ERDC/ITL SR-22-5

Information Technology Laboratory

US Army Corps of Engineers®
Engineer Research and Development Center

ERDC
ENGINEER RESEARCH & DEVELOPMENT CENTER

Navigation Systems Research Program

Risk-Based Prioritization of Operational Condition Assessments

Methodology and Case Study Results

Jonathan K. Alt, Willie H. Brown, John P. Richards, George E. Gallarno, Jennifer M. Olszewski, and Titus L. Rice

November 2022

ERDC/ITL SR-22-5
November 2022

Risk-Based Prioritization of Operational Condition Assessments: Methodology and Case Study Results

Jonathan K. Alt, Willie H. Brown, George E. Gallarno, John P. Richards, Jennifer M. Olszewski, and Titus L. Rice

Information Technology Laboratory
US Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Final report

Prepared for Navigation Systems Research Program
Coastal Hydraulics Laboratory
US Army Engineer Research and Development Center
Vicksburg, MS 39180

Under Funding Account Code U4375151; AMSCO Code 031391

Abstract

USACE operates, maintains, and manages more than $232 billion of the Nation's water resource infrastructure. USACE uses the Operational Condition Assessment (OCA) to allocate limited resources to assess condition of this infrastructure in efforts to minimize risks associated with performance degradation. The analysis of risk associated with flood risk management (FRM) assets includes consideration of how each asset contributes to its associated FRM watershed system, understanding the consequences of the asset's performance degradation, and a determination of the likelihood that the asset will perform as expected given the current OCA condition ratings of critical components. This research demonstrates a proof-of-concept application of a scalable methodology to model the probability of a dam performing as expected given the state of its gates and their components. The team combines this likelihood of degradation with consequences generated by the application of designed simulation experiments with hydrological models to develop a risk measure. The resulting risk scores serve as an input for a mixed-integer optimization program that outputs the optimal set of components to conduct OCAs on to minimize risk in the watershed. This report documents the results of the application of this methodology to two case studies.

Contents

Abstract ii

Figures and Tables v

Preface vi

1 Introduction 1
- 1.1 Background 1
- 1.2 Objective 2
- 1.3 Approach 3

2 Methodology 5
- 2.1 Facility performance model 5
- 2.2 Initializing conditional probability tables 7
- 2.3 Subject matter expert elicitation methodology 8
- 2.4 Consequence development 10
  - *2.4.1 Experimental design* 11
  - *2.4.2 Statistical modeling* 11
- 2.5 Determining risk 12
- 2.6 Prioritization model 12
- 2.7 Summary 14

3 Case Study: Jennings Randolph Lake Results 15
- 3.1 Review of previous results 15
  - *3.1.1 Subject matter expert elicitation* 15
  - *3.1.2 Initializing Bayesian models* 16
- 3.2 Update on consequence development 16
- 3.3 Updated prioritization results 17
- 3.4 Proof of concept prioritization tool 17

4 Case Study: Trinity River 19
- 4.1 Overview 19
- 4.2 Data exploration 19
- 4.3 Subject matter expert elicitation 21
  - *4.3.1 Conduct* 21
  - *4.3.2 Results* 21
- 4.4 Initializing Bayesian networks 22
- 4.5 Developing consequences 24
  - *4.5.1 Scenario configuration* 24
  - *4.5.2 Analysis of results, experiment 1* 24
  - *4.5.3 Analysis of results, experiment 2* 25
- 4.6 Prioritizing components by risk 27
  - *4.6.1 Developing risk scores* 27
  - *4.6.2 Prioritization* 28

5 Summary and Way Ahead **31**
5.1 Modeling methodology 31
5.2 Case study 1 31
5.3 Case study 2 31
5.4 Way ahead 32

References **34**

Appendix A: Terms of Reference **35**

Appendix B: OCA Rating Scales **36**

Appendix C: CPT Initialization Methodology **37**

Appendix D: Risk Determination Methodology **39**

Appendix E: Single Facility Case **41**

Appendix F: Subject Matter Elicitation Materials **42**

Appendix G: Initializing Bayesian Networks Example **64**

Appendix H: SMEs for Both Case Studies **65**

Acronyms and Abbreviations **66**

Report Documentation Page

Figures and Tables

Figures

Figure 1. OCA strategic objectives; those addressed by this research are highlighted. ... 1
Figure 2. OCA hierarchy. ... 2
Figure 3. General approach for the execution of the project. ... 3
Figure 4. Example Bayesian network for facility operational status, where C represents components critical to the function of systems, S, that in turn determine the operational status of the facility, F, and E represents environmental factors. ... 6
Figure 5. Exploratory Data Analysis Tool screenshot of the OCA and FEM hierarchies of the JRL facility. (https://oca-eda.erdc.dren.mil/dashboard/) ... 7
Figure 6. Subject matter expert elicitation process. ... 8
Figure 7. Screenshot of the SME Elicitation Tool used for data collection in the Trinity River Case Study. (https://oca-eda.erdc.dren.mil/osea) ... 9
Figure 8. Screenshot of the Group Session Application used to determine consensus on system and component relative influence weights. (https://oca-eda.erdc.dren.mil/delphi) ... 9
Figure 9. Screenshot of the Level of Agreement Application used to elicit level of agreement with system and component relative influence weights. (https://oca-eda.erdc.dren.mil/delphi_loa/) ... 10
Figure 10. Risk mitigated by scenario with increased condition assessments. Consequences for flood conditions at the 25-, 50-, and 100-year events. ... 17
Figure 11. Proof of concept prioritization tool. ... 18
Figure 12. Trinity River Sub-basin. Ray Roberts, Lewisville, and Grapevine Lakes sit in the Elm Fork of the Trinity River. ... 19
Figure 13. Case study 2 individual results for relative influence of systems to facility under normal conditions (Grapevine Lake). ... 21
Figure 14. Coefficients of the regression model with corresponding confidence intervals. ... 25
Figure 15. Sample regression tree of Trinity River facilities. ... 26
Figure 16. Engineering Risk (not including consequence) mitigated as OCAs increase across facilities in the Trinity Watershed. ... 28
Figure 17. Components selected by facility in the Trinity Watershed. ... 29
Figure 18. Operational risk (including consequences) mitigated as OCAs increase across facilities in the Trinity Watershed. ... 29
Figure 19. Unique components selected by facility with increasing number of OCAs. ... 30
Figure 20. General approach for the execution of the project in FY22. ... 33
Figure F-1. CAC authentication. ... 43
Figure F-2. Select Facility. ... 44

Figure F-3. Type name. 44
Figure F-4. Overall page view. 45
Figure F-5. System relative influence (normal). 45
Figure F-6. Verify that like-type gates have same relative influence (normal). 46
Figure F-7. Provide comments (normal). 47
Figure F-8. Chart visualization (normal). 47
Figure F-9. Save responses (normal). 47
Figure F-10. System relative influence (flood). 48
Figure F-11. Verify that like-type gates have same relative influence (flood). 48
Figure F-12. Provide comments (flood). 49
Figure F-13. Chart visualization (flood). 50
Figure F-14. Save responses (flood). 50
Figure F-15. Service discharge gate relative influence. 50
Figure F-16. Water quality gate relative influence. 51
Figure F-17. Component relative influence. 51
Figure F-18. Grapevine Lake. 57
Figure F-19. Lewisville Lake. 57
Figure F-20. Ray Roberts Lake. 57
Figure F-21. Grapevine Lake. 58
Figure F-22. Lewisville Lake. 58
Figure F-23. Ray Roberts Lake. 58
Figure F-24. Grapevine Lake. 59
Figure F-25. Lewisville Lake. 59
Figure F-26. Ray Roberts Lake. 59
Figure F-27. Grapevine Lake. 60
Figure F-28. Lewisville Lake. 60
Figure F-29. Ray Roberts Lake. 60
Figure F-30. Case study 2 individual SME vs. consensus relative influence results—Grapevine Lake. 61

Tables

Table 1. Systems associated with Grapevine, Ray Roberts, and Lewisville Lakes in OCA hierarchy. 20
Table 2. Table for assigning system rating to probability of failure. 23
Table B-1. OCA rating scale and definitions (USACE 2019). 36
Table F-1. List of respondents to the subject matter expert elicitation. 42
Table F-2. Level of agreement results for case study 2—Trinity River. 62
Table F-3. Example system-component OCA ratings. 63
Table G-1. Example system-component OCA ratings. 64
Table G-2. Example system components normalized relative influence. 64

Preface

This study was conducted for the Navigation Systems Research Program, Coastal Hydraulics Laboratory (CHL), US Army Engineer Research and Development Center (ERDC), under Funding Account Code U4375151, AMSCO Code 031391. Ms. Morgan Johnston was the Program Manager for the Navigation Systems Research Program, and Mr. Peter Dodgion was the Program Manager for Asset Management, Headquarters, US Army Corps of Engineers.

