SAND2022-5662

SANDIA REPORT

SAND201X-XXXX
Unlimited Release
Printed September 2017

Integration of Electric Power Infrastructure into the Drinking Water Shared Risk Framework: Prototype Development

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Abstract

An existing shared risk framework designed for assessing and comparing threat-based risks to water utilities is being extended to incorporate electric power. An important differentiating characteristic of this framework is the use of a system-centric rather than an asset-centric approach. This approach allows anonymous sharing of results and enables comparison of assessments across different utilities within an infrastructure sector. By allowing utility owners to compare their assessments with others, they can improve their self-assessments and identification of "unknown unknowns". This document provides an approach for extension of the framework to electric power, including treatment of dependencies and interdependencies. The systems, threats, and mathematical description of associated risks used in a prototype framework are provided. The method is extensible so that additional infrastructure sectors can be incorporated. Preliminary results for a proof of concept calculation are provided.

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NOMENCLATURE

Abbreviation	Definition
GDP	Gross Domestic Product
RAMCAP	Risk Analysis and Management for Critical Asset Protection
SME	Subject Matter Expert
SNL	Sandia National Laboratories
SRF	Shared Risk Framework

1. INTRODUCTION

This report describes the application of a shared risk framework (SRF) to electric power utilities. The SRF is a web-based risk assessment framework that promotes the anonymous sharing of results among drinking water utilities.[1] The framework, while consistent with the Risk Analysis and Management for Critical Asset Protection (RAMCAP) methodology,[2] uses a system- or subsystem-centric approach to assessing risk rather than an asset-based approach. While different utilities may have different specific assets, they generally have the same systems and subsystems. This approach allows comparisons across utilities and is therefore useful in detecting bias and identifying outliers in risk assessments. A risk framework for high impact, low frequency events affecting the electric power sector uses a similar methodology but a threat-asset approach.[3]

Milestones and deliverables for this work are provided in the table below. This document comprises the July 1 Draft Report deliverable amended to include discussion of the systems and threats relevant to electric power, the potential impacts of those threats, and modifications to the risk equations to make them appropriate for this sector. An additional section provides discussion of a proof-of-concept calculation.

Table 1: Milestones for DWRP/EP - Task 5

Deliverable	Due
Conceptual design white paper. Description of plan to develop electric power infrastructure component and integrate it into the existing model.	December 20, 2016
Identify key underlying analytical features specific to electrical power, including dependencies between water and electrical power.	March 30, 2017
Prototype integration of electrical power analytics into risk assessment interface.	June 14, 2017
Deliver Draft Report addressing addition of Electric Power to DWRP	July 1, 2017
Deliver Report addressing addition of Electric Power to DWRP	September 30, 2017

[1] Tidwell VC, Lowry TS, Peplinski WJ, Mitchell R, Binning D, and Meszaros J, 2016. Framework for Shared Drinking Water Risk Assessment. SAND2017-XXXX, in review.

[2] White Richard, Randy George, Terrance Boult, and C. Edward Chow. "Apples to Apples: RAMCAP and Emerging Threats to Lifeline Infrastructure." *Homeland Security Affairs* 12, Article 2 (September 2016). https://www.hsaj.org/articles/12012

[3] Veeramany A, Unwin SD, Coles GA, Dagle JE, Millard WD, Yao J, Glantz CS, Gourisetti SNG, Framework for Modeling High-Impact, Low-Frequency Power Grid Events to Support Risk-Informed Decisions, Prepared for U.S. Department of Energy, December 2015.

2. CONCEPTUAL MODEL

The conceptual model was provided in a December 2016 deliverable. Since that time the conceptual model for incorporation of electric power into the SRF was slightly modified and streamlined. This revision was provided in the March deliverable and is included here for completeness.

The current SRF status and capabilities used to assess risk for a single water utility are illustrated in Figure 1. This model structure can be duplicated for the electric power sector, as shown in Figure 2. The natural hazards are the same for both sectors, while the human-caused threats can differ. The impacts of natural and human-caused threats to electric power can be calculated using the same metrics as those used for drinking water: community disruption, health and safety, and financial impact. Dependencies for disruptions in the water sector that originate within the electrical power sector are shown in Figure 3, while interdependencies for disruptions that propagate from one infrastructure into the other are provided in Figure 4. The method provided here should be extensible to additional infrastructures.

