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A Proposed Procedure for Conducting an Ice Storm Evaluation in a RAMCAP Risk & Resilience Analysis

C. David Binning, P.E. and Jenyl L. Meszaros

February 2012

ABSTRACT

The Risk Analysis and Management for Critical Asset Protection (RAMCAP) approach requires the user to assess their risk and resilience to multiple types of threats. The ANSI/ASME-ITI/AWWA J-100 standard for water and wastewater systems outlines specific approaches to performing the analysis using a set of predefined natural threats, which currently include hurricanes, tornadoes, earthquakes, and floods. Ice storms and wildfires are potentially important naturally occurring threats but have not yet been defined for use in a RAMCAP analysis. Procedures for evaluating ice storms and wildfires have lagged the other natural threats due in part to the lack of readily accessible historical data on which consequence and threat probability can be developed with confidence. Using data readily available, this paper proposes an approach for ice storms that complies with the J-100 standard.

Due to its largely buried configuration, the assumption is made that the major impact that an ice storm will have on a water sector utility is the loss of commercial power feeding the facility being evaluated. Consequence and threat likelihood determinations are based on the 2007 work of Sidney Sperry of the Oklahoma Association of Electric Cooperatives, and Steven Piltz of the National Weather Service who described damage from the combination of ice accumulation and winds on a 0-5 scale of expected power outages. Vulnerability of a particular site is a function of the capacity of on-site emergency power to be able to endure the length of commercial power loss. Finally, the authors make a distinction between the duration of commercial power loss and the actual time that the utility is impacted before the restoration of normal commodity sales.

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Background

The J-100 standard for the water sector[1] establishes procedural requirements for risk and resilience analysis that must be followed to produce a RAMCAP-compliant analysis. Currently, the J-100 standard gives explicit instructions on how to perform a risk analysis for natural hazards including tornadoes, hurricanes, floods, and earthquakes, but ice storms and wildfires are left to the user to assess if they are important for the operation of a facility. This paper proposes an approach for analyzing ice storms in a RAMCAP analysis. Although there may be a variety of consequences from an ice storm (e.g. damage to above ground equipment, impassable roads), this approach assumes that the major impact on the water sector from an ice storm is the loss of electrical power. The primary risk of an ice storm to the utility is the consequences that result from an inability to provide service to its customers. Ice storm risk (R), like all RAMCAP risk analysis, is defined as the product of the threat likelihood (T), its vulnerability (V), and the consequences (C) to the utility of a successful threat: R = C * V * T.

Consequences, as defined by RAMCAP, are expressed in terms of "the number of fatalities, number of serious injuries, financial losses to the owner, and economic losses to the metropolitan region in which the facility operates" (J-100). Vulnerability is "the likelihood, given that the threat occurs, that the threat to a particular asset results in the consequences estimated" (J-100). The vulnerability therefore assesses the likelihood that the threat will succeed to inflict the maximum reasonable damage. For for the case of loss of power, the countermeasure to reduce vulnerability and consequences is therefore the capacity of on-site generation to outlast the outage of the commercial power supplier. Threat likelihood is the probability of a specific threat occurring to the asset in question over a time period of 1 year (J-100). This is the probability that a severe enough ice storm occurs and sufficiently damages the electric transmission lines to the facility to cause an "actionable"[2] loss of power.

The Sperry-Piltz Ice Accumulation (SPIA) Index was developed by Sidney Sperry of the Oklahoma Association of Electric Cooperatives, and Steven Piltz of the National Weather Service in 2002. They developed an algorithm that predicts the damage category of an ice storm based on ice thickness and wind speed. The resulting damages are categorized on a scale from one to five as illustrated in Figure 1. The SPIA was chosen because it is a scaled system that relates storm severity to a defined set of damage severities. The predefined damage descriptions links the threat probability (T) with the associated consequences (C), giving the utility performing a RAMCAP assessment the ability to easily compare itself to other utilities. When assessing a utility's RAMCAP risk, only levels three through five of this scale are pertinent as these damage levels result in power outages. Levels zero, one, and two do not include power outages for any significant amount of time or create substantial damages to the electric provider. This index defines the consequences severity categories.

[1] As used here the term "Water Sector" encompasses water, wastewater and stormwater utilities

[2] Interruption of electrical power impacts each utility differently. Due to the ability of water and wastewater utilities to store and gravity feed (collect) water, relatively short outages may have little or no impact. For other utilities, an outage of virtually any length can create significant operating problems. Therefore, each utility will have some power outage duration beyond which it must begin to undertake extraordinary "actions" should the outage persist.