The work was performed by the Institute for Systems Engineering Research, Computational Science and Engineering Division, Information Technology Laboratory (ITL), ERDC, and the Hydrologic Systems Branch (HSB), Flood and Storm Protection Division (FSPD), ERDC-CHL. At the time of publication of this report, Dr. Simon R. Goerger was Director, ITL Institute for Systems Engineering Research; Dr. Jeffrey Hensley was Division Chief, ITL Computational Science and Engineering Division; and Dr. Robert Wallace was Technical Director for ITL Engineered Resilient Systems. The Deputy Director of ERDC-ITL was Dr. Jacqueline Pettway, and the Director of ERDC-ITL was Dr. David Horner.

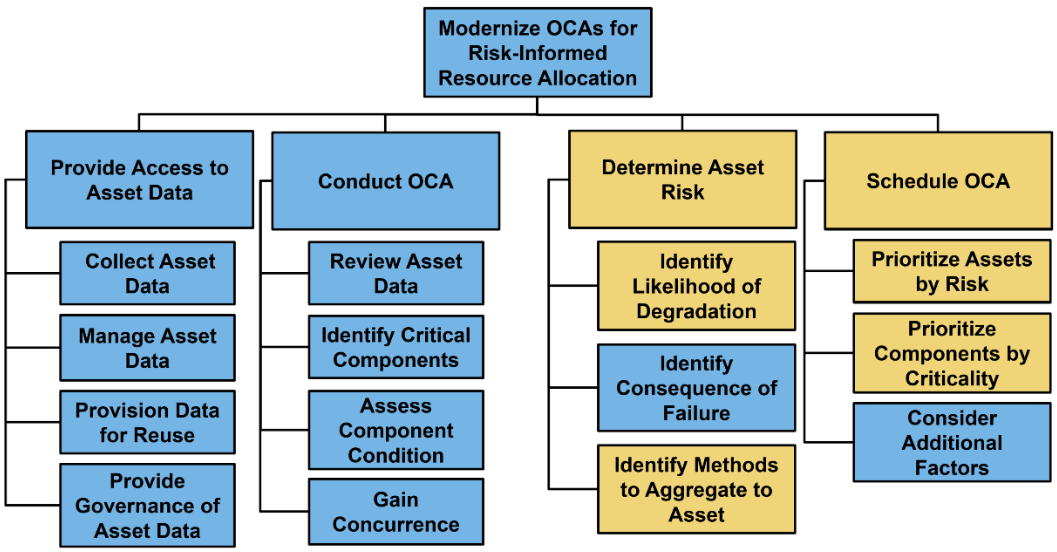
COL Christian Patterson was the Commander of ERDC, and the Director was Dr. David W. Pittman.

This page intentionally left blank.

1 Introduction

USACE operates, maintains, and manages more than $232 billion worth of the Nation's water resource assets. Ensuring the proper functioning of these assets, particularly those associated with flood risk management (FRM), impacts the lives of American citizens on a daily basis. USACE personnel perform operational condition assessments (OCAs) on these assets' components at a minimum of every 5 years. Having investigated the OCA system, the team recommended strategic objectives to achieve a transparent, consistent, and traceable risk-based OCA system (see Figure 1) (Brown and Alt 2021).

Figure 1. OCA strategic objectives; those addressed by this research are highlighted.

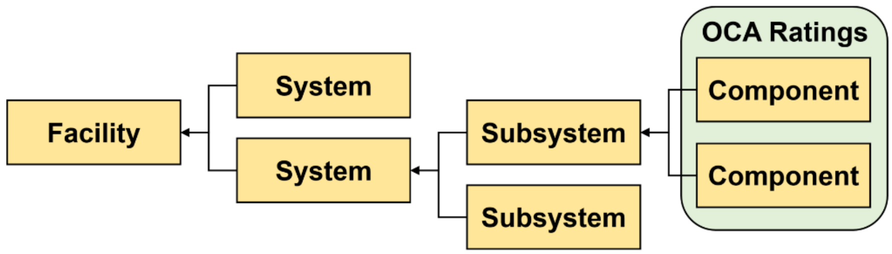


This research develops a methodology to understand how the condition of components impacts system performance and how each system impacts the performance of the facility in which it sits. The purpose of this document is to provide the updated methodology and its application to a case study on the Elm Fork of the Trinity River.

1.1 Background

USACE OCA teams conduct OCAs each year without considering risk, resulting in the expenditure of resources on assets that pose minimal risk to the enterprise's ability to execute its mission. A risk-based prioritization framework requires an understanding of probability of failure of a system as a function of the state of its components, as defined by the OCA ratings (see Appendix B), and the consequence of a system's failure in the context of the FRM watershed. This framework must be robust enough to accommodate a range of facility types and configurations, and it must be feasible to implement at scale given the rapidly growing number of components and their interactions in a single facility (see Figure 2).

Figure 2. OCA hierarchy.



The previous literature review and the results of the Jennings Randolph Lake Facility and Baltimore District staff interviews are outlined in Alt et al. (2021). The results from the Jennings Randolph* and the Trinity River case studies inform the current methodology.

1.2 Objective

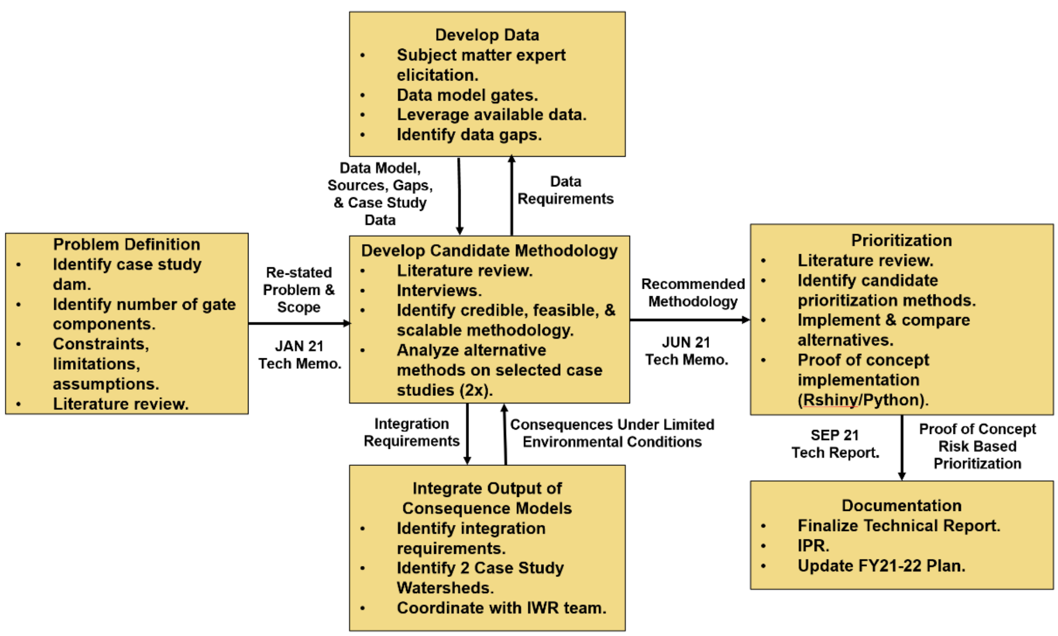
The objective of this 3-year effort is to develop an enterprise framework for risk-based prioritization of OCAs. This project will help decision-makers understand which FRM facility components to prioritize for assessment and maintenance based on their contribution to overall operational risk and current conditions. This project focuses on facilities associated with FRM, but the prioritization methodology developed should generalize to other business lines in the future. The output of the framework will be (1) the set of FRM risk-driving components to prioritize for OCAs and maintenance given limited resources, (2) the uncertainty associated with model results, and (3) an easily understandable presentation of potential trade-offs. The tasks associated with determining asset risk are (1) calculate probability of degradation, (2) calculate consequence of failure, and (3) identify methods to the facility and the watershed.

