the Beta distribution for the Latin Hyper-cube simulation. Table IV summarizes the comparison of Monte Carlo and Latin Hyper-cube simulations.

The second way that sensitivity was addressed was to determine which model parameters contributed most to output. Figure XIIII shows each parameter's contribution to variance within the model. This is useful because it allows the user to focus in on what assumptions are most important and which are not important. Eight of 14 detection probabilities are sensitive. A change in detection weights could modify the overall system score. Put another way, detection probability is very important in the model and lends insight into where one might study the system closely to determine where one might improve system performance. Delay is also sensitive. Three of 14 components were affected by the delay measure weight. As in the case of detection, delay offers insight into how one might improve system performance. The area shaded grey in Table V indicates sensitive parameters. The implication here is that significant changes to the weights from Figure XIII could change the score. But just as importantly, the parameters inform the practitioner where improvements could be made to improve vulnerability in the system.

Verification and Validation

Model verification consisted of the logic and math checks in the model. At every level within the model, the sum of the weights must equal one, $\sum_{i=1}^{m} w_m = 1$. In addition, the value at the component level product sum must equal the value of the product sum at the subsystem level $\sum_{i=1.1}^{1.6} w_m v(x_m) = \sum_{i=1.1.1}^{1.6.1} w_m v(x_m)$. The assessed value of the system must always be less than or equal to the ideal or max possible score of the system. Finally, the x, v(x), w must be greater than or equal to zero. By following the research design for sensitivity and verification, it was assured that that the model performed in its intended design. Last, sensitivity as it was designed helped to see what places within the model had the greatest impact on the model output.

Model validity was accomplished by using the decomposition of a clean water system given by the research of AWWA (2000a) and through interviews with SME-II and SME-II. Value model validity was assured by adhering to the prinicples of Keeney, R.L. (1992); Keeney, R.L. and Raiffa, H. (1993); and Parnell, G.S., Jackson, J.A., Jones, B.L., Lehmkuhl, L.J., Conley, H.W., and Andrew, J.M., (1998). For example, the model was decomposed into generally agreed to independent components and subsystems and validated with the literature of AWWA (2002). To the greatest extent possible, measures were used that held no dependence and supported by the literature from Sandia (2000). Face validity of the decomposed medium sized clean water system was validated by the research of (Ezell 2000a) and AWWA (2002). In the following section, the methodology for scoring and the notional system description used by the subject matter experts is presented.

4. Conclusion

This paper defined vulnerability as the susceptibility of the infrastructure to threat scenarios. Second, that the scenario that is the link between vulnerability and risk. Third, the paper has demonstrated that vulnerability can be quantified by the protection measures of deterrence, detection, delay and response. Quantification of vulnerability is meaningful because the omega value of vulnerability can be readily compared to the system's ideal score as shown in I-VAM. Quantifying vulnerability to clean water systems is a significant because the US alone has 54,000 systems providing water to 263 million customers American Water Works Association (AWWA) 2002. The logic of I-VAM was focused on water in this paper but applies to other infrastructures as well.

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TABLES

Table I. I-VAM Clean Water System Structure

Component	Subsystem	System
River (1.1.1)	Source (1.1)	Clean Water System
Well(1.1.2)		
Pump Station (1.2.1)	Transmit (1.2)	
Pipelines (1.2.2)		
Valves (1.2.3)		
Facilities (1.3.1)	Treat (1.3)	
Processes (1.3.2)		
Clearwell (1.4.1)	Store (1.4)	
Tank (1.4.2)		
Reservoir (1.4.3)		
Pump Station (1.5.1)	Distribute (1.5)	
Del Piping System (1.5.2)		
Svc Piping System (1.5.3)		
SCADA (1.6.1)	Control (1.6)	