The Sperry-Piltz Ice Accumulation Index, or "SPIA Index" – Copyright, February, 2009

ICE DAMAGE INDEX	* AVERAGE NWS ICE AMOUNT (in inches) *Revised-October, 2011	WIND (mph)	DAMAGE AND IMPACT DESCRIPTIONS
0	< 0.25	< 15	Minimal risk of damage to exposed utility systems; no alerts or advisories needed for crews, few outages.
1	0.10 – 0.25	15 - 25	Some isolated or localized utility interruptions are possible, typically lasting only a few hours. Roads and bridges may become slick and hazardous.
	0.25 – 0.50	> 15	
2	0.10 – 0.25	25 - 35	Scattered utility interruptions expected, typically lasting 12 to 24 hours. Roads and travel conditions may be extremely hazardous due to ice accumulation.
	0.25 – 0.50	15 - 25	
	0.50 – 0.75	< 15	
3	0.10 – 0.25	> = 35	Numerous utility interruptions with some damage to main feeder lines and equipment expected. Tree limb damage is excessive. Outages lasting 1 – 5 days.
	0.25 – 0.50	25 - 35	
	0.50 – 0.75	15 - 25	
	0.75 – 1.00	< 15	
4	0.25 – 0.50	> = 35	Prolonged & widespread utility interruptions with extensive damage to main distribution feeder lines & some high voltage transmission lines/structures. Outages lasting 5 – 10 days.
	0.50 – 0.75	25 - 35	
	0.75 – 1.00	15 - 25	
	1.00 – 1.50	< 15	
5	0.50 – 0.75	> = 35	Catastrophic damage to entire exposed utility systems, including both distribution and transmission networks. Outages could last several weeks in some areas. Shelters needed.
	0.75 – 1.00	> = 25	
	1.00 – 1.50	> = 15	
	> 1.50	Any	

(Categories of damage are based upon combinations of precipitation totals, temperatures and wind speeds/directions.)

These values are not being assessed due to lack of power outages. (Index levels 0–2)

These values are being assessed because the severities cause power outages of 1 or more days. (Index levels 3–5)

Figure 1. SPIA Index (McManus et. al. 2002)

To determine the frequency of each of these damage levels, two sources are referenced. In 2003 Stanley Changnon, an Illinois climatologist, analyzed the frequency of damaging ice storms across the US by state. His analysis incorporates historical data of ice build-up thicknesses from damaging storms. His findings of the frequency of ice thicknesses by state is used in this approach to determine the probability of an storm of specified ice accumulation (build-up) within a given state for use with the SPIA Index. Wind speed determinations are based on average monthly wind speed data (by US latitude and longitude) collected by NASA (NASA 2011). By combining the probabilities of average wind speeds with ice thickness, the likelihood of each SPIA Index damage level can be determined for any point in the United States.

ICE THICKNESS

Changnon studied ice storms that occurred between 1949 and 2000 that produced "catastrophic damage". The term catastrophic, as used by Changnon, is based on the total monetary damage suffered over the entire area of that storm. The definition of Changnon's catastrophic damage has changed over time due primarily to inflation and increasing sophistication of facilities as shown during the following time periods:

- 1949-1982: greater than $1 million in damages
- 1983-1996: greater than $5 million in damages
- 1997-2000: greater than $25 million in damages (Changnon 2003)

These damage levels align with the level three to five range on the SPIA Index, noting that the Changnon levels represent total damage, not just damage to the electric power system. Changnon incorporated ice thicknesses from large storms, finding the average, or mean, ice thickness as well as the 75th percentile thickness for each region in the United States as shown in Table 1.

Region	Ice thickness (cm)	
	Average Size	25% had larger sizes
Northern Plains	1.0	1.6
Southern Plains	1.3	2.0
Upper Midwest	0.6	1.6
Lower Midwest	1.3	1.6
Northeast	1.0	2.0
New England	1.0	2.0
Southern Appalachia	1.0	1.6
Deep South	1.6	2.2
Northwest	0.6	1.3

Table 1. Regional radial thickness values of ice on telegraph wires during 1928–37, showing the average values, and the thickness values at which 25% of the sizes were larger (Changnon 2003).