* Alt, J. K., W. H. Brown, G. E. Gallarno, and J. P. Richards. n.d. Risk-Based Prioritization of Operational Condition Assessments: Jennings Randolph Case Study.

1.3 Approach

The results of the initial literature review informed the development of the methodology (reviewed in Section 2), which was applied to both case studies. Expanded results of the application of this methodology to the first case study, Jennings Randolph Lake, are documented in Section 3 (Alt et al., n.d.). Section 4 documents the results of the second case study application, Elm Fork of the Trinity River Basin. Data development for each study leveraged OCA and Facilities and Equipment Maintenance (FEM) databases and existing Corps Water Management Systems (CWMS) models, but the data exploration identified gaps in data required to determine the probability of degradation. This required the elicitation of input from subject matter experts (SMEs) at each facility using custom web-based tools. In order to develop consequence data, the project team included consequence modelers from the Institute for Water Resources (IWR) and the ERDC Environmental Laboratory (EL). These two teams collaborated to develop risk scores for both case studies, and these risk scores serve as input into a mixed-integer optimization program that outputs the optimal set of components requiring OCAs in order to minimize risk in the watershed. Those results are shown in Section 3.3. Figure 3 illustrates the approach.

Figure 3. General approach for the execution of the project.



1.4 Scope

The report provides a brief review of the developed methodology, expanded results from the first case study, results of the second case study, roadmap for future work, and conclusions.

2 Methodology

This section provides a brief review of the modeling methodology, development of consequences, determination of risk, and prioritization framework developed as a result of a previous review of the literature (Alt et al. 2021, n.d.).

2.1 Facility performance model

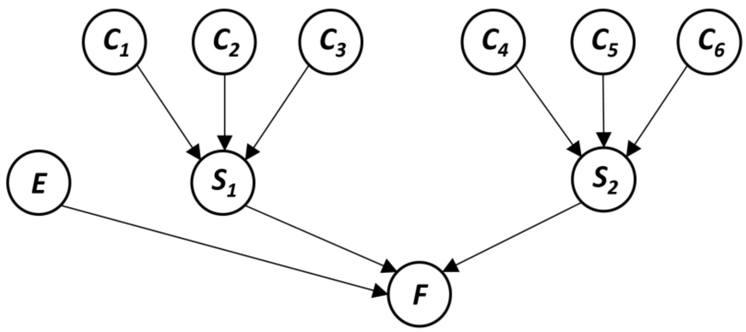
Bayesian (Belief) networks leverage Bayes' theorem to determine the conditional probability of an event occurring given some event B has occurred (alternatively called the posterior probability of A given B).

By combining Bayes' theorem and notional information about the relationship between events, it is possible to formulate a Bayesian network. Graphical depictions of Bayesian networks are directed acyclic graphs of events in which each node conditions itself on the immediately preceding node(s). Modelers refer to nodes from which arcs originate as *parent nodes* and the nodes in which arcs terminate as *child nodes* (Alt et al. 2021).

In this case, components, systems, and the facility are nodes in the network. By incorporating these three levels into the Bayesian network, it is possible to examine the influence of components on their respective system, which in turn influences the operational status of a facility.

Figure 4 presents an example Bayesian network modeling the probability that a facility (F) functions given the state of its systems, S_i, where i = 1…n and n is the number of systems critical to the functioning of the facility, $P(F|S_1, S_2, \dots, S_n, E)$. The team also includes the impact of environmental conditions on the facility.

Figure 4. Example Bayesian network for facility operational status, where C represents components critical to the function of systems, S, that in turn determine the operational status of the facility, F, and E represents environmental factors.



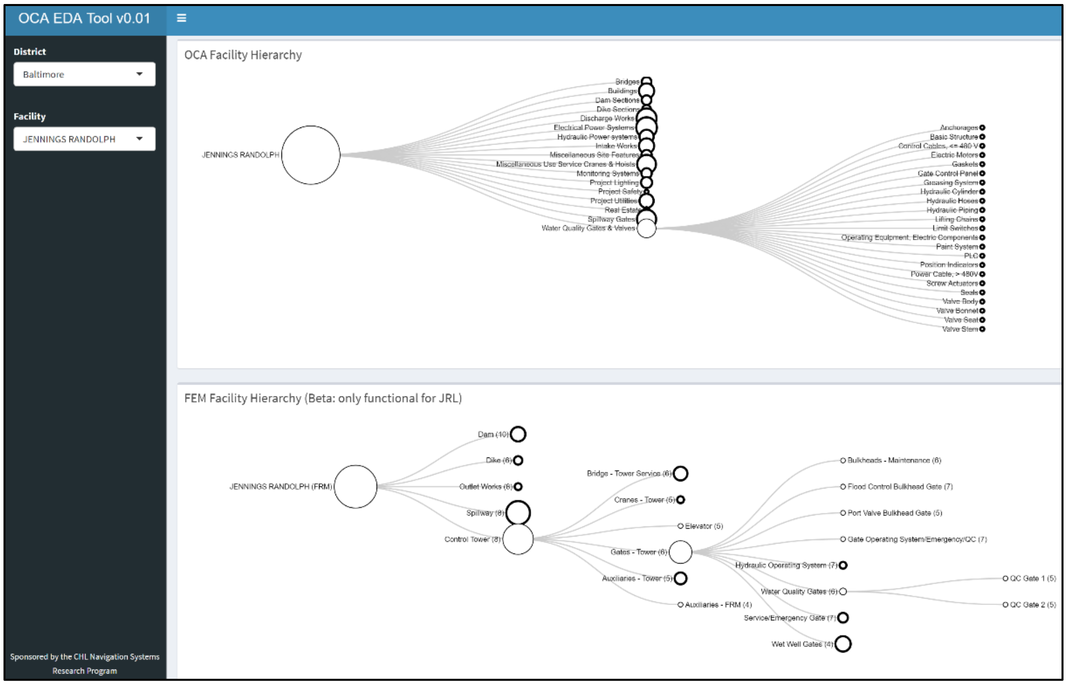
In this case, the variables at the facility and system level have only two states, fully operational or degraded. Figure 4 also presents an example Bayesian network modeling the probability that a system functions given the state of its components, C_j, where $j = 1 \ldots m$ and m is the number of components critical to the proper functioning of the system, $P(S_i | C_1, C_2, \ldots, C_m)$.

The state of critical components is determined by observation of the component during its most recent OCA. This assessment can take on values *A* through *F*, but the state space can also be reduced to a simple Pass or Fail where an OCA rating of A, A−, B+, or B are a Pass with anything less than a B being a Fail.

In the absence of failure or downtime data, the team used SME knowledge to initialize conditional probability tables required to use this model for inference.

The team developed an R-Shiny application to aid in exploratory data analysis. One of the key findings is the fact that the OCA and FEM databases have different component hierarchies which have no points of interaction/integration. Figure 5 is a screenshot of the Exploratory Data Analysis tool showing the difference between these two hierarchies when navigating to the level below Water Quality Gates at Jennings Randolph Lake. The top pane illustrates the OCA hierarchy, and the bottom pane illustrates the FEM hierarchy. A glance at these hierarchies reveals that they are different in terms of the number of hierarchy levels, the number of facility assets represented in the hierarchy, and the type of facility representation. Future tool development will begin to provide tools to allow the differences between these two data sources to be reconciled to develop initial conceptual models for use in this effort.