Table IIa. Relative Importance and Weights

Measure	Rel. Imp.	wt	Component	Rel. Imp.	wt	Sub system	Rel. Imp.	wt
1.1.1.1	10	0.263	1.1.1	9	0.75	1.1	3	0.09
1.1.1.2	10	0.263						
1.1.1.3	9	0.237						
1.1.1.4	9	0.237						
1.1.2.1	7	0.259	1.1.2	3	0.25			
1.1.2.2	8	0.296						
1.1.2.3	6	0.222						
1.1.2.4	6	0.222						
1.2.1.1	9	0.265	1.2.1	9	0.43	1.2	9	0.26
1.2.1.2	9	0.265						
1.2.1.3	8	0.235						
1.2.1.4	8	0.235						
1.2.2.1	9	0.237	1.2.2	8	0.38			
1.2.2.2	10	0.263						
1.2.2.3	9	0.237						
1.2.2.4	10	0.263						
1.2.3.1	9	0.273	1.2.3	4	0.19			
1.2.3.2	9	0.273						
1.2.3.3	8	0.242						
1.2.3.4	7	0.212						
1.3.1.1	10	0.256	1.3.1	10	0.53	1.3	9	0.26
1.3.1.2	10	0.256						
1.3.1.3	9	0.231						
1.3.1.4	10	0.256						
1.3.2.1	10	0.278	1.3.2	9	0.47			
1.3.2.2	10	0.278						
1.3.2.3	8	0.222						
1.3.2.4	8	0.222						
1.4.1.1	10	0.263	1.4.1	9	0.36	1.4	6	0.17
1.4.1.2	10	0.263						
1.4.1.3	9	0.237						
1.4.1.4	9	0.237						
1.4.2.1	9	0.281	1.4.2	6	0.24			
1.4.2.2	8	0.250						
1.4.2.3	8	0.250						
1.4.2.4	7	0.219						
1.4.3.1	10	0.250	1.4.3	10	0.40			
1.4.3.2	10	0.250						
1.4.3.3	10	0.250						
1.4.3.4	10	0.250						

Table IIb. Relative Importance and Weights

Measure	Rel. Imp.	wt	Component	Rel. Imp.	wt	Sub system	Rel. Imp.	wt
1.5.1.1	8	0.267	1.5.1	6	0.55	1.5	3	0.09
1.5.1.2	8	0.267						
1.5.1.3	7	0.233						
1.5.1.4	7	0.233						
1.5.2.1	7	0.304	1.5.2	3	0.27			
1.5.2.2	6	0.261						
1.5.2.3	5	0.217						
1.5.2.4	5	0.217						
1.5.3.1	4	0.286	1.5.3	2	0.18			
1.5.3.2	4	0.286						
1.5.3.3	3	0.214						
1.5.3.4	3	0.214						
1.6.1.1	9	0.265	1.6.1	10	1.00	1.6	5	0.14
1.6.1.2	9	0.265						
1.6.1.3	8	0.235						
1.6.1.4	8	0.235						

Table III. Summary of assessments for SME-I and SME-II

SME-I(0.6)				SME-II (0.4)		
Comp	Min	ML	Max	Min	ML	Max
1.1.1.2	5.00	30.00	60.00	15.00	25.00	60.00
1.1.1.3	0.10	0.40	0.75	0.20	0.25	0.50
1.1.1.4	10.00	30.00	60.00	1.00	10.00	60.00
1.1.2.2	10.00	20.00	60.00	10.00	20.00	45.00
1.1.2.3	0.40	0.75	1.00	0.20	0.80	1.00
1.1.2.4	5.00	30.00	60.00	5.00	10.00	15.00
1.2.1.2	15.00	30.00	60.00	20.00	35.00	60.00
1.2.1.3	0.50	0.80	0.90	0.50	0.80	1.00
1.2.1.4	1.00	10.00	20.00	5.00	15.00	25.00
1.2.2.2	1.00	5.00	15.00	1.00	5.00	8.00
1.2.2.3	0.40	0.80	1.00	0.50	0.80	1.00
1.2.2.4	2.00	10.00	20.00	5.00	15.00	25.00
1.2.3.2	5.00	20.00	60.00	15.00	25.00	40.00
1.2.3.3	0.20	0.60	1.00	0.20	0.70	0.90
1.2.3.4	5.00	20.00	60.00	5.00	10.00	15.00
1.3.1.2	15.00	30.00	60.00	10.00	20.00	60.00
1.3.1.3	0.50	0.80	1.00	0.50	0.70	1.00
1.3.1.4	5.00	50.00	60.00	10.00	25.00	45.00
1.3.2.2	1.00	10.00	15.00	5.00	15.00	20.00
1.3.2.3	0.40	0.80	1.00	0.10	0.30	0.70
1.3.2.4	2.00	10.00	20.00	5.00	10.00	25.00
1.4.1.2	5.00	30.00	60.00	15.00	35.00	60.00
1.4.1.3	0.40	0.70	0.90	0.50	0.80	1.00
1.4.1.4	5.00	20.00	60.00	5.00	10.00	30.00
1.4.2.2	5.00	20.00	60.00	10.00	30.00	45.00
1.4.2.3	0.50	0.80	1.00	0.40	0.60	0.70
1.4.2.4	0.00	5.00	10.00	1.00	10.00	15.00
1.4.3.2	10.00	30.00	60.00	5.00	20.00	30.00
1.4.3.3	0.00	0.10	0.30	0.00	0.10	0.30
1.4.3.4	2.00	10.00	20.00	5.00	15.00	25.00
1.5.1.2	20.00	45.00	90.00	20.00	55.00	90.00
1.5.1.3	0.40	0.80	0.90	0.10	0.40	0.70
1.5.1.4	5.00	20.00	60.00	5.00	25.00	45.00
1.5.2.2	5.00	30.00	60.00	15.00	40.00	60.00
1.5.2.3	0.50	0.70	0.95	0.40	0.80	0.90
1.5.2.4	5.00	30.00	60.00	10.00	20.00	45.00
1.5.3.2	5.00	15.00	40.00	10.00	20.00	45.00
1.5.3.3	0.60	0.80	0.90	0.70	0.75	0.80
1.5.3.4	10.00	20.00	45.00	10.00	30.00	45.00
1.6.1.2	2.00	10.00	20.00	5.00	20.00	25.00
1.6.1.3	0.50	0.75	0.80	0.60	0.75	0.90
1.6.1.4	5.00	10.00	15.00	10.00	15.00	20.00