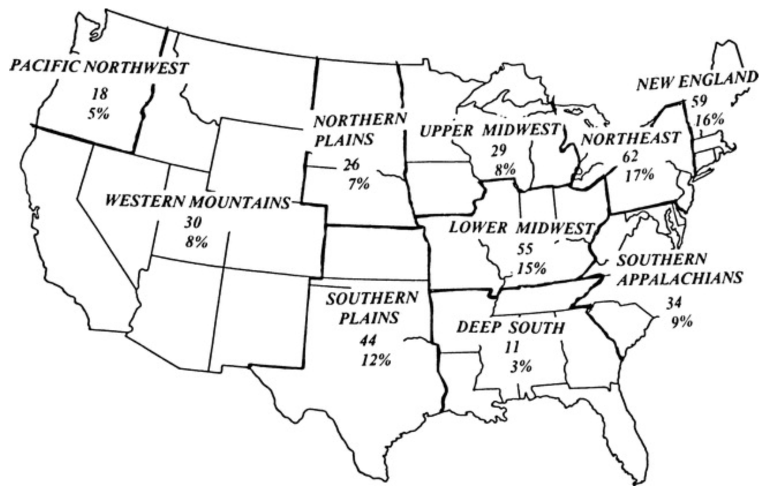

Figure 2. Map of US divided by region described in Table 1

Assuming a normal distribution, a cumulative probability curve can be developed for each region using the "average size" and "25% had larger sizes" as the mean and 75th percentile, respectively. The normal distribution is assumed for this analysis because of the general lack of reliable data for ice thicknesses in the United States. Having only the mean and 75th percentile data for each region limited the statistical methods that could be utilized. The probabilities for each range in the SPIA Index by geographical region are shown in Table 2. An example of the cumulative probability curve for Southern Appalachia is shown in Figure 3. This curve represents the probability that an ice storm event with an accumulation of ice equal to or greater than a specific thickness will occur in a specific region of the US.

	Ice Thickness Probabilities					
Region	P (0.1 ≤ Ti < 0.25)	P (0.25 ≤ Ti < 0.5)	P (0.5 ≤ Ti < 0.75)	P (0.75 ≤ Ti < 1.0)	P (1.0 ≤ Ti < 1.5)	P (Ti ≥ 1.5)
Northern Plains	**0.140**	**0.278**	**0.226**	**0.113**	**0.041**	**0.001**
Southern Plains	**0.093**	**0.182**	**0.184**	**0.149**	**0.146**	**0.030**
Upper Midwest	**0.102**	**0.165**	**0.136**	**0.094**	**0.080**	**0.015**
Lower Midwest	**0.058**	**0.406**	**0.440**	**0.084**	**0.003**	**0.000**
Northeast	**0.095**	**0.169**	**0.157**	**0.121**	**0.120**	**0.029**
New England	**0.095**	**0.169**	**0.157**	**0.121**	**0.120**	**0.029**
Southern Appalachia	**0.140**	**0.278**	**0.226**	**0.113**	**0.041**	**0.001**
Deep South	**0.074**	**0.216**	**0.279**	**0.221**	**0.139**	**0.006**
Pacific Northwest	**0.144**	**0.227**	**0.155**	**0.074**	**0.030**	**0.001**

Table 2. Probabilities of SPIA Index ranges by region

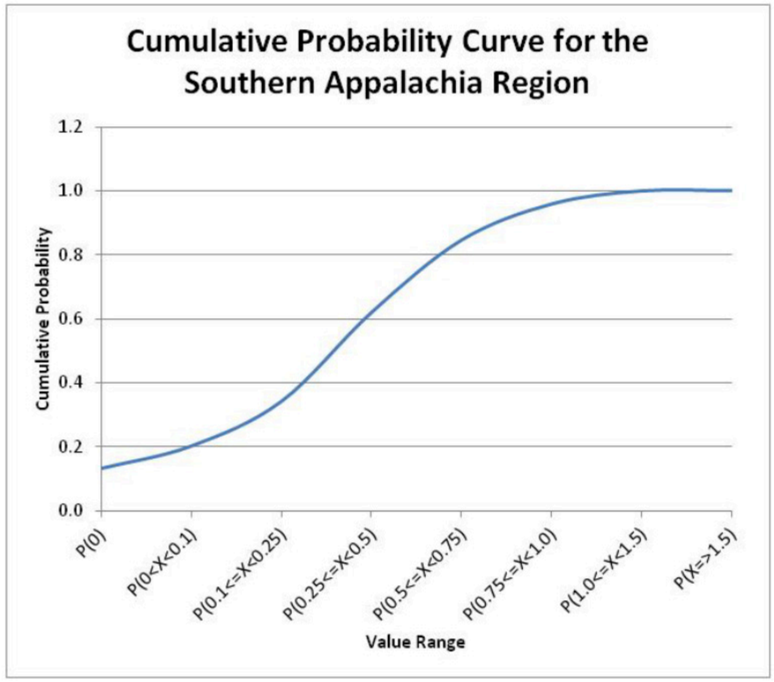

Figure 3. Cumulative probability curve of each range of ice thicknesses for the southern Appalachia region