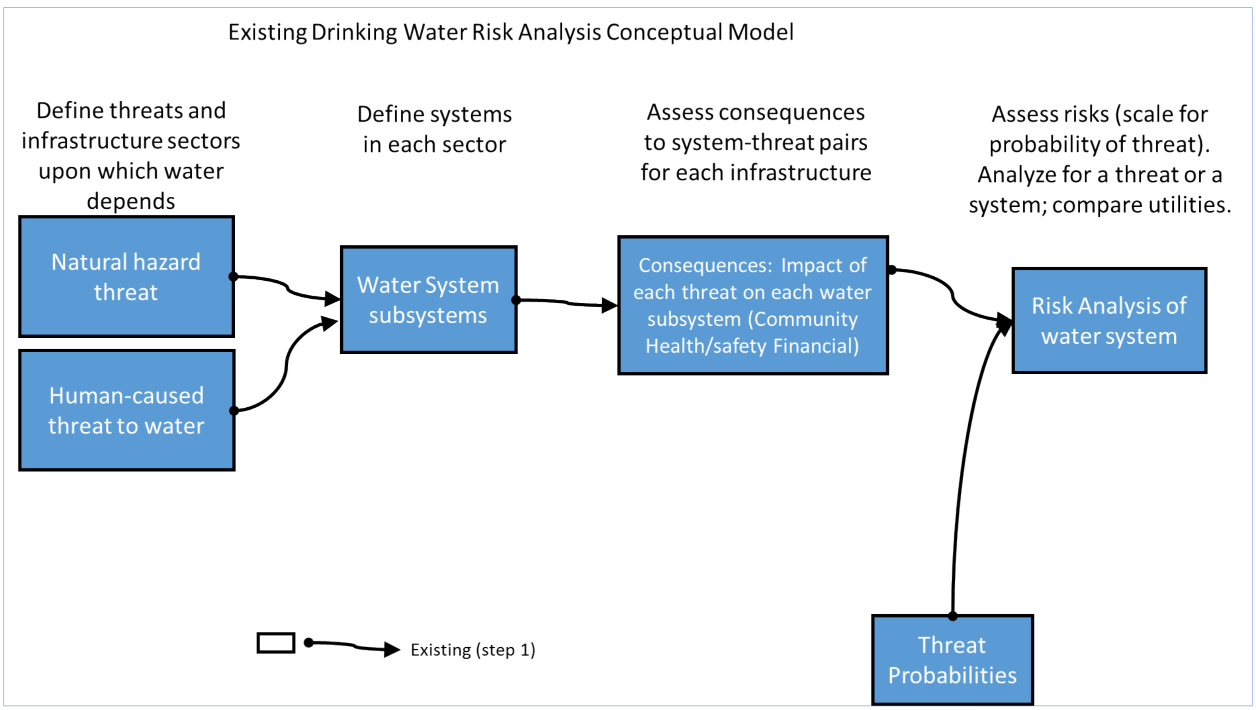

Figure 1: Current capabilities of shared risk framework (SRF). Arrows indicate inputs.

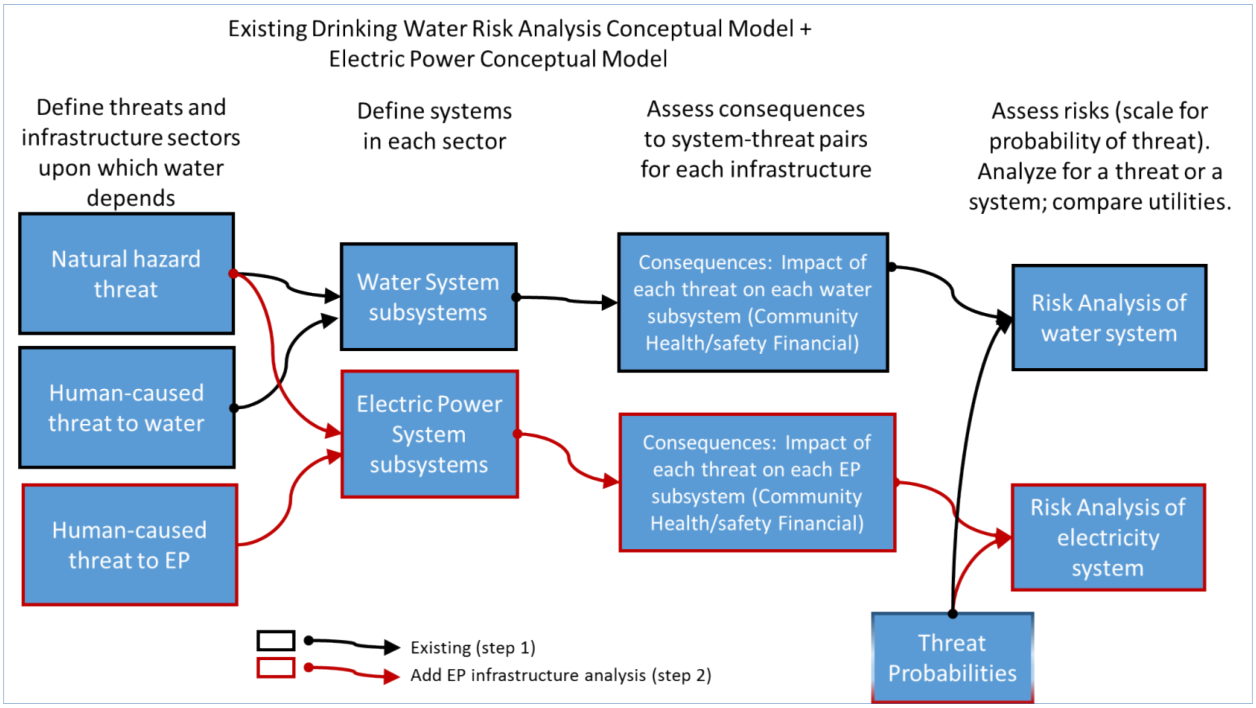

Figure 2: Existing capabilities with additional electric power risk analysis conceptual model. Arrows indicate inputs