Table IIIa. Results from I-VAM

<table>
<tr><th></th><th>wt</th><th>x</th><th>v(x)</th><th>Comp</th><th>wt</th><th>v(x)</th><th>Ω</th><th>Sub sys</th><th>wt</th><th>v(x)</th><th>Ω</th><th>V(X)</th><th>Ω</th></tr>
<tr><td>1.1.1.1</td><td>0.26</td><td>3.00</td><td>1.69</td><td rowspan="4">1.1.1</td><td rowspan="4">0.75</td><td rowspan="4">4.96</td><td rowspan="4">1.47</td><td rowspan="8">1.1</td><td rowspan="8">0.09</td><td rowspan="8">6.22</td><td rowspan="8">2.35</td><td rowspan="40">68.1</td><td rowspan="40">31.9</td></tr>
<tr><td>1.1.1.2</td><td>0.26</td><td>28.65</td><td>1.10</td></tr>
<tr><td>1.1.1.3</td><td>0.24</td><td>0.70</td><td>0.87</td></tr>
<tr><td>1.1.1.4</td><td>0.24</td><td>35.10</td><td>1.29</td></tr>
<tr><td>1.1.2.1</td><td>0.26</td><td>3.00</td><td>0.56</td><td rowspan="4">1.1.2</td><td rowspan="4">0.25</td><td rowspan="4">1.27</td><td rowspan="4">0.88</td></tr>
<tr><td>1.1.2.2</td><td>0.30</td><td>6.34</td><td>0.11</td></tr>
<tr><td>1.1.2.3</td><td>0.22</td><td>0.60</td><td>0.19</td></tr>
<tr><td>1.1.2.4</td><td>0.22</td><td>32.98</td><td>0.41</td></tr>
<tr><td>1.2.1.1</td><td>0.26</td><td>3.00</td><td>1.75</td><td rowspan="4">1.2.1</td><td rowspan="4">0.43</td><td rowspan="4">6.72</td><td rowspan="4">4.30</td><td rowspan="12">1.2</td><td rowspan="12">0.26</td><td rowspan="12">14.92</td><td rowspan="12">10.79</td></tr>
<tr><td>1.2.1.2</td><td>0.26</td><td>10.00</td><td>0.84</td></tr>
<tr><td>1.2.1.3</td><td>0.24</td><td>0.75</td><td>1.84</td></tr>
<tr><td>1.2.1.4</td><td>0.24</td><td>28.33</td><td>2.29</td></tr>
<tr><td>1.2.2.1</td><td>0.24</td><td>0.40</td><td>0.04</td><td rowspan="4">1.2.2</td><td rowspan="4">0.38</td><td rowspan="4">4.67</td><td rowspan="4">5.12</td></tr>
<tr><td>1.2.2.2</td><td>0.26</td><td>26.64</td><td>1.63</td></tr>
<tr><td>1.2.2.3</td><td>0.24</td><td>0.58</td><td>0.74</td></tr>
<tr><td>1.2.2.4</td><td>0.26</td><td>34.41</td><td>2.26</td></tr>
<tr><td>1.2.3.1</td><td>0.27</td><td>3.00</td><td>1.20</td><td rowspan="4">1.2.3</td><td rowspan="4">0.19</td><td rowspan="4">3.53</td><td rowspan="4">1.37</td></tr>
<tr><td>1.2.3.2</td><td>0.27</td><td>22.04</td><td>0.70</td></tr>