The first part of the SPIA Index analysis is complete once the probability that an ice storm producing a given ice thickness is determined yielding the chance that an ice storm severity of three, four, or five will occur in any given year. Next, the probability of a wind of a given average speed occurring at the same time as an ice accumulation of given thickness is calculated to complete the probability of a specific SPIA damage and impact level.

WIND SPEEDS

The second element of the SPIA Index is wind speed. To determine the probability of an average wind speed occurring on any given day was determined in a similar way as the ice thickness. Data from the NASA Atmospheric Science Data Center from July 1983 to June 1993 provides the average monthly wind speeds at an altitude of 50m above the surface of the Earth (NASA 2011). The impacts due to the height difference between the ice accumulations of concern (essentially ground level) and the height of the NASA wind speed data is de minimis as freezing rain ice formation occurs uniformly within 500m of the surface as shown in figure 4 (Gay 1993).

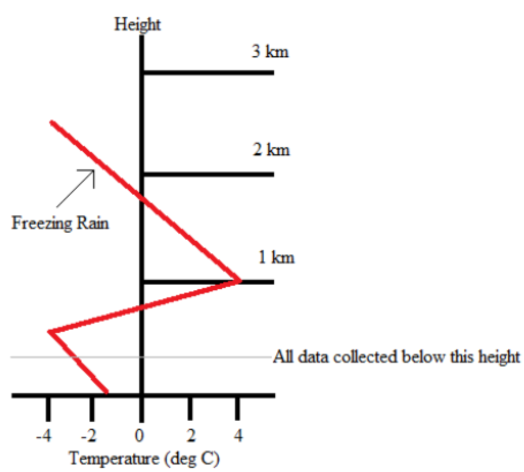

Figure 4. The formation of freezing rain in relation to temperature and height above ground, adapted from (Gay 1993).

Only the average wind speeds for the months of October through March (winter months in the northern hemisphere) were used to develop the cumulative exceedance as these same wind speeds typically cause little or no damage during the summer months when there is no ice accumulation. This exceedance provides the probability that any given average wind speed will occur on any given day during the winter months for a selected latitude and longitude. Table 3 shows a sample of locations and their corresponding wind speed probabilities.

Wind Speed (mph) during period Oct - March					
City	Zip Code	$V < 15$	$15 \leq V < 25$	$25 \leq V < 35$	$V \geq 35$
New York, NY	10004	0.673	0.265	0.052	0.010
Washington, DC	20001	0.698	0.258	0.035	0.008
Chicago, IL	60601	0.503	0.435	0.060	0.002
Los Angeles, CA	90006	0.755	0.242	0.000	0.000
Seattle, WA	98101	0.893	0.103	0.003	0.000

Table 3: Wind Speed Probabilities for select major cities in the US

Wind speed probabilities for a given location are more accurately defined than the ice thickness probabilities because wind speed data is available at specific latitude and longitudes, whereas ice accumulation data is aggregated at the regional level.

THREAT LIKELIHOOD

The SPIA Index combines the ice thickness and wind speed to determine the appropriate damage index for a given event and to calculate the probability that an ice thickness and a wind speed will occur at the same place, at the same time.

$$P(T_i \text{ AND } W) = P(T_i) * P(W)$$

Where,
P (Ti) = the probability that an ice thickness within a given range will occur at a given location;
P (W) = the probability that an average wind speed within a given range will occur at a given location.
The possible ice thickness ranges and wind speeds as used by the SPIA are:

Ice Thickness (in)
$0.1 \leq T_i < 0.25$
$0.25 \leq T_i < 0.5$
$0.5 \leq T_i < 0.75$
$0.75 \leq T_i < 1.0$
$1.0 \leq T_i < 1.5$
$T_i \geq 1.5$

Table 4a. Possible ice thickness ranges

Wind Speed (mph)
$W < 15$
$15 \leq W < 25$
$25 \leq W < 35$
$W \geq 35$

Table 4b. Possible wind speed ranges

Or shown another way, the relationship between the wind speeds, ice build-up and the level of damage can be as shown in Table 5:

Weather Conditions and SPIA Index Levels at a Glance:

Ice and Wind: *Average NWS Ice in Inches; Wind in MPH.	< 15 mph	15-25 mph	25-35 mph	> = 35 mph
0.10 – 0.25 inches	0	1	2	3
0.25 – 0.50 inches	1	2	3	4
0.50 – 0.75 inches	2	3	4	5
0.75 – 1.00 inches	3	4	5	5
1.00 – 1.50 inches	4	5	5	5
> 1.50 inches	5	5	5	5

SPIA Index, Copyright February 10, 2009. Registration #TX 7-027-591. *Graphics revised – October, 2011.