Figure 5. Exploratory Data Analysis Tool screenshot of the OCA and FEM hierarchies of the JRL facility. (https://oca-eda.erdc.dren.mil/dashboard/)



2.2 Initializing conditional probability tables

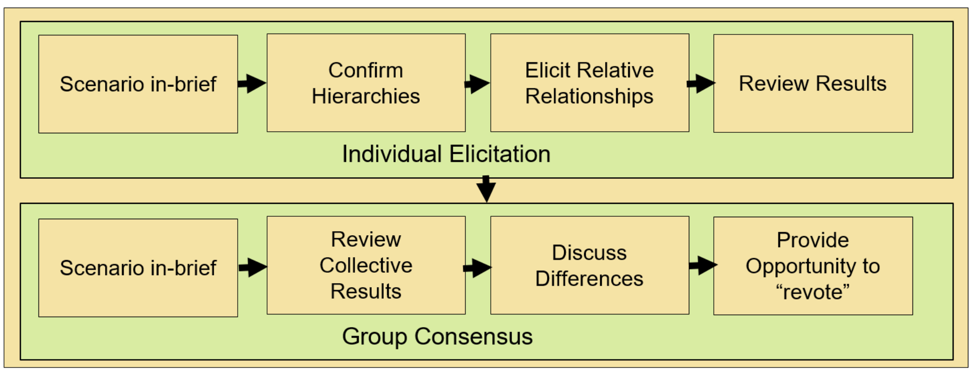
To decrease the time- and data-intensive burden of asking SMEs to provide or estimate a probability of failure for every system and component in each facility, this research leveraged the technique presented by Hassall et al. (2019). Hassall et al. initialize conditional probability tables (CPT) by eliciting the relative influence of parent and child nodes within the proposed Bayesian network. This resulted in drastic reductions in the number of elicitations required to initialize a conditional probability table. First, this study used SMEs' input to determine critical components within the key gate systems. Next, SMEs identified the relative influence of the critical components for each key gate system under assessment. Lastly, the SMEs assessed the relative influence of the key gate systems to operational status of the Jennings Randolph Lake facility during "normal" and "flood" operating conditions (Alt et al., n.d.).

Note that after initializing the CPT with the relative relationship information, it is possible to refine the probability estimates using empirical data should it become available.

2.3 Subject matter expert elicitation methodology

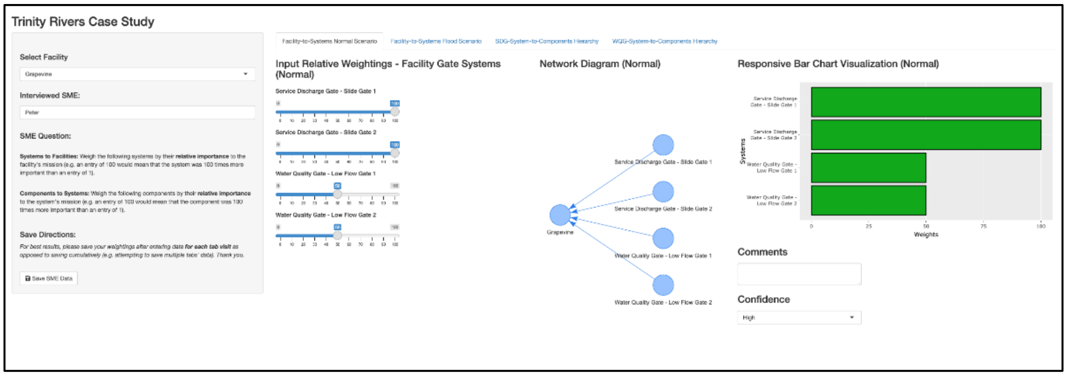
For the collection of expert opinion on the relative influence of systems on the facility and components on the systems, a modified Delphi Method was utilized to elicit SME input through multiple rounds to build consensus (Richards et al. 2021). This places the elicitation into a specific scenario setting and asks relative value judgements with the intent to generate relative comparisons that will be used to calculate the conditional probabilities. The team conducted SME elicitation in two stages: individual elicitation and group consensus, as shown in Figure 6 (Alt et al. n.d.).

Figure 6. Subject matter expert elicitation process.



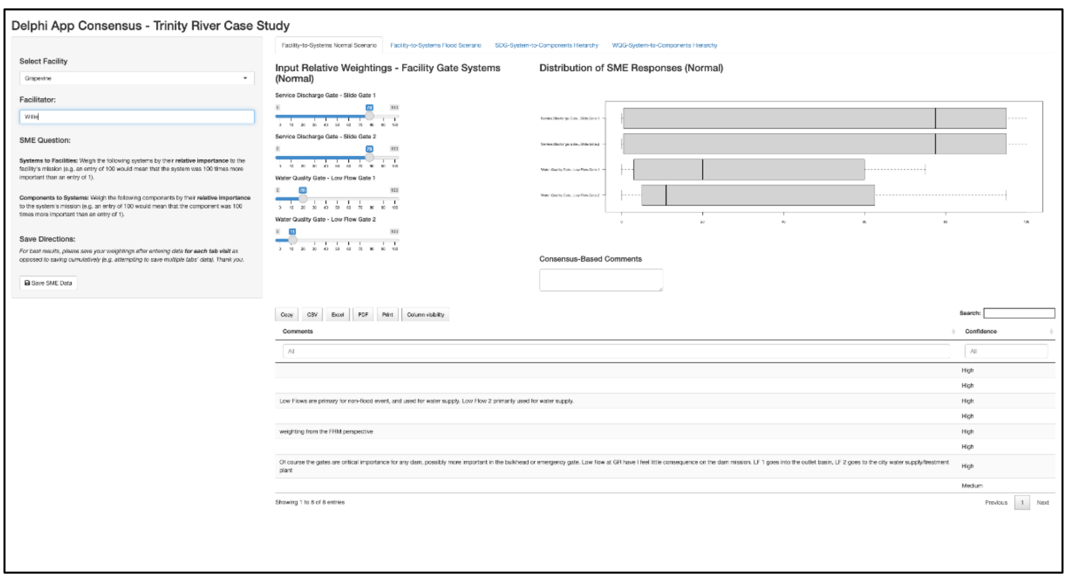
In order to facilitate distributed SME elicitation and reduce the burden on SMEs, the team developed a set of CAC-enabled, web-based applications hosted on ERDC's Cloud Computing Environment. Intuitive and easy-to-use applications support both the first round of individual input and the second consensus-building rounds. The sliders used in the first round allow individual SMEs to assignee a numeric value for their assessment of the relative influence of each system or component on the facility (system) or system (component) (Figure 7). A dynamic bar chart visualizes the value of the relative influences, providing the SME an indicator of the differences in relative influence across the facility (or system). Additionally, a network diagram of the relationship of the system (or component) to the facility (or system) was displayed in the center of the screen. Finally, a free text block was provided to allow for any SME comments, as was a block for them to indicate their level of confidence in making the relative influence assignments.

Figure 7. Screenshot of the SME Elicitation Tool used for data collection in the Trinity River Case Study. (https://oca-eda.erdc.dren.mil/osea)



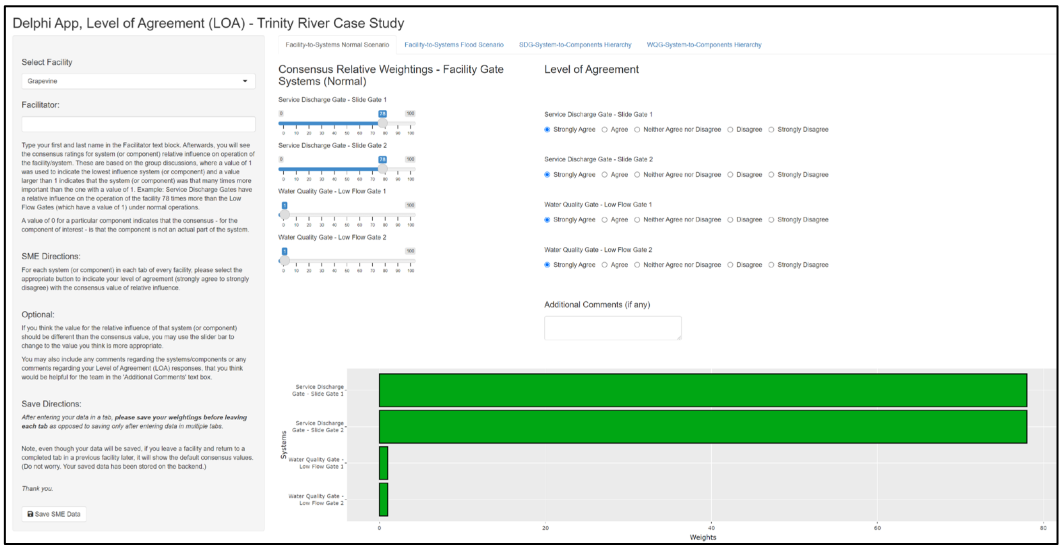
After the data for the individual SMEs were collected, they were processed and then visualized for the group session. A dynamic slider, initially set at the average value for the relative influence, provided the group facilitator the ability to adjust the value to the group consensus. A box-and-whisker plot on the right-hand side provided a visual indication of the spread of the individual responses across the SMEs, indicating how close (or disparate) their initial assignments of relative influence were. Finally, any free text comments from the individual SMEs were displayed in the table at the bottom of the screen (Figure 8).