<tr><td>1.2.3.3</td><td>0.24</td><td>0.71</td><td>0.73</td></tr>
<tr><td>1.2.3.4</td><td>0.21</td><td>33.32</td><td>0.89</td></tr>
<tr><td>1.3.1.1</td><td>0.26</td><td>4.00</td><td>3.47</td><td rowspan="4">1.3.1</td><td rowspan="4">0.53</td><td rowspan="4">10.90</td><td rowspan="4">2.63</td><td rowspan="8">1.3</td><td rowspan="8">0.26</td><td rowspan="8">20.62</td><td rowspan="8">5.10</td></tr>
<tr><td>1.3.1.2</td><td>0.26</td><td>22.99</td><td>1.90</td></tr>
<tr><td>1.3.1.3</td><td>0.23</td><td>0.75</td><td>2.18</td></tr>
<tr><td>1.3.1.4</td><td>0.26</td><td>12.42</td><td>3.34</td></tr>
<tr><td>1.3.2.1</td><td>0.28</td><td>4.00</td><td>3.38</td><td rowspan="4">1.3.2</td><td rowspan="4">0.47</td><td rowspan="4">9.72</td><td rowspan="4">2.46</td></tr>
<tr><td>1.3.2.2</td><td>0.28</td><td>21.10</td><td>1.55</td></tr>
<tr><td>1.3.2.3</td><td>0.22</td><td>0.75</td><td>2.18</td></tr>
<tr><td>1.3.2.4</td><td>0.22</td><td>12.39</td><td>2.61</td></tr>
<tr><td>1.4.1.1</td><td>0.26</td><td>2.40</td><td>0.49</td><td rowspan="4">1.4.1</td><td rowspan="4">0.36</td><td rowspan="4">3.43</td><td rowspan="4">2.74</td><td rowspan="12">1.4</td><td rowspan="12">0.17</td><td rowspan="12">10.30</td><td rowspan="12">6.84</td></tr>
<tr><td>1.4.1.2</td><td>0.26</td><td>21.00</td><td>0.83</td></tr>
<tr><td>1.4.1.3</td><td>0.24</td><td>0.69</td><td>0.81</td></tr>
<tr><td>1.4.1.4</td><td>0.24</td><td>26.99</td><td>1.30</td></tr>
<tr><td>1.4.2.1</td><td>0.28</td><td>3.00</td><td>0.87</td><td rowspan="4">1.4.2</td><td rowspan="4">0.24</td><td rowspan="4">2.92</td><td rowspan="4">1.19</td></tr>
<tr><td>1.4.2.2</td><td>0.25</td><td>26.99</td><td>0.71</td></tr>
<tr><td>1.4.2.3</td><td>0.25</td><td>0.70</td><td>0.54</td></tr>
<tr><td>1.4.2.4</td><td>0.22</td><td>26.35</td><td>0.80</td></tr>
<tr><td>1.4.3.1</td><td>0.25</td><td>3.00</td><td>1.71</td><td rowspan="4">1.4.3</td><td rowspan="4">0.40</td><td rowspan="4">3.95</td><td rowspan="4">2.91</td></tr>
<tr><td>1.4.3.2</td><td>0.25</td><td>10.02</td><td>0.56</td></tr>
<tr><td>1.4.3.3</td><td>0.25</td><td>0.38</td><td>0.16</td></tr>
<tr><td>1.4.3.4</td><td>0.25</td><td>28.01</td><td>1.52</td></tr>
</table>