Table 5: The relationship between wind speeds, ice build-up, and damage levels in the SPIA Index

To obtain the probability of any level storm, the sum of the possible combinations for that level is calculated. The equations to calculate the probabilities for levels three, four, and five ice storms are as follows. Level five probability must accommodate all cases that exceed a level 4

$$P(3) = [P(0.1 \leq T_i < 0.25) * P(W \geq 35)] + [P(0.25 \leq T_i < 0.5) * P(25 < W < 35)] + [P(0.5 \leq T_i < 0.75) * P(15 < W < 25)] + [P(0.75 \leq T_i < 1.0) * P(W < 15)]$$

$$P(4) = [P(0.25 \leq T_i < 0.5) * P(W \geq 35)] + [P(0.5 \leq T_i < 0.75) * P(25 < W < 35)] + [P(0.75 \leq T_i < 1.00) * P(15 < W < 25)] + [P(1.00 \leq T_i < 1.5) * P(W < 15)]$$

$$P(5) = [P(0.5 \leq T_i < 0.75) * P(W \geq 35)] + \{P(0.75 \leq T_i < 1.00) * [P(25 < W < 35) + P(W \geq 35)]\} + \{P(1.00 \leq T_i < 1.5) * [P(15 < W < 25) + P(25 < W < 35) + P(W \geq 35)]\} + \{P(T_i \geq 1.5) * [P(W < 15) + P(15 < W < 25) + P(25 < W < 35) + P(W \geq 35)]\}$$

OR

$$P(X) = T(X) = \sum (P\ (T_i \text{ AND } W))$$

Where,

$P(X)$ = the probability of a level "x" storm occurring;
$T(X)$ = the threat likelihood of a level "x" storm occurring;
$P(T_i$ AND $W)$ = the probability of an ice thickness and a wind speed occurring on the same day.

If the utility is located in a part of the country that does not experience ice storms, then the threat likelihood will be zero, resulting in a risk for ice storms of zero.

VULNERABILITY

The vulnerability of a facility to an ice storm is the "probability that the estimated consequences would result if the specific hazard occurs" (J-100). The estimated consequence of ice storms is the loss of power from the power utility. The vulnerability is found using two variables: the probability of an outage falling between the days specified in the SPIA Index and the number of days of alternative power (on-site generation) available to the water utility. The North American Electric Reliability Corporation (NERC) collects nationwide data regarding power outages. Information collected and reported in their yearly System Disturbance Reports includes the reason for the outage, the amount of time until power was restored, and a description of the event. The data used for this study was extracted from the NERC reports between 2003 and 2009 and covers ice events nationwide with power outages ranging from 17 minutes to 21 days. Fifty outage reports were used that spanned the seven-year period (NERC). The fifty reports were normalized, giving a mean of 2.13 days and a standard deviation of 1.59 days. The exceedance probability curve was then found and is shown in Figure 5.