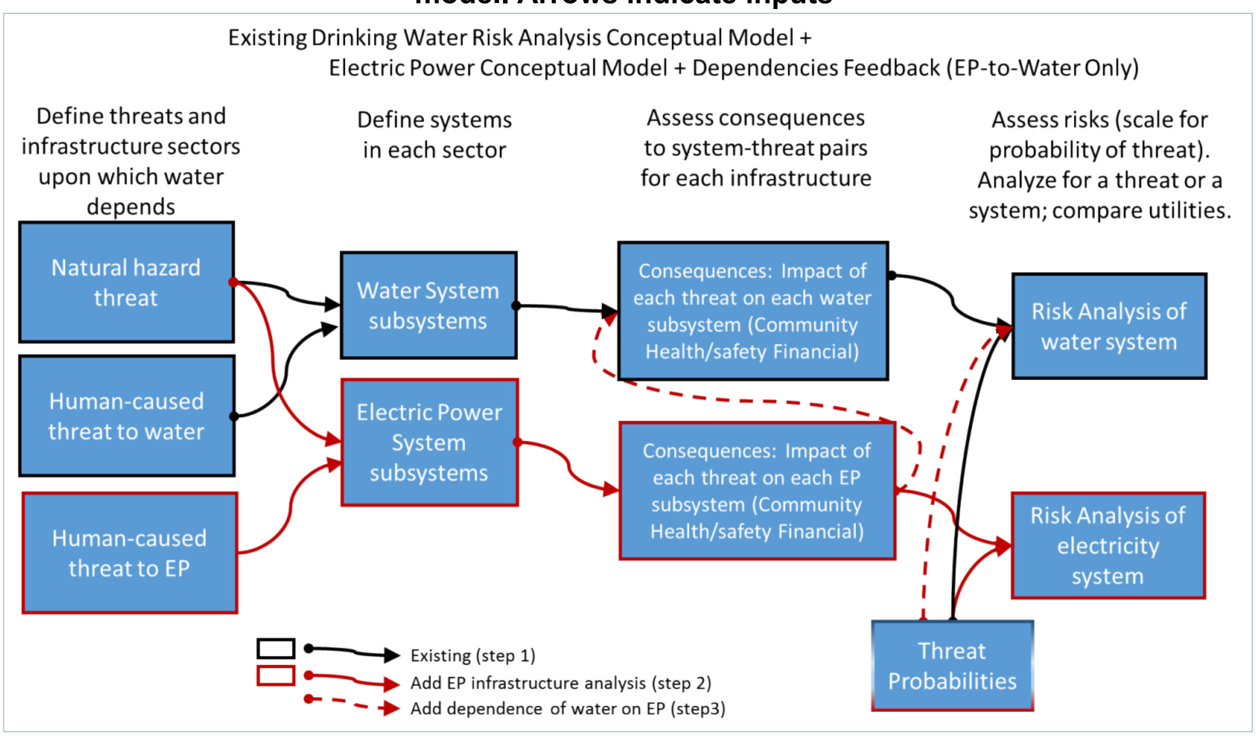

Figure 3: Existing capabilities, additional electric power risk analysis conceptual model, and dependence of water system on electric power. Arrows indicate inputs