Table IIIb. Results from I-VAM

	wt	x	v(x)	Comp	wt	*v(x)*	*Ω*	*Sub sys*	wt	*v(x)*	*Ω*	*V(X)*	*Ω*
1.5.1.1	0.27	3.00	0.31	1.5.1	0.55	3.07	1.60	1.5	0.09	4.99	3.59		
1.5.1.2	0.27	12.22	0.46										
1.5.1.3	0.23	0.75	0.77										
1.5.1.4	0.23	27.70	1.54										
1.5.2.1	0.30	1.00	0.01	1.5.2	0.27	1.39	0.95						
1.5.2.2	0.26	33.57	0.46										
1.5.2.3	0.22	0.59	0.17										
1.5.2.4	0.22	33.62	0.74										
1.5.3.1	0.29	0.00	0.00	1.5.3	0.18	0.52	1.04						
1.5.3.2	0.29	6.45	0.10										
1.5.3.3	0.21	0.13	0.01										
1.5.3.4	0.21	51.80	0.41										
1.6.1.1	0.26	2.80	0.79	1.6.1	1.00	11.07	3.21	1.6	0.14	11.07	3.21		
1.6.1.2	0.26	29.03	2.71										
1.6.1.3	0.24	0.76	2.44										
1.6.1.4	0.24	11.07	5.13										

Table IV. Sensitivity of Simulation Runs: Monte Carlo vs. Latin Hyper-cube

Trials	Monte Carlo	Latin Hyper-cube
150K	Mean: 32.26	Mean: 32.27
	Median: 32.23	Median: 32.22
	Mode: 32.18	Mode: 32.13
	Stand. Dev.: 33.60	Stand. Dev.: 33.63
	Distr: Beta	Distr: Beta

Table V. Location of Sensitive Measures in the Model

Measure	Component	Subsystem	System
Detect (.3)	River (1.1.1)	Source (1.1)	Clean Water System
Detect (.3)	Pump Station (1.2.1)	Transmit (1.2)	
Delay (.2)	Pipelines (1.2.2)		
Detect (.3)	Valves (1.2.3)		
Delay (.2)	Facilities (1.3.1)	Treat (1.3)	
Detect (.3)			
Delay (.2)	Processes (1.3.2)		
Detect (.3)			
Detect (.3)	Clearwell (1.4.1)	Store (1.4)	
Detect (.3)	Pump Station (1.5.1)	Distribute (1.5)	
Delay (.2)	SCADA (1.6.1)	Control (1.6)	
Detect (.3)			

FIGURES

Figure I. Extensive Size of US Water System

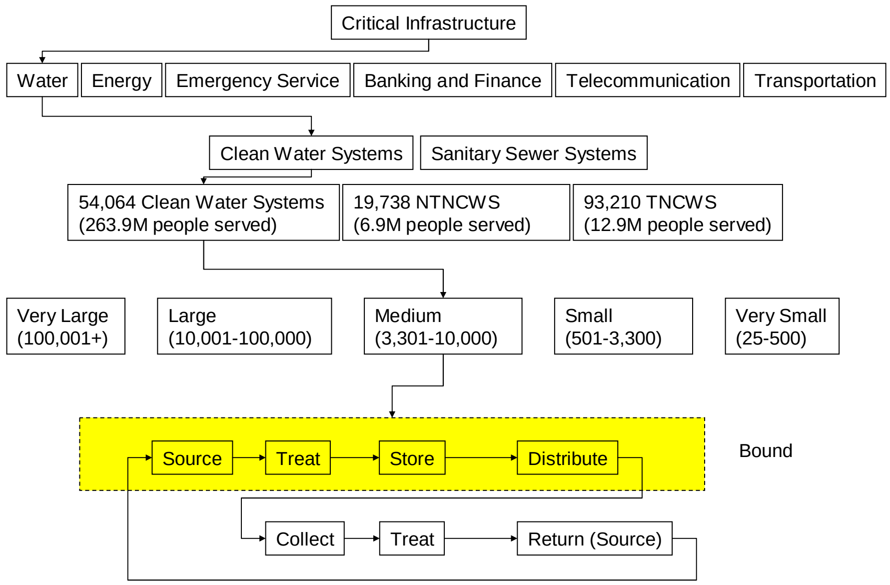


Figure II. Deterrence Value Function Example

River Source

Deterrence value function	x	v(x)
None	0	0
Posting signs	1	10
Posting signs and night lighting	2	50
Posting signs, night lighting and fencing	3	100
Posting signs, night lighting and multiple barriers	4	90
Posting signs, night lighting, multiple barriers and audible warngings	5	40
The measures implemented that are perceived by adversaries as too difficult to defeat.		
Source: Garcia (2001)	SME-1	