Figure 8. Screenshot of the Group Session Application used to determine consensus on system and component relative influence weights. (https://oca-eda.erdc.dren.mil/delphi)



The final tool implemented in the SME elicitation process was the Level of Agreement Application (Figure 9). This was sent out to the SMEs after the group consensus session for two purposes. The first was to provide an opportunity for each SME to indicate how much they agree or disagree with the group consensus for the values of relative influence for each system or component discussed. Second, the tool provided the SME with the ability to change the values using the slider (dynamically shown in the bar chart at the bottom of the screen) to values they preferred. Additionally, a free text block was provided to allow the SME to comment on why they did not agree with the group consensus or to provide any additional input.

Figure 9. Screenshot of the Level of Agreement Application used to elicit level of agreement with system and component relative influence weights. (https://oca-eda.erdc.dren.mil/delphi_loa/)



Future development will allow these tools to be instantiated from data for each facility under study and create a database that SME input is stored in for use by other tools developed to support this workflow.

2.4 Consequence development

In order to generate consequences associated with engineered systems that operate as part of a watershed's FRM system, team members from the Institute for Water Resources made use of simulation models developed using the Hydrologic Engineering Center (HEC) Watershed Assessment Tool (HEC-WAT) (Alt et al., n.d.; HEC IWR USACE 2017).

In order to generate consequences at the gate level, the HEC-WAT model of the facility or watershed must have a representation of the capacity of a gate and the functions of the gate. As part of scenario construction, the team defined the environmental conditions under which the system would be studied, identifying four flood events (10, 25, 50, and 100 year).

2.4.1 Experimental design

In order to make use of this modeling suite to determine consequences at the gate level, the model of the engineered system in the watershed must be perturbed through a series of designed simulation experiments. Methods from the design of experiments literature can be used to design simulation experiments that provide good insights into the independent variables of interest to the response—in this case gates and damages, respectively—that are also feasible within the computational budget available (e.g., Oehlert 2000). In a simple case with a single facility or several small facilities, the use of a full factorial design of experiments might be employed, but as the complexity of the modeled systems grows, the use of other designs will be required. In the simplest case, gates can be treated as either operational or not with a given set of environmental conditions as input. The goal of this effort is to generate data to inform the development of a statistical model of the consequences as a function of gate status.

2.4.2 Statistical modeling

Using the consequences generated from each model run as the response variable and each combination of inputs as the independent variables, the team employed multivariate statistical modeling methods to generate a meta-model or surrogate model that provided an understanding of each independent variable's contribution to the response. In this case, treating the consequence observed in dollars from each design point as the response, the model predicted consequences in dollars as a function of the state of each of the gate systems modeled, the independent variables. The team made use of a multivariate regression model of the form $\hat{y} = b_0 + b_1X_1 + \cdots + b_nX_n$ in order to facilitate ease of interpretation of the coefficients of the regression model as the contribution of the gate system to the overall consequences (Rencher and Schaalje 2008). Note that the team can also develop estimates of the uncertainty around both the coefficients and the predicted consequences as well.

2.5 Determining risk

The research team defines risk as a combination of the likelihood of an event and the consequences of an event. The team determines the likelihood of an event making use of data derived from SME elicitation used to populate the conditional probability tables of the Bayesian network and combines that with consequences from HEC-WAT model outputs. In this way, it is possible to arrive at an estimate of the risk associated with each gate and with each component. While the team developed several methods to determine risk, the team discusses methods here that rely on the output of simulation models at the gate level (Alt et al., n.d.).

Given the facility, f, the systems that compose the facility, s, and the components that make up the systems, c, a Bayesian network model can be developed for use in inference around the probability that the system will be in a degraded state based on the condition of its systems or components. SME input provides an understanding of the relationships between the systems and the facility's performance and the components and their respective system's performance and initializes the conditional probability tables of the Bayesian model. The results of a designed experiment that systematically varies the state of the gate systems and collects consequence data for each simulated run under a set of fixed environmental conditions yields data suitable for the development of a meta-model. Assuming the use of a multivariate regression model of the form $\hat{y} = b_0 + b_1X_1 + \cdots + b_nX_n$, the coefficients of the regression model provide an estimate of the consequences associated with the state of each gate. Given estimated consequences at the gate level and the relative influence from our SME, each contribution of each system to overall facility risk can be determined. Treating this as an upper bound on the risk associated with the system, the team can then make use of relative influence data to determine the contribution of each component to the risk associated with the system in which it sits. This provides an upper bound on the contribution of each component to the risk of the system and the systems to risk at the facility level.

2.6 Prioritization model

In order to identify the set of components to prioritize at a facility or set of facilities given a constraint on the number of condition assessments available, the team formulates the problem as a mixed integer program that seeks to maximize the risk mitigated through the selection of components. In order to address practical considerations with the execution of condition assessments, the team further constrains the model to select sets of components across like-type systems at a facility. If the model chooses one hydraulic pump on a water quality gate, it must select all the hydraulic pumps on water quality gates at the facility. The team considered multiple formulations but includes only the formulation relevant to our second case study—multiple facilities in a single watershed—in this discussion. The team first defines the following sets and indices.

Index

- i Components, *1…n*
- j Systems, *1…m*
- k Facilities, *1…l*

Data

- $Risk_{i,j,l}$ Risk of component i in system j at facility l
- *OCABudget* The total number of OCAs available across all facilities
- $NumOCA_{i,j,l}$ The number of OCAs required to complete an OCA on all like-type components at a facility

Variables

$X_{i,j,l}$ Binary decision variable for each component i in system j and facility l

Formulation

$$\max \sum_{i,j,l} X_{i,j,l}\, Risk_{i,j,l}$$

Constraints

$$\sum_{i,j,l} X_{i,j,l} NumOCA_{i,j,l} \leq OCABudget$$

This model identifies the set of components across all facilities that provides the maximum risk reduction across facilities within the watershed but could result in solutions that do not allocate condition assessments to some facilities. Additional constraints could be added to ensure that some minimum number of assessments are conducted at each facility if that was appropriate.

2.7 Summary

This section provided an overview of the methodology, as well as variations on the methodology, that was developed for this effort (Alt et al., n.d., 2021; Brown and Alt, 2021). The methodology is intended to be robust to different data sources and provide a framework for developing risk measures for FRM facilities across the enterprise. The next section provides an update of the application of this methodology to the Jennings Randolph Lake facility, the first case study (Alt et al., n.d.).

3 Case Study: Jennings Randolph Lake Results

This section provides an update to the previously reported results of the application of the developed methodology to the Jennings Randolph Lake case study. (Alt et al., n.d.)

3.1 Review of previous results

The North Potomac Watershed served as the backdrop for the first case study, where three dams work in series: Mt. Storm, Savage River, and Jennings Randolph. The team focused its efforts on Jennings Randolph—the only dam managed and operated by USACE. Jennings Randolph contains three gate systems: Spillway Gates (5), Water Quality Gates (2), and Service Discharge Gates (2).

In the OCA hierarchy, Jennings Randolph Lake decomposes into 17 unique major systems, with 76 unique subsystems and 175 unique component types. The USACE maintenance tracking system, FEM, contains a similar but inconsistent hierarchy. The Corps Water Management Systems (CWMS) models represent a third representation of the dam. Given the inconsistencies in the three data sources, the team required the use of SME input from members of the facility team to develop an adequate representation of the dam, its systems, and the systems' components.

3.1.1 Subject matter expert elicitation

The initial individual SME discussions conducted through the modified Delphi method highlighted the need to clearly identify the operating scenarios (flood conditions versus normal operating conditions) for the facility since scenarios may change the relative influence of the systems on the facility. The process produced excellent consensus. Of the 72 responses for the relative influence of the nine systems to the facility under flood and normal operations, 83.33% were strongly agree and 16.67% were agree responses. All 120 responses (100%) for the components were agree responses. This denotes a strong level of agreement among the SMEs for the assignment of relative influence at the end of the process.