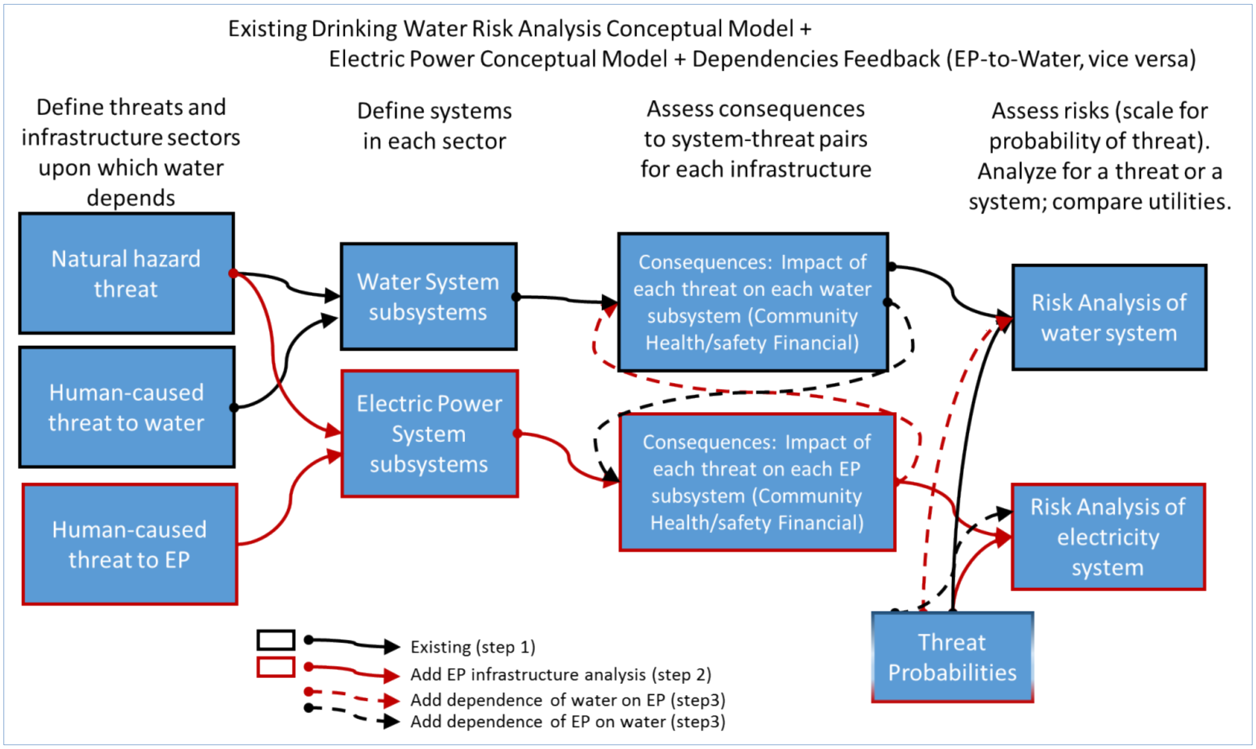

Figure 4: Existing capabilities, additional electric power risk analysis conceptual model, and interdependencies between water and electric power systems. Arrows indicate inputs.

3. SYSTEMS AND THREATS FOR ANALYSIS

3.1. Electric Power Systems

In this section we examine the systems that comprise an electric utility that will be used for analysis. We consider the electric power grid as comprised of three asset domains: generation, transmission, and distribution/end users. A fourth domain, Planning and Operations, is added to the analysis for systems that integrate these larger domains. We identify relevant systems in Table 2. Combining assets into systems and subsystems can be accomplished at different levels of aggregation. Our goal is to aggregate as much as possible to ensure comparability across utilities, but not aggregating so much as to lose required resolution.

Table 2: Systems Relevant to Providing Electric Power

System and Subsystem Names	Description
Generation	Electricity generation system including fuel supply, transportation of fuel to power plants.
Fuel supply*	
Power plants	
Power Transmission	Transportation of electricity from power plants to distribution system
Transmission lines and towers	
High voltage substations	
Power Distribution	Distribution between transmission system and the consumer
Poles and feeder lines	
Low voltage substations	
Planning and Operations	Administration, maintenance of physical and information systems, maintain and recruit employees, knowledge base
Employees	
Information Technologies, telecommunications	
Maintenance and Administration	

* *Fuel sources for electric power generation include coal (33%), natural gas (33%), nuclear (6%), other renewables (7%), petroleum (1%).* http://www.eia.gov/tools/faqs/faq.cfm?id=427&t=3

All of the systems shown in Table 2 are required to provide power to individuals; however, adaptability of the system makes some components less essential. Power plants and their associated substations generate electricity and put it out onto the grid. If a power plant goes off line, other power plants can increase output to maintain supply. If a transmission line goes down, in some cases power can be rerouted to a locality. These adaptations make these systems of less direct consequence to a local utility. Because the SRF examines risk at the local level, we are most concerned with threats affecting distribution. The transmission system is therefore of lower priority for this application, and the generation system would be of lowest priority because other power plants can compensate by increasing output. Threats to planning and operations can be applicable to distribution, transmission or generation.

3.2. Threats for Analysis

The threats identified for the water sector include natural and human-caused hazards. These are shown in Tables 3 and 4 below, respectively with an initial description of how each threat could impact delivery of electric power, and a proposed approach for assessing the probability of occurrence. The probabilities of occurrence for natural threats would be the same as probabilities for those threats in the drinking water assessment, while the probabilities for human-caused threats may differ. The first section of each table lists threats identified as directly affecting drinking water that would also directly affect electric power. These would indirectly affect drinking water through its dependence on electric power. The second section of each table addresses additional threats identified as affecting electric power directly. These threats could indirectly affect drinking water through its dependence on electric power. Emerging threats related to possible changes in the environment are presented in Table 5. While many of the impacts of these threats are redundant with the general considerations provided in Tables 3 and 4, their probabilities will be different and may change over time.

For each identified threat, the proposed approach to be used for determining event probability are also provided in each table. It is anticipated that probabilities would be determined using historical data, future projections, or subject matter expert (SME) estimates. For some events there will be very high uncertainty in the probability of occurrence and a range of probabilities may be analyzed. Some threats have sparse historical records or are hypothetical future events. Probabilities for these threats may be based on hypothetical scenarios.

In the following tables, rows shaded in blue indicate threats most likely to directly affect electric power service to individuals. These affect the distribution or transmission systems and may occur with little or no warning.