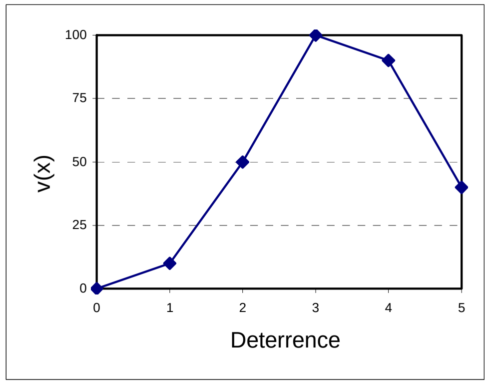


Figure III. I-VAM Protection Measures

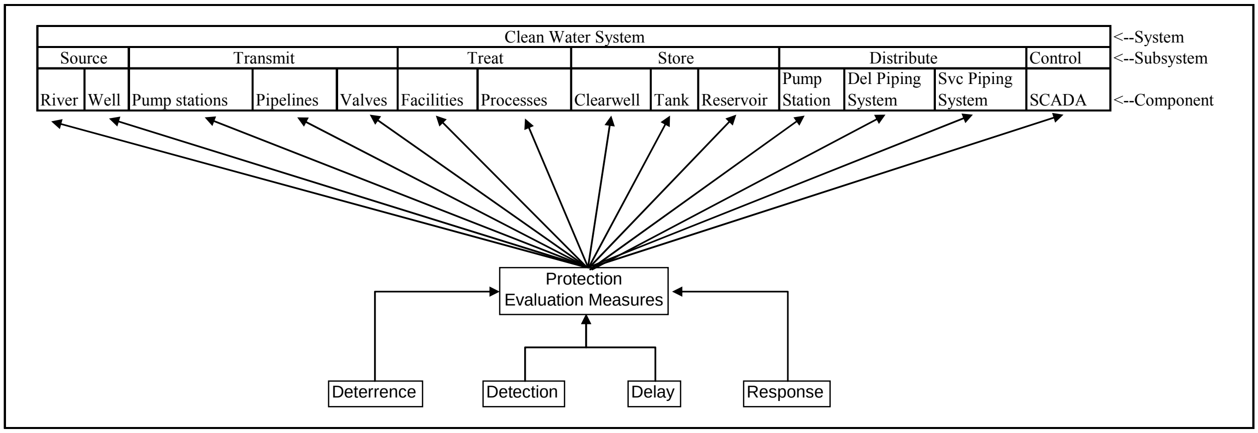


Figure IV. Sample from inner loop aggregation of SME-I and SME-II

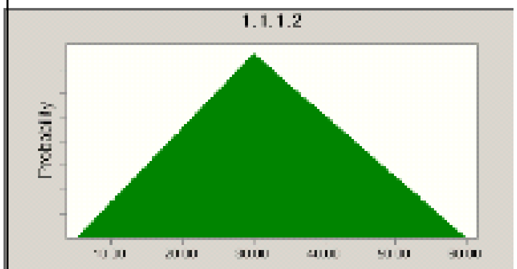
SME1

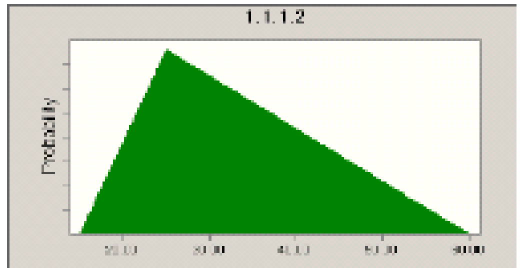
1.1.1.2 (=B4)