3.1.2 Initializing Bayesian models

The information collected during the SME elicitation was leveraged to initialize the conditional probability tables required to instantiate the Bayesian network model following the methodology laid out by Hassall et al. (2019). The team can make use of this information for inference about the state of the facility. In the example below, the team determines the probability that the facility is operational given the state of its gates, $P(F=O|S_1,S_2,\ldots,S_9)$.

$$\begin{aligned} P(F=O\,|\,1,0,0,0,0,0,0,0,0)_{FLOOD} &\approx \frac{\sum_i w_{i\{1,0,0,0,0,0,0,0,0\}}}{\sum_i w_i} \\ &\approx 0.1845*\left(\frac{2-2}{2-1}\right)+\sum_{i=2}^{5}0.1845*\left(\frac{2-1}{2-1}\right) \\ &+\sum_{i=6}^{7}0.002*\left(\frac{2-1}{2-1}\right)+\sum_{i=8}^{9}0.0369*\left(\frac{2-1}{2-1}\right) \\ &\approx 0.8155 \end{aligned} \quad (1)$$

That is, if only spillway gate 1 is inoperable at the case study 1 facility, there is only an 81.55% chance of that facility being operationally sufficient to handle a 100-year flood event. The next section reviews the development of consequences using the CWMS models.

3.2 Update on consequence development

The team used a full factorial design to explore all combinations of gates functional status under four environmental conditions. A total of 216 gate outage alternatives were defined for the Jennings Randolph Dam, which represent all possible combinations of the two water quality, two flood, and five tainter gates located in the dam under each condition (10-, 25-, 50-, and 100-year flood events). The team ran all alternatives through the North Branch Potomac HEC-WAT model to determine downstream flood damages ($) and life loss associated with each gate outage combination.

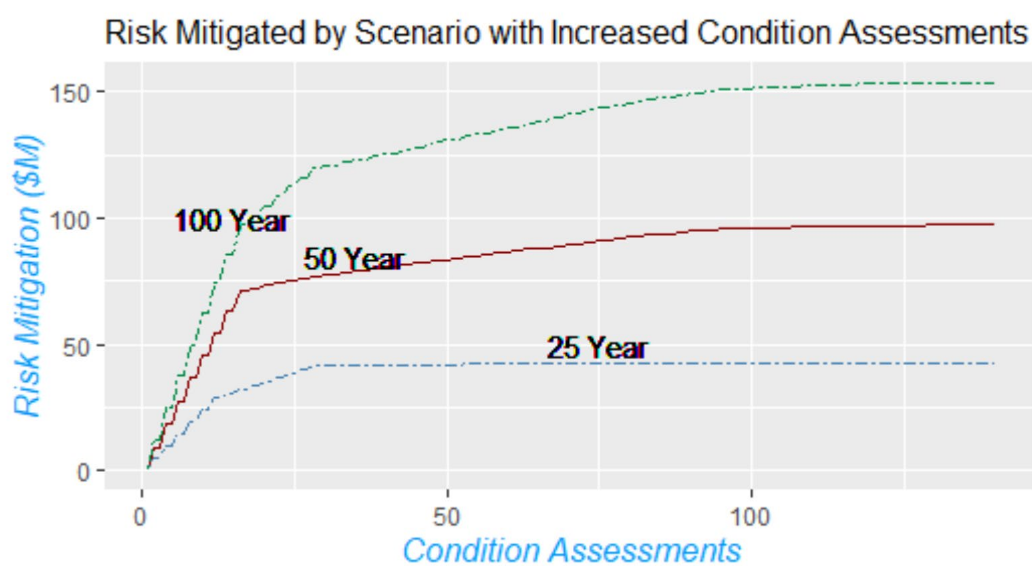
The team previously reported on results making use of consequences from the 100-year case, but subsequently consequences became available for the 10-, 25-, and 50-year cases. The team did not generate consequences for the 10-year case, so it was excluded from the model building effort, but the team did develop models for a case that included all data as well as models for each of the 25-, 50-, and 100-year cases. As previously reported, models with good qualities that rely exclusively on the status of the gates can be developed for the 100-year case. At the 25- and 50-year event, the state of gates accounts for much less of the variance in the response. In future work, the starting levels of the reservoirs should be considered to better estimate the consequences and the importance of the gate systems during these more frequent events. Under each condition, the relative importance of modeling coefficients remained consistent.

3.3 Updated prioritization results

The team previously reported on the use of consequences generated from a 100-year event. The consequence generation team also provided consequences for 10-, 25-, and 50-year events, which are presented in Figure 10.

Results indicate differing component selection and risk mitigation under differing consequence generating scenarios. This highlights the importance of identifying planning scenarios. Note that for the 10-year event, no consequences were generated under the conditions explored.

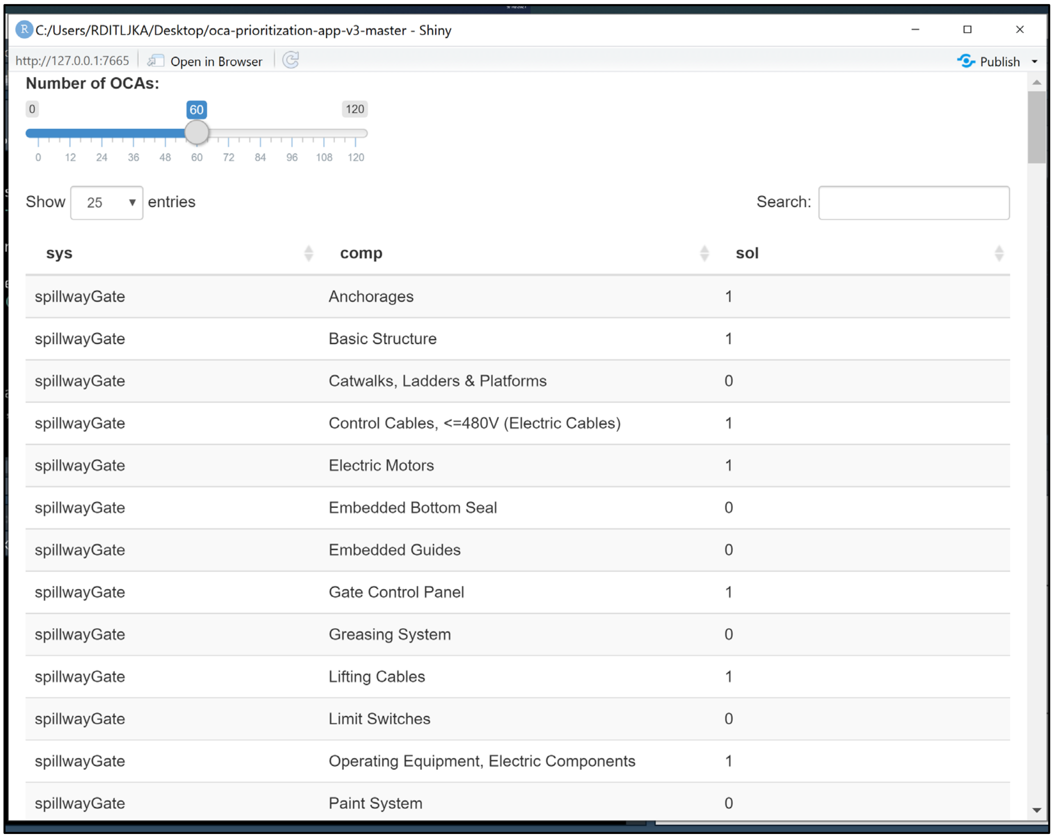
Figure 10. Risk mitigated by scenario with increased condition assessments. Consequences for flood conditions at the 25-, 50-, and 100-year events.



3.4 Proof of concept prioritization tool

As part of this effort, a proof-of-concept prioritization tool was developed in RShiny (Figure 11). The tool allows a user to adjust the number of OCAs to be conducted and obtain a recommended set of components to conduct assessments on independent of condition. Selected components are designated with a “1” in the “sol” column on the right in Figure 11. These components would be considered the risk-driving components associated with the facility under the specified scenario conditions.

Figure 11. Proof of concept prioritization tool.



The tool also allows a user to input the condition of the components per the OCA scale and obtain a recommended set of components to maximize risk mitigation given the current condition of components.