Table 3: Natural Threats and Their Applicability to the Electric Power Sector

Natural threats	Potential impacts to electric power	Approach for assessing probability
Natural threats identified in SRF for drinking water		
Drought	Potential issue for hydro-generation, power plant cooling. Likely to have a long lead time. Reduced water availability may constrain electricity production.	Historical data; future projections.
Earthquake	Ground accelerations and soil liquefaction can cause damage to transmission and distribution system assets.	Historical data.
Flood	Can cause temporary shut-downs and water damage to transmission and distribution assets	Historical data; future projections if available.
Hurricane/Severe Storms	High winds and water can damage transmission and distribution system assets.	Historical data; future projections if available.

Natural threats	Potential impacts to electric power	Approach for assessing probability
Ice storm	Wind and weight of ice can cause damage to transmission and distribution system assets.	Historical data; future projections if available.
Tornado	Can cause damage to transmission and distribution system assets. Damage is expected to be localized.	Historical data.
Tsunami	Flooding can cause temporary shut-downs and damage to transmission and distribution system assets	Historical data.
Wildfire	Can cause damage to transmission and distribution system assets.	Historical data; future projections if available.
Additional natural threats identified for electric power		
Pandemic	Loss of employees; service disruptions may be more likely or lengthier, but would not necessarily cause impacts.	Historical data.
Geomagnetic storm; extreme solar weather	Possible service disruptions. Damage to power lines due to increased currents, damage to transformers.	Historical data; future projections if available.
High-altitude EMP	Service disruptions, possible damage to transmission or distribution assets	Hypothetical scenario.
Heat wave/high summer temperatures	Disruption due to high peak loads. Service disruptions due to sagging power lines.	Historical data; future projections if available.
Rising sea levels	Possible issue for hydro-generation or near-coast facilities. Likely to have a long lead time to allow for adaptation.	Future projections; hypothetical scenario.

Note: Rows shaded in blue indicate threats most likely to directly affect electric power service to individuals with little or no warning.

Table 4: Human-caused Threats and their Applicability to the Electric Power Sector.

Human-caused threats	Potential impacts to electric power	Approach for assessing probability
Human-caused threats identified in SRF for drinking water		
Aging infrastructure	Degradation of electric power assets. Failure as a function of progress towards smart grid implementation	Utility SME
Contamination	Identified for drinking water, not applicable to electric power.	N/A
Human Error (non-intentional)	Service disruptions, possible damage to assets	Historical data; utility SME
Loss of customers	Financial impacts to electric power. Unlikely to propagate to drinking water unless losses are sustained for long duration causing curtailment of services.	Utility SME
Loss of employees	Service disruptions may be more likely or lengthier, but would not necessarily cause impacts.	Utility SME
Loss of suppliers	Service disruptions may be more likely or lengthier, but would not necessarily cause impacts.	Utility SME
Sabotage, insider threat – cyber; cyberattack	Service disruptions, possible damage to assets.	Utility SME
Sabotage, insider threat – physical	Service disruptions, possible damage to assets. Damage is expected to be localized.	Utility SME
Additional human-caused threats identified in other documents for electric power		
Accidents	Can result in wide range of possible impacts, from service disruptions to asset damage.	Utility SME
Adversarial actions	Impacts anticipated to be same as for sabotage (cyber and physical). Service disruptions, possible damage to assets.	Utility SME
Operational error	Impacts anticipated to be same as for accidents, human error (non-intentional). Service disruptions, possible damage to assets.	Utility SME

Note: Rows shaded in blue indicate threats most likely to directly affect electric power service to individuals with little or no warning.

Table 5:Emerging Threats due to Potential Environmental Changes and Applicability to the Electric Power Sector[4] [5]

Emerging threats	Potential impacts to electric power	Approach for assessing probability
Extreme weather events	Impacts covered under natural threats: severe storms/hurricane, flood, drought. See Table 3	Future projections. Expect range of inputs.
Higher summer temperatures	Impacts covered under natural threats. See Table 3	Future projections. Expect range of inputs.
Reduced water availability	Impacts covered under natural threats: drought. See Table 3.	Future projections. Expect range of inputs.
Rising sea levels	Impacts covered under natural threats. See Table 3.	Future projections. Expect range of inputs.
Regulations	Climate-change related changes to governing regulations. Regulated utilities may need approval before making new investments. The regulatory approval process can be complicated by the lack of established and broadly accepted data sources or assessment methodologies, impact metrics, and solution strategies.	Hypothetical scenario.
New dependencies	Climate change may affect other sectors upon which electric power depends.	Hypothetical scenario.