Minimum	5.00
Likeliest	30.00
Maximum	60.00

SME2

Minimum	15.00
Likeliest	25.00
Maximum	60.00





Minimum	6.73
Maximum	62.16
Alpha	5.49
Beta	6.39

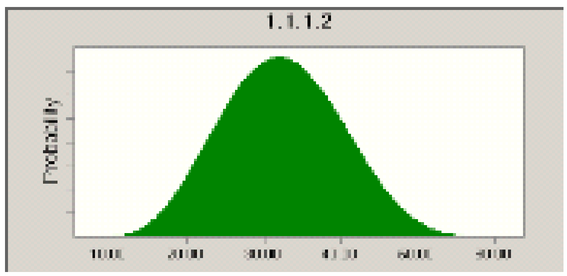


Figure V. Ideal and Actual System Value

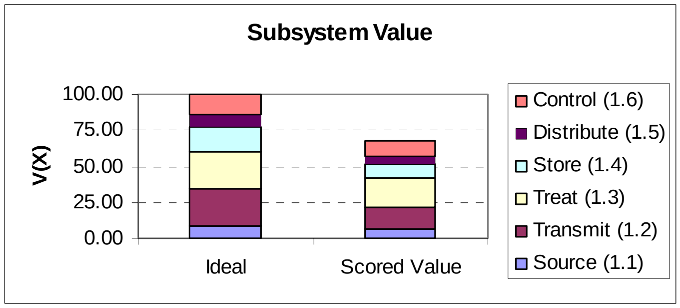


Figure VI. Source Subsystem Value

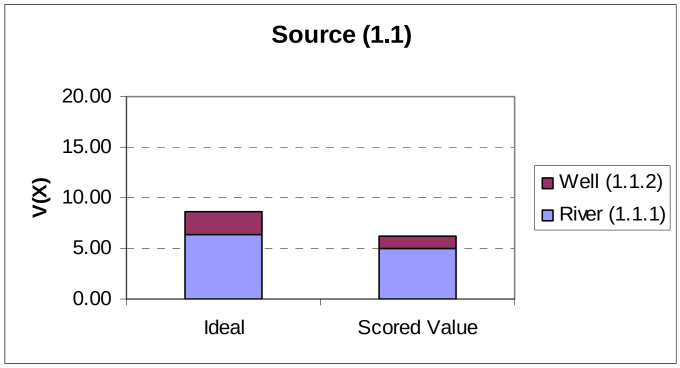


Figure VII. Transmit Subsystem Value

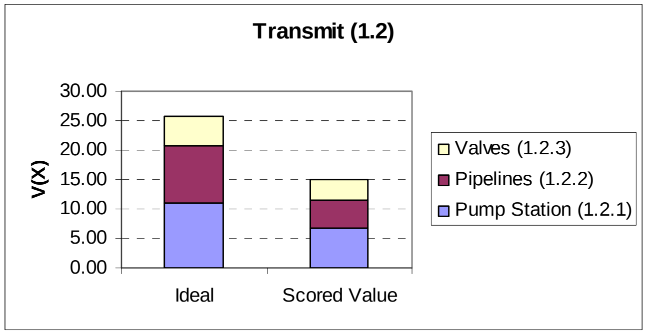