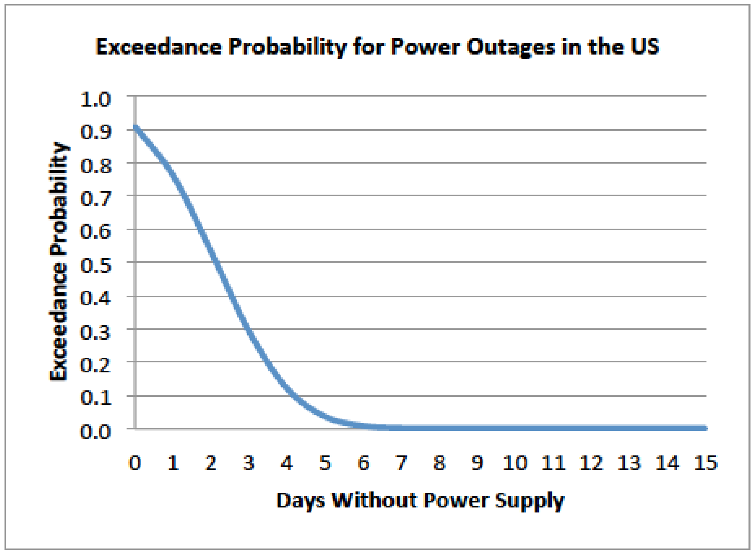

Figure 5: Exceedance probability for power outages in the US

From this curve, the probabilities of a power outage were found for each level of the SPIA Index. The SPIA Index specifies that for a level three storm, power will be unavailable for one to five days. For a level four storm, power will be unavailable for over five days up to ten days. Finally, for a level five storm, power will be unavailable for up to several weeks. Due to the vagueness of the level five description, the NERC data was used to estimate the time frame for an outage. The exceedance shows that the probability of the power company taking longer than 15 days to restore power goes to zero and the highest data point taken from the reports is 21 days. The range for the number of days without power for a level five storm was selected to be over ten days up to twenty-one days to give a larger window. This choice minimally affects the overall risk of an ice storm. The values found for the probability that a utility will be unable to provide power for each SPIA Index level are:

- P_p (3) = 0.874
- P_p (4) = 0.0349
- P_p (5) = 3.54×10^{-7}

The equation for vulnerability of a facility to an ice storm is:

$$V(X) = \left(\frac{t_D - t_B}{t_D} \right) * P_p(x)$$

Where,
$0 \leq V(X) \leq 1$

And,
V(X) = the vulnerability of a facility to an ice storm of level X;
t_D = the maximum number of days of lost commercial power for an X level storm;
t_B = the number of days of backup power available onsite at the utility;
P_p(X) = The probability that the electric provider will be down for the specified number of days for an ice storm of level X.

The SPIA values for t_D are:

- Level 3: 5 days
- Level 4: 10 days
- Level 5: 21 days

These values coincide with the maximum power outage for all three applicable levels in the SPIA Index. If V(X) is negative, then a value of zero should be used for the risk calculation. This means there is no vulnerability to the storm, If V(X) is greater than one, it should be treated as one due to the fact that probability of occurrence cannot be greater than 1.0 or 100%.

CONSEQUENCES

The major consequence from an ice storm for the water sector is the resultant loss of power. If power is lost for a significant amount of time, then the utility will be unable to meet its mission with resulting loss of income. The backup or alternate power capacity of a utility determines its vulnerability to the threat of an ice storm. The days of lost income sustained by the utility as a result of a category 3 or greater ice storm can be expressed as:

$$L(X) = t_D - t_B + t_R \quad (\text{if } t_D - t_B > 0, \text{ otherwise } L(X) = 0)$$

Where,
L(X) = the effective total downtime of the utility;
t_D = the maximum number of days of lost commercial power for a X-level storm;
t_B = the number of days of backup power available onsite at the utility;
t_R = the number of recovery days needed to achieve pre-ice storm operating levels after utility shuts down.

The values for t_D are:

- Level 3: 5 days
- Level 4: 10 days
- Level 5: 21 days

Since this approach assumes that ice storms will produce relatively little physical damage to water sector infrastructure, the utility's consequence of a given ice storm is the lost revenue for each day that the plant is out of operation, the number or value of lives lost, and the number or value of serious injuries. If the statistical value of life and serious injury is not used, then the equation for consequence is:

$$C(X) = I_D * L(X)$$

Where,
C = the total financial consequences;
I_D = pre-ice storm daily income from product distribution;
L(X) = the effective downtime for the utility.

If the statistical value of life and statistical value of serious injury are used in the analysis, then the equation is as follows:

$$C(X) = (I_D * L(X)) + (LL*SVL) + (SI*SVSI)$$

Where,
C = the total financial consequences;
I_D = pre-ice storm daily income from product distribution;
L(X) = the effective downtime for the utility;
LL = number of lives lost;
SVL = statistical value of life;
SI = number of serious injuries;
SVSI = statistical value of serious injury.

Loss of human life and serious injuries are losses and injuries that occur as a result of the utility not providing service. This includes losses that occur during the storm as well as losses in the community due to the lack of water being provided after the storm, but is limited to only the incidents that can be directly linked to the water utility. The time frame for these losses ends once full functionality of the water system is restored. Utility personnel loss of life and number of utility personnel serious injuries are anticipated to be very low for an ice storm event and are relatively independent of the days of lost power within each severity level. These losses may change with increasing severity levels requiring that each level be separately calculated for the worst reasonable case.