Note: Rows shaded in blue indicate threats most likely to directly affect electric power service to individuals with little or no warning

4. RISK CALCULATIONS

4.1. Impacts for Each Threat-System Pair

Impact calculations for electric power follow the same methodology used as in the drinking water SRF. Impacts related to community disruption, health and safety, and financial concerns are calculated individually for each threat-system pair. The relevant equations, modeled after those used for water systems and adapted to the electric

[4] White Richard, Randy George, Terrance Boult, and C. Edward Chow. "Apples to Apples: RAMCAP and Emerging Threats to Lifeline Infrastructure." *Homeland Security Affairs* 12, Article 2 (September 2016). https://www.hsaj.org/articles/12012

[5] A Review of Climate Change Vulnerability Assessments: Current Practices and Lessons Learned from DOE's Partnership for Energy Sector Climate Resilience. Office of Energy Policy and Systems Analysis U.S. Department of Energy, May 2016.

power sector are shown in Table 6 where variables in red are supplied by the user and other variables are provided by the framework. Note that the inputs needed to calculate the community disruption impact are also used to calculate the financial impact.

Table 6: Impact calculations for three impact categories.

Impact Category	Description	Calculation
Community Disruption	Costs borne by the local community	$I_{CD} = t_{out} \times n_{cust} \times D_s \times D_u \times GDP$
Health and Safety	Deaths and illness or injury	$I_{HS} = n_D \times VSL + n_I \times VSI$
Financial	Costs borne by the utility	$I_f = t_{out} \times n_{cust} \times D_s \times D_u \times \bar{S} \times r + R_c + O_c$

Where:

- t_{out} = outage time [days]
- n_{cust} = number of hookups
- D_S = % of total demand served
- D_U = % unmet demand
- GDP = metropolitan GDP [GDP/person/day]
- n_D = number of deaths
- VSL = value of a statistical life
- n_I = number of illnesses or injuries
- VSI = value of a statistical illness/injury
- S = average daily service [kWh]
- r = average power rate [$/kWh]
- R_c = repair costs [$]
- O_c = other costs [$]

These impact equations show that most of the inputs are expected to come from the local utilities.

4.2. Combining Impacts: Electric Power and Drinking Water

The equations above are appropriate for assessing the impacts and risks associated with threats to a single infrastructure sector. When an event affects both the electric power and drinking water sectors additional concerns must be addressed.

The primary dependency between the electric power and drinking water system is power outage. The drinking water system may have some backup power, but ultimately requires a supply of utility power. The inverse dependency is less important; electric utility power is less likely to depend on the drinking water system than drinking water is to depend upon power. A power plant may require cooling water to operate, but this may be provided by a non-drinking water system. Also, as noted earlier, loss of a power plant does not necessarily result in a section of the grid being non-operational.

Many threats, such as hurricanes and earthquakes will impact both sectors. Other threats, such as human-cause sabotage, ice storms, geomagnetic storms, etc., may impact electric power but not impact drinking water directly.

Outage time is used in calculating both community disruption and financial impact. If a threat causes outages in both the water and electric power sectors, then one must consider which outage time to use. If the water system requires electric power to operate, then the outage time used for the water utility impact calculation should be the duration associated with whichever system, electric power or water, takes longer to repair. This relationship and recommended values for all variables used to calculate impact metrics are shown in Table 7.

Table 7: Impact metrics variables and how they should be incorporated into impact equations for each sector

Input Variable	Value to Use for Drinking Water (DW) Sector Impacts	Value to Use for Electric Power (EP) Sector Impacts	Comments
t_{out} = outage time [days]	The longer of EP outage to treatment facility and DW outage to community	The EP outage to community	Water cannot come back on until EP is supplied to facility.
n_{cust} = number of hookups	Value appropriate to DW utility	Value appropriate to EP utility	Each sector is impacted by its own customer base
D_S = % of total demand served	Value appropriate to DW utility	Value appropriate to EP utility	Each sector is impacted by its own customer base
D_U = % unmet demand	Value appropriate to DW utility	Value appropriate to EP utility	Each sector is impacted by its own unmet demand
GDP = metropolitan GDP [GDP/person/day]	Value for the locality	Value for the locality	
n_D = number of deaths	Value appropriate to DW utility	Value appropriate to EP utility	Each sector accounts for its own health and safety issues
VSL = value of a statistical life	Value for the locality	Value for the locality	
n_I = number of illnesses or injuries	Value appropriate to DW utility	Value appropriate to EP utility	Each sector accounts for its own health and safety issues

Input Variable	Value to Use for Drinking Water (DW) Sector Impacts	Value to Use for Electric Power (EP) Sector Impacts	Comments
VSI = value of a statistical illness/injury	Value for the locality	Value for the locality	
S = average daily service	Value appropriate to DW utility (MGD)	Value appropriate to EP utility (kWh)	
r = average rate	Average water rate ($/1000 gal)	Average power rate ($/kWh)	
R_c = repair costs [$]	Value appropriate to DW utility	Value appropriate to EP utility	Each sector is impacted by its own repair costs
O_c = other costs [$]	Value appropriate to DW utility	Value appropriate to EP utility	Each sector is impacted by its own other costs

Note: Variables in red are supplied by the user. Other variables are provided by the framework.