Figure VIII. Treatment Subsystem Value

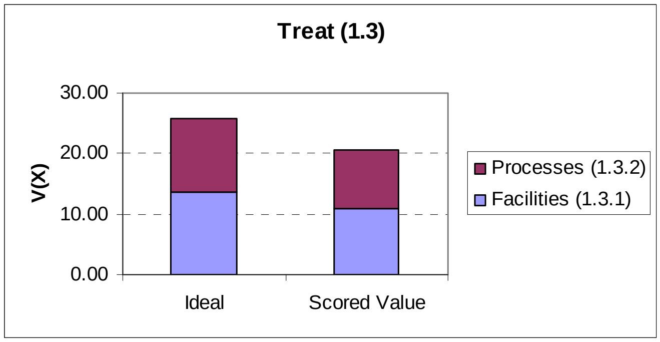


Figure IX. Storage Subsystem Value

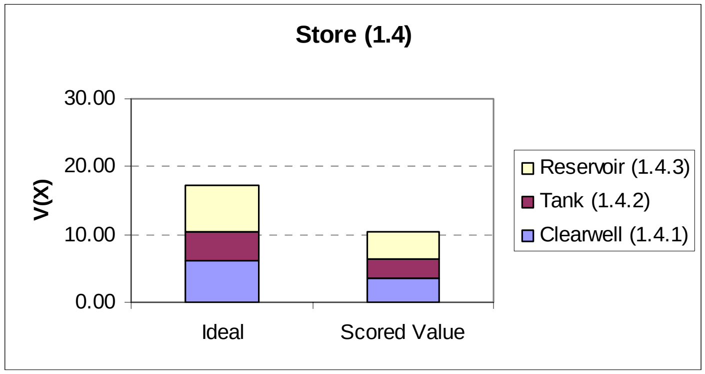


Figure X. Distribution Subsystem Value

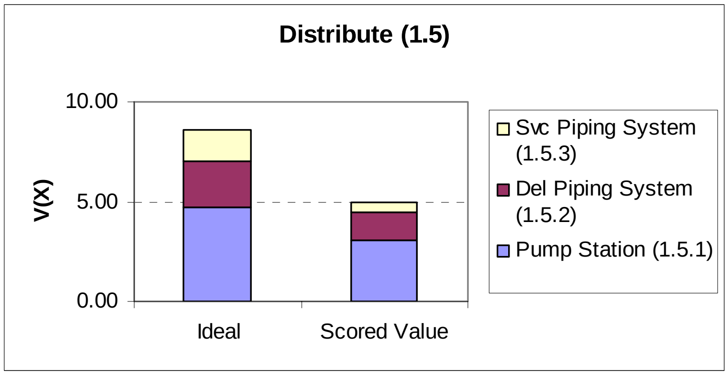


Figure XI. Control Subsystem Value

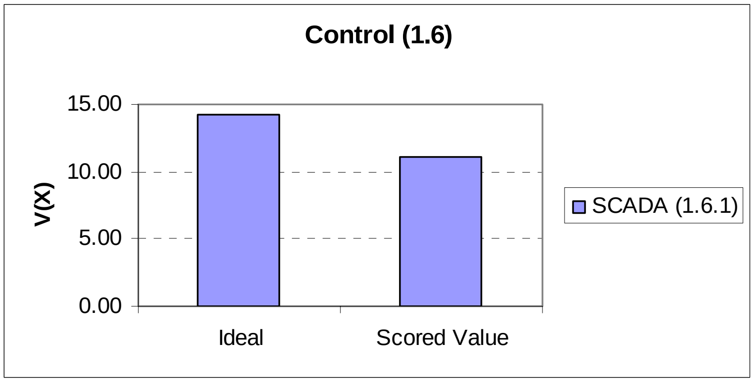


Figure XII. System Distribution of Vulnerability (Ω)

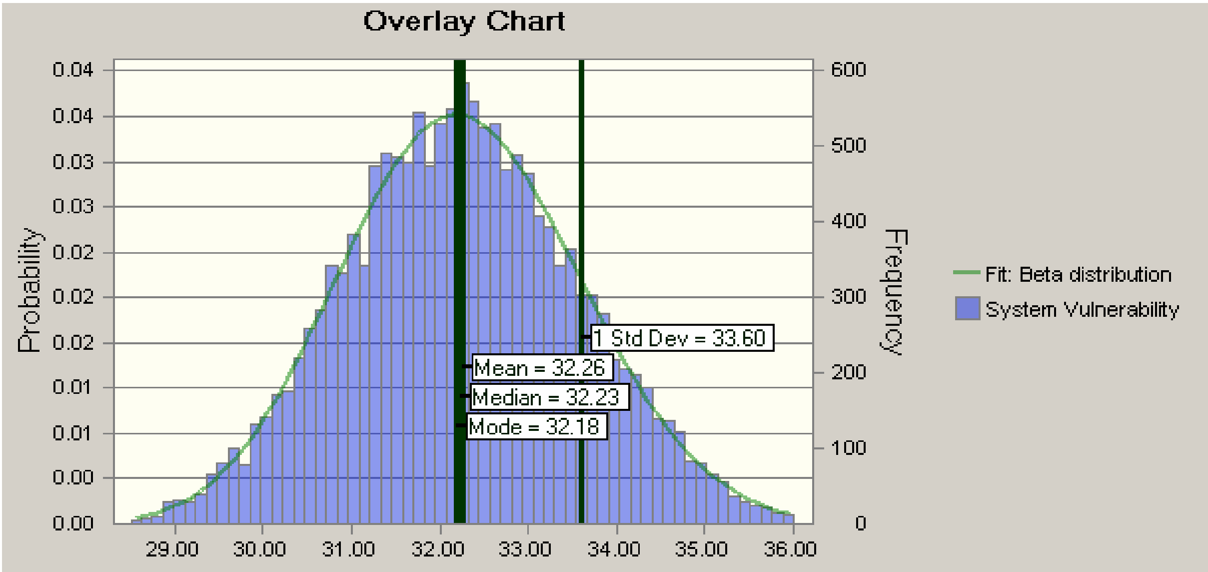


Figure XIII. Output Sensitivity to Input Parameters