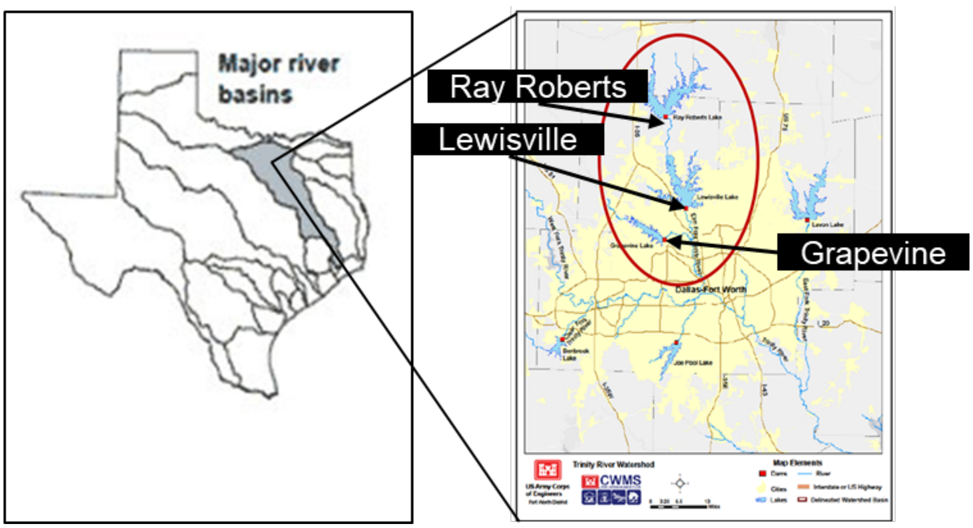
4 Case Study: Trinity River

This section provides an overview of the second case study selected for this work, the Elm Fork of the Trinity River sub-basin.

4.1 Overview

The Elm Fork of the Trinity River sub-basin provides a second case study in the application of these methods. Figure 12 presents the three USACE-owned facilities located on the Elm Fork of the Trinity River: Ray Roberts Lake, Lewisville Lake, and Grapevine Lake.

Figure 12. Trinity River Sub-basin. Ray Roberts, Lewisville, and Grapevine Lakes sit in the Elm Fork of the Trinity River.



Modeling three facilities for the second case study required more coordination for data collection from the Fort Worth District and facility SMEs and increased the complexity of generating consequence-of-failure data. The methodology and supporting tools were refined to address this additional complexity in a scalable manner.

4.2 Data exploration

Each facility is represented in the OCA database with a hierarchy that decomposes the facility to its constituent parts with the lowest level, the component being the target for condition assessment. The unique major systems that compose the Grapevine, Ray Roberts, and Lewisville Lakes are shown in Table 1. In each case, the Service Discharge Gates and Water Quality Gates are the only systems under study for this project because they are most critical to FRM. The Grapevine facility is composed of 318 components, the Ray Roberts facility is composed of 292 components, and the Lewisville facility is composed of 431 components. These major systems decompose to subsystems and components. In contrast to the first case study, the OCA gates and CWMS models for this second case study were aligned; therefore, the team did not have to consult the FEM database for additional data.

Table 1. Systems associated with Grapevine, Ray Roberts, and Lewisville Lakes in OCA hierarchy.

Grapevine Facility OCA Systems	Ray Roberts Facility OCA Systems	Lewisville Facility OCA Systems
Bridges	Bridges	Bridges
Buildings	Dam Sections	Buildings
Dam Sections	Discharge Works	Dam Sections
Discharge Works	Electrical Power Systems	Discharge Works
Electrical Power Systems	Emergency Closure Systems	Electrical Power Systems
Intake Works	Intake Works	Intake Works
Maintenance (only) Closure Systems	Maintenance (only) Closure Systems	Miscellaneous Site Features
Miscellaneous Site Features	Miscellaneous Site Features	Miscellaneous Use Service Cranes and Hoists
Miscellaneous Use Service Cranes and Hoists	Miscellaneous Use Service Cranes and Hoists	Monitoring Systems
Project Lighting	Monitoring Systems	Project Lighting
Project Safety	Project Lighting	Project Safety
Project Utilities	Project Safety	Project Utilities
Service Discharge Gates	Service Discharge Gates	Service Discharge Gates
Water Quality Gates and Valves	Water Quality Gates and Valves	Water Quality Gates and Valves

As in Case Study 1, SME input was required to understand the relative contributions and influence of each component, system, or subsystem to the functioning of the facility.

4.3 Subject matter expert elicitation

4.3.1 Conduct

The team conducted SME elicitation for the Elm Fork of the Trinity River basin per the methodology in Section 2.3. Appendix F provides the tools used to perform the SME elicitation. The USACE Fort Worth District identified 11 SMEs for this case study based on their knowledge and experience with the operation of the three facilities as well as FRM operations. Eight of the SMEs serve at the district level while the other three SMEs serve as staff at the actual facilities involved in their day-to-day operations (see Appendix H for names). The team conducted four 1-hour group sessions. The first session oriented the group to the online data collection tool and provided a scenario overview of normal and flood scenarios (Figure 7). The SMEs were provided the link to complete their individual assessments. Three consensus-building sessions, one per facility, followed. Finally, each SME was provided a link to an online assessment to gauge their level of agreement with the consensus values using the online tool (Figure 9).

4.3.2 Results

The Delphi methodology employed in this effort seeks to generate consensus across the group of experts through individual elicitations followed by a group discussion of differences as discussed in the methodology.

Figure 13. Case study 2 individual results for relative influence of systems to facility under normal conditions (Grapevine Lake).

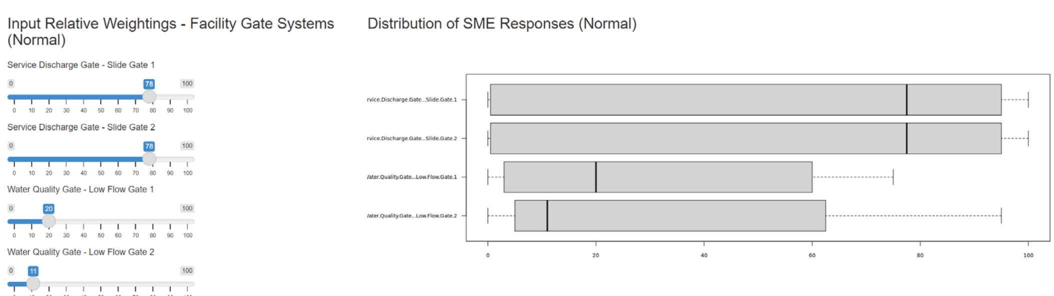


Figure 13 shows example results from the first round of elicitations. During the group sessions, the facilitator displayed the distribution of ratings from the individual assessments and facilitated a discussion around the differences. These discussions led to a consensus on the relative influence values and uncovered why differences in expert opinion existed at the outset.

There were differences between the relative influences assigned for similar systems in different facilities. Across all facilities, the Low Flow Gates were all assigned a relative influence of 1 (least influential) for Normal Operations. The SMEs assigned a much larger relative influence for the Service Discharge Gates than the Low Flow Gates at the Grapevine Lake, while at Lewisville Lake this relationship was much different. Through the discussion, it became apparent that this difference was due to the purpose and utilization of the facility for water supply versus FRM. This demonstrates the importance of the SME input as each individual facility is unique in its main purpose and utilization of the systems, which significantly impacts the relative influence of those systems on the operation of the facility.

The process produced excellent consensus. Eight of the 11 SMEs provided feedback on their level of agreement with the consensus values for relative influence of the components and systems using an online data collection tool. Each respondent was also afforded the opportunity to provide a different value for the relative influence of the systems or components under each scenario.

Additionally, the respondents were provided the opportunity to provide free text responses. Approximately one-third (9 of 27) of the responses were confirmation of agreement with the consensus. The other two-thirds of the free text responses provided some level of explanation for a differing value of relative influence.