4.3. Aggregating Risks for Electric Power and Multiple Infrastructure Sectors

Once impacts are calculated for each system-threat pair, risk can be calculated for each threat, each system and each utility. Risk is the product of consequence, vulnerability and threat, or:

$$Risk = Consequence\ x\ Vulnerability\ x\ Threat \qquad [1]$$

Following the methodology in the SRF, vulnerability for a hazard is incorporated into the threat, i.e., the probability that an estimated impact will occur. As per the example provide in the Tidwell et al., 2017, a heavily fortified facility may have a high probability of attack (i.e., it gets attacked frequently) but if it has a low vulnerability then the probability of an attack being successful is low. In this way, we distinguish between the probability of a threat to a facility, and the probability that the threat will be sufficiently significant to cause consequences. We consider impact to be synonymous with consequence and so:

$$Risk = Impact\ x\ Probability\ of\ Damaging\ Event \qquad [2]$$

The system-threat risks for the community disruption, health and safety, and financial impact categories are calculated as for the DW SRF, using the appropriate version of:

$$\begin{aligned}(R_{CD})_{i,j} &= (I_{CD})_{i,j} \times p_j \\ (R_{HS})_{i,j} &= (I_{HS})_{i,j} \times p_j \\ (R_F)_{i,j} &= (I_F)_{i,j} \times p_j\end{aligned} \qquad [3]$$

where R represents risk, I represents impacts calculated from Table 5, and p represents the yearly probability of the threat occurring. The subscripts, i,j refer to the system and threat, respectively, thus R represents the risk to system i from threat j where risks are due to community disruption, CD, health and safety, HS, and financial impact, F.

The total risk to a system is then calculated by summing across all risks for threats to that system:

$$R_i = \sum_{j=1}^{n_T} \left[(R_{CD})_{i,j} + (R_{HS})_{i,j} + (R_F)_{i,j}\right] \quad [4]$$

where R_i is the total risk to a system across all threats, and n_T is the number of threats. Likewise, the risk to a utility from a single threat is calculated as:

$$R_j = \sum_{i=1}^{n_S} \left[(R_{CD})_{i,j} + (R_{HS})_{i,j} + (R_F)_{i,j}\right] \quad [5]$$

where R_j is the total risk to the utility from a single threat and n_S is the number of systems. The total risk to a utility across all system threat pairs is calculated using:

$$R_{util} = \sum_{i=1}^{n_S} R_i \quad [6]$$

or

$$R_{util} = \sum_{j=1}^{n_T} R_j \quad [7]$$

where R_{util} is the total risk to a utility from all threats. The total risk to a community or geographical area if it contains utilities for multiple infrastructure sectors (e.g., water and electric power utilities) would be calculated using:

$$R_{tot} = \sum_{util=1}^{n_u} R_{util} \quad [8]$$

where $R_{tot}$is the total risk across all utilities, and n_u is the number of utilities.

5. PROOF OF CONCEPT TESTING

Sandia National Laboratories worked with Oak Ridge National Laboratory to identify an appropriate data set to test the model. The test required an outage corresponding to a defined area, extended for a reasonable length of time (e.g., at least one day), and for which community disruption, financial and health and safety costs were compiled. For this proof-of-concept, the entire US was used as it provides a defined region for which data are available and examples exist in the literature of estimated costs for loss of electrical power with which to compare our results. To conduct these calculations for a particular utility would require working with that utility and obtaining utility-specific data, which is beyond the scope of this project.

An implementation of this model was executed using Excel. Inputs and references are provided in Table 8. The model results, shown in Table 9, indicate a total cost of $36.4B. We compare this with a cost of $41.5B (in 2011 dollars) calculated by Oughton et al. 2017[6] for a 1-day outage. The Oughton et al. calculation includes direct losses for 66% of the US plus indirect upstream and downstream losses that lead to a loss of 100% of daily US GDP. Given the varied data sources, different assumptions and different methodologies, only an order-of-magnitude type of comparison is achievable. We consider this a sufficiently satisfactory match to conclude that the model is providing reasonable results to justify further development and testing.

Table 8: Inputs Used for Calculated Results Shown in Error! Reference source not found.

Variables	Values Used for Test Case	References
t_{out} = outage time [days]	1	
n_{cust} = number of hookups	148,633,022	https://www.eia.gov/electricity/annual/html/epa_01_02.html (All US) (Does not include U.S. territories)
D_S = % of total demand	100	
D_U = % unmet demand	100	
N_{out} *(Number of customers out of power)* = $n_{cust} * D_S * D_U$	148,633,022	
GDP per person per day	238	USGDP: $19,028B https://www.bea.gov/iTable/iTable.cfm?ReqID=9&step=1#reqid=9&step=3&isuri=1&903=5 number people: 0.32B; number days: ~365 GDP/person/day=19028/0.32/365 = 238$/person/day
n_D = number of deaths	0	None in this scenario
VSL = value of a statistical life [$]	9,600,000	https://www.transportation.gov/sites/dot.gov/files/docs/2016%20Revised%20Value%20of%20a%20Statistical%20Life%20Guidance.pdf . Value not used in this calculation.
n_I = number of illnesses or injuries	0	