If the utility has sufficient backup or alternate power capacity to maintain relatively normal plant activates during the duration of a commercial power outage, the equation will result in a value less than or equal to zero, and shall be treated as zero (e.g. it is not vulnerable to the threat) and the risk to this threat is zero. Determining the effective length of a power loss needs some thought when analyzing electrical power outages to facilities of the water sector. The majority of water and wastewater systems are able to rapidly resume full service and operations following short power interruptions. However, extended power losses, while perhaps not particularly damaging to a plant's infrastructure, can result in days (and perhaps weeks) before the utility is able to restore service to its pre-loss levels. Prolonged production outages will drain the distribution system providing increased opportunities for system contamination and require extensive fieldwork to purge air from the system and flush. Further, restarting large treatment plants requires a slow, deliberate process to assure that all units are producing a safe, reliable product. Therefore, for purposes of calculating the consequences of a power outage, the effective length of the outage is calculated from the beginning of service degradation until full service is restored; not merely the length of time that electrical power is not supplied to the plant.

FINAL RELATIONSHIPS

In a RAMCAP analysis, risk is defined as the product of the consequences, vulnerability and threat probability (R = C*V*T). Using the approach suggested here, the risk to a utility for ice storms in the United States can be determined. This equation is repeated for each SPIA ice damage category, and then summed to determine the total risk.

$$R = \sum_{x=3}^{5} (T(X) * V(X) * C(X))$$

Where,

$$T(X) = \sum(P(T_i \text{ AND } W))$$

$$V(X) = \left(\frac{t_D - t_B}{t_D}\right) * P_p(x)$$

$$C(X) = I_D * L(X) + LL * SVOL + SI * SVSI$$

EXAMPLE OF ICE STORM RISK DETERMINATION

Assumptions:

- City: Chantilly, VA, Fairfax County
- Latitude: 38.9°
- Longitude: -77.45°
- Days of backup power available on-site = 4 days
- Recovery Time:
  - o Level 3 – 0.5 days
  - o Level 4 – 3 days
  - o Level 5 – 6 days
- Lives Lost:
  - o Level 3 – 0 lives
  - o Level 4 – 1 life
  - o Level 5 – 2 lives
- Serious injuries
  - o Level 3 – 1 person
  - o Level 4 – 2 people
  - o Level 5 – 3 people
- Daily operation income = $500,000
- Statistical Value of Life (SVL) = $9,100,000
- Statistical Value of Serious Injury = $518,000

SPIA Index Probabilities – the probability of ice thickness formation in a specific range is:

- P(Ti) Southern Appalachia Region:
  - o $0.1 \leq Ti < 0.25 = 0.140$
  - o $0.25 \leq Ti < 0.5 = 0.278$
  - o $0.5 \leq Ti < 0.75 = 0.226$
  - o $0.75 \leq Ti < 1.0 = 0.113$
  - o $1.0 \leq Ti < 1.5 = 0.041$
  - o $Ti \geq 1.5 = 0.001$

SPIA Index Probabilities – the probability of average wind speeds from October to March in a specific range is:

- P(W):
  - o $W < 15 = 0.698$
  - o $15 \leq W < 25 = 0.258$
  - o $25 \leq W < 35 = 0.035$
  - o $W \geq 35 = 0.008$

Calculated risk of a Class 3 ice storm

$P(3) = [P(0.1 \leq T_i < 0.25) * P(W \geq 35)] + [P(0.25 \leq T_i < 0.5) * P(25 < W < 35)] + [P(0.5 \leq T_i < 0.75) * P(15 < W < 25)] + [P(0.75 \leq T_i < 1.0) * P(W < 15)]$
P(3)= (0.140 * 0.008) + (0.278 * 0.035) + (0.226 * 0.258) + (0.113 * 0.698)

T(3) = P(3) = 0.14803

$V(3) = [(t_D - t_B) / t_D] * P_P$
V(3) = [(5-4) / 5] * 0.874

V(3) = 0.1748

$L(3) = t_D – t_B + t_R$
L(3) = 5 days – 4 days + 0.5 days
L(3) = 1.5 days

NOT using SVL&SVSI
$C(3) = I_D * L(3)$ = $500,000 * 1.5

C(3) = $750,000

Using SVL&SVSI
$C(3) = (I_D * L(3)) + (LL*SVOL) + (SI*SVSI)$
C(3) = ($500,000 * 1.5) + (0 * $9,100,000) + (1 * $518,700)

C(3) = $1,268,700

NOT using SVL&SVSI
R(3) = 0.14803 * 0.1748 * $750,000

R(3) = $19,406.73

Using SVL&SVSI
R(3) = 0.14803 * 0.1748 * $1,268,700

R(3) = $32,828.43

Calculated risk of a Class 4 ice storm

$P(4) = [P(0.25 \leq T_i < 0.5) * P(W \geq 35)] + [P(0.5 \leq T_i < 0.75) * P(25 < W < 35)] + [P(0.75 \leq T_i < 1.00) * P(15 < W < 25)] + [P(1.00 \leq T_i < 1.5) * P(W < 15)]$
P(4)= (0.278 * 0.008) + (0.226 * 0.035) + (0.113 * 0.258) + (0.041 * 0.698)

T(4) = P(4) = 0.0679

$V(4) = [(t_D - t_B) / t_D] * P_p$
V(4) = [(10-4) / 10] * 0.0349

V(4) = 0.0.0209

$L(4) = t_D – t_B + t_R$
L(4) = 10 days – 4 days + 3 days
L(4) = 9 days

NOT using SVL&SVSI
$C(4) = I_D$ * L(4) = $500,000 * 9

C(4) = $4,500,000

Using SVL&SVSI
$C(4) = (I_D * L(4)) + (LL*SVOL) + (SI*SVSI)$
C(4) = ($500,000 * 9) + (1 * $9,100,000) + (2 * $518,700)

C(4) = $14,637,400

R(4) = T(4) + V(4) + C(4)

NOT using SVL&SVSI
R(4) = 0.0679 * 0.0209 * $4,500,000

R(4) = $6,398.22

Using SVL&SVSI
R(4) = 0.0679 * 0.0209 * $14,637,400

R(4) = $20,772.08

Calculated risk of a Class 5 ice storm

$P(5) = [P(0.5 \leq T_i < 0.75) * P(W \geq 35)] + \{P(0.75 \leq T_i < 1.00) * [P(25 < W < 35) + P(W \geq 35)]\} + \{P(1.00 \leq T_i < 1.5) * [P(15 < W < 25) + P(25 < W < 35) + P(W \geq 35)]\} + \{P(T_i \geq 1.5) * [P(W < 15) + P(15 < W < 25) + P(25 < W < 35) + P(W \geq 35)]\}$

P(5)= (0.226 * 0.008) + [0.113 * (0.035 + 0.008)] + [0.041 * (0.258 + 0.035 + 0.008)] + [0.001 * (0.698 + 0.258 + 0.035 + 0.008)]

T(5) = P(5) = 0.02

$V(5) = [(t_D - t_B) / t_D] * P_p$

$V(5) = [(21-4) / 21] * 3.54x10^{-7}$

$V(5) = 2.866 \times 10^{-7}$

$L(5) = t_D – t_B + t_R$

L(5) = 21 days – 4 days + 6 days

L(5) = 23 days

NOT using SVL&SVSI

$C(5) = I_D * L(5)$ = $500,000 * 23

C(5) = $11,500,000

Using SVL&SVSI

$C(5) = (I_D * L(5))$ + (LL*SVOL) + (SI*SVSI)

C(5) = ($500,000 * 23) + (2 * $9,100,000) + (3 * $518,700)

C(5) = $31,256,100

R(5) = T(5) + V(5) + C(5)

NOT using SVL&SVSI

R(5) = 0.02 * $3.54x10^{-7}$ * $11,500,000

R(5) = $0.07

Using SVL&SVSI

R(5) = 0.02 * $3.54x10^{-7}$ * $50,756,100

R(5) = $0.18

Calculated Total Risk of an Ice Storm

Total Risk

NOT using SVL&SVSI

$$R = \sum_{x=3}^{5} (T(X) * V(X) * C(X))$$

R = $19,406.73 + $6,398,22 + $0.07

R = $25,805.02

Using SVL&SVSI

$$R = \sum_{x=3}^{5} (T(X) * V(X) * C(X))$$

R = $32,828.43 + $20,772.08 + $0.18

R = $53,600.69

CONCLUSIONS

This paper has suggested an approach to calculating ice storm risk for the water and wastewater utilities conducting a RAMCAP-consistent analysis. This model uses the SPIA Index to calculate threat likelihood, the vulnerability from loss of power, and the consequences of financial loss. The risk from ice storms can be incorporated into the RAMCAP analysis along with the other natural hazards.

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