[6] Oughton, Edward, J., A. Skelton, R.B. Horne, A.W.P. Thomson, C.T. Gaunt, Quantifying the daily economic impact of extreme space weather due to failure in electricity transmission infrastructure. January, 2017. http://onlinelibrary.wiley.com/doi/10.1002/2016SW001491/full

Variables	Values Used for Test Case	References
VSI = value of a statistical illness or injury		Value not used in this calculation
S = average daily service [KWhrs per customer per day]	69.29	Per EIA: Total sales ~3,758,992,000 MW-hours for 2015. https://www.eia.gov/electricity/annual/html/epa_01_02.html 1000*3,758,992,000 MW-hours /number customers served/365 days = 69.28 kW-hrs/cust/day
r = average rate [$/kWh]	0.104	https://www.eia.gov/electricity/annual/html/epa_01_02.html
R_c = repair costs [$]	0	Value not used in this calculation
O_c = other costs [$]	0	Value not used in this calculation

Table 9: Model Results for Test Case (Total is slightly different from sum of components due to rounding)

Impacts:	$
Community disruption	$ 35.4B
Health and Safety	-
Financial	$ 1.1B
Total	$ 36.4B

6. SUMMARY AND CONCLUSIONS

A conceptual model is presented for calculating risks associated with an electrical power utility that is coupled to water utilities. The risk assessments comprise those associated with community disruption, financial impacts, and health and safety. This work leverages a shared risk framework designed for assessing and comparing threat-based risks to water utilities. The framework, while consistent with the Risk Analysis and Management for Critical Asset Protection (RAMCAP) methodology, uses a system, or subsystem-centric approach to assessing risk rather than an asset-based approach. Based on the original framework and literature searches, the systems and threats relevant to the electrical power system are compiled, and the mathematical description of associated risks are provided. The method is extensible so that additional infrastructure sectors can be incorporated. This approach allows comparisons across utilities and is therefore useful in detecting bias and identifying outliers in risk assessments.

A proof of concept calculation was conducted. Sandia National Laboratories worked with Oak Ridge National Laboratories to identify an appropriate data set to test the model. An outage was required that corresponded to a defined area, extended for a reasonable length of time (e.g., at least one day), and for which community disruption, financial, and health and safety costs were compiled. For this proof-of-concept, we use the entire US because data are available, and costs have been estimated for loss of electrical power with which we can compare our results. To conduct these calculations for a particular utility would require working with that utility and is beyond the scope of this project.

The proof of concept calculation was executed using Excel and data were compared with a published estimate of a similar but not identical outage. Given that the analyses used different data sources, different assumptions and different methodologies, a rough order-of-magnitude-type comparison is used to assess viability of the conceptual model. The two estimates were reasonably comparable, and so we conclude that the model is providing reasonable results that justify further, continued development and testing.

7. PATH FORWARD

The ultimate goal for this project is to develop an objective system for prioritizing investments and encouraging anonymous sharing of results to improve risk-based analysis. In this report we provided a methodology for incorporating interdependencies with the electric power system.

A further advancement would be to integrate data from multiple sectors, beginning with electric power. To do this we need to accomplish the following tasks.

1. Electric Sector Risk Analysis Completion
    a. Work with individual electric utilities to obtain data on their risk assessment methods and potential available data. (~ 1 year, ~$400k)
    b. Propose/establish a broadly accepted standard for characterizing risk. This involves:
        i. Begin with existing generic standards (RAMCAP) and map them into a form that is meaningful for the electric power sector. (~6 months, $300k)
        ii. If industry standard tools are not available, then propose/create a risk assessment tool specific to the electric power sector (e.g., VSAT for the water system). (Level of effort dependent on initial findings.)

iii. Establish and vet metrics. Our report provides three overall metrics for evaluating risk. Modify these as-needed to get buy-in from industry for a set of metrics for describing risk. (Large range of possible levels of effort, would require engagements with organizations such as EPRI, NERC.) (1 -3 years, \$500k – \$2M,)
iv. Work with electric utilities to understand and mitigate barriers to anonymous sharing of risk information. To be conducted simultaneously with step iii above. Costs captured above.

2. Water Sector Risk Analysis
    a. Establish and vet metrics. Our report provides three overall metrics for evaluating risk. Modify these as-needed to get buy-in from industry for a set of metrics for describing risk. (Large range of possible levels of effort, would require engagements with organizations such as AWWA.) (1 -3 years, \$500k – \$2M,)
    b. Work with water utilities to understand and mitigate barriers to anonymous sharing of risk information. To be conducted simultaneously with step a above. Costs captured above.
3. Water and Electric Power Sector Integration
    a. Vet model framework to ensure that linkages among sectors are reasonable and calculations of risks are normalized among sectors.
    b. Expand the model framework to
        i. Incorporate data from multiple sources for electric and water infrastructure sectors. Extract information from other tools.
        ii. Create visualization functions to facilitate interpretation of results.
    c. Extensive demonstration and testing of capabilities.
4. Replicate conceptual model development for additional lifeline infrastructure sectors.

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