4.4 Initializing Bayesian networks

The team generalized the methodology of Hassal et al. to allow for the initialization of a Bayesian network capable of making use of the OCA rating scales to describe the state of components. Instead of two component states (operational and insufficiently operational), there are now five component states (1, 2, 3, 4, and 5, which represent OCA ratings of A, B, C, D, and F, respectively).

$$
\begin{aligned}
P(S=O\,|\,5,4,3,4,2)_{FLOOD} &\approx \frac{\sum_i w_{i\{5,4,3,4,2\}}}{\sum_i w_i} \\
&\approx 0.575\times\left(\frac{5-5}{5-1}\right)+0.025\times\left(\frac{5-4}{5-1}\right) \\
&+0.075\times\left(\frac{5-3}{5-1}\right)+0.075\times\left(\frac{5-4}{5-1}\right) \\
&+0.25\times\left(\frac{5-2}{5-1}\right) \\
&\approx 0.575(0)+0.025(0.25)+0.075(0.5+0.25)+0.25(0.75) \\
&\approx 0.25
\end{aligned} \tag{2}
$$

Next, assigning the system a rating of A, B, C, D, or F, it is possible to assess the probability the facility is operational. In this case, the team leverages a five-point scale to assign a letter grade rating to the assessed system (see Table 2).

Table 2. Table for assigning system rating to probability of failure.

System Rating	Range (Probability of Failure)
A = 1	[1, 0.9)
B = 2	[0.9, 0.8)
C = 3	[0.8, 0.7)
D = 4	[0.7, 0.6)
F = 5	[0.6, 0]

The result below leverages the example from case study 1 to estimate the probability of facility operability given a single gate system operating in a failed state (i.e., all gates except for one are perfectly performing their intended function).

$$
\begin{aligned}
P(F=O\,|\,F,A,A,A,A,A,A,A,A)_{FLOOD} &\approx \frac{\sum_i w_i P_{i\{F,A,A,A,A,A,A,A,A\}}}{\sum_i w_i} \\
&\approx 0.1845\times\left(\frac{5-5}{5-1}\right)+\sum_{i=2}^{5}0.1845\times\left(\frac{5-1}{5-1}\right) \\
&+\sum_{i=6}^{7}0.002\times\left(\frac{5-1}{5-1}\right)+\sum_{i=8}^{9}0.0369\times\left(\frac{5-1}{5-1}\right) \\
&\approx 0.8155
\end{aligned} \tag{3}
$$

That is, if only spillway gate system 1 is inoperable (in a failed state) at the facility, there is an 81.55% chance of that facility being operationally sufficient to handle a flood event.

4.5 Developing consequences

4.5.1 Scenario configuration

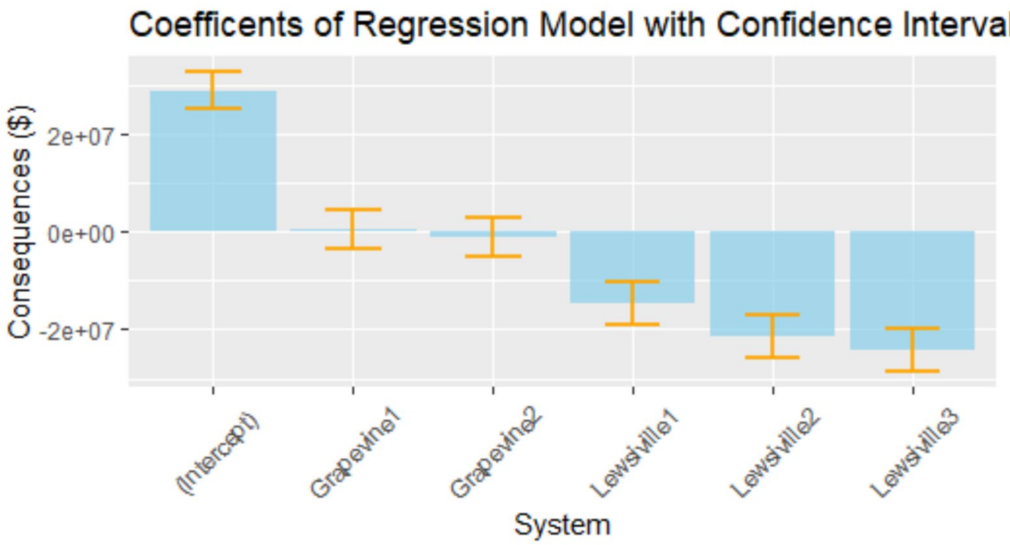
The modeling team represented the three facilities examined in the hydrological model down to the gate level. Following consultation with the hydrological engineering team at the district, the team chose to initially examine only two facilities, Grapevine and Lewisville, since the district experts did not believe that Ray Roberts significantly impacted the watershed. The team examined multiple event levels (2-, 5-, 10-, 25-, 50-, 100-, 200-, and 500-year events) and two storm locations. The state of the service gates were systematically explored in this initial proof of concept for the two facilities modeled, resulting in 352 unique cases.

A second set of computational experiments utilizing all gates and all three facilities was completed as well, resulting in 648 unique cases evaluated under a 100-year event and where gate failures were in the completely open or completely closed state for a total of 1,296 unique experiments.

4.5.2 Analysis of results, experiment 1

The output of the initial proof-of-concept experimentation was used to develop a statistical model to estimate the expected consequences of gates at the two facilities modeled. As described in the methodology section and consistent with case study 1, multiple regression was used to fit a linear model, where the numbers of operational service gates at each facility were treated as the independent variables and the expected consequences generated by each case were treated as the dependent variables (see Figure 14). The expected consequences are calculated as an expected value, a weighted sum given the likelihood of the event, and used as the response. This results in a model that accounts for 89% of the variance in the dependent variable while meeting appropriate assumptions.

Figure 14. Coefficients of the regression model with corresponding confidence intervals.



This provides an estimate of the reduction in the expected consequences achieved based on the number of service gates operational at each of the two facilities.

As the complexity of the watershed systems increase, efficient means of exploring the contribution of gates must be developed. One approach might be to make use of space-filling designs, such as nearly orthogonal Latin hypercubes, which allow the exploration of multiple independent variables with a relatively low number of experimental cases. This family of designs could be particularly well suited for developing an understanding of the contribution of each gate and the interaction of gates within a watershed. This would also allow the treatment of each gate as a continuous variable, where the value indicates the percentage of gates opening when failure occurred.

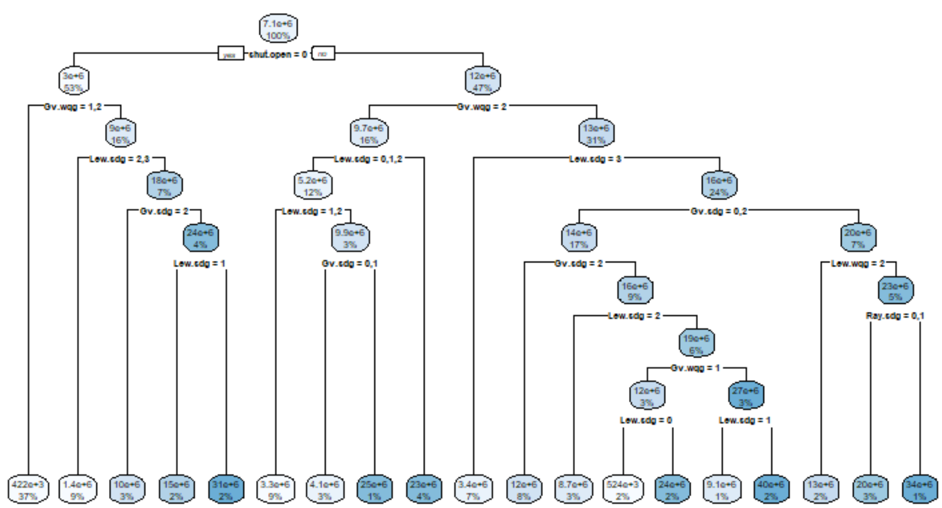
4.5.3 Analysis of results, experiment 2

The output of the second set of computational experiments was used to develop a statistical model to estimate the expected consequences of gates at the three facilities modeled. A variety of statistical modeling techniques were employed to develop estimates of the consequences associated with each gate system within the watershed. The damages generated by the consequence models possess a relatively long tail and interactions occur between the gates, requiring statistical modeling techniques that can capture these relationships. In order to capture the complex interactions within the watershed and their relationship to the overall damages, a random forest model was developed. Measures of variable importance indicate that across all runs and in the presences of the other gate systems, the status of the Lewisville Service Discharge Gates was the most important factor in predicting the cumulative damages in the watershed, followed by the Grapevine Water Quality Gates and the Grapevine Service Discharge Gates.

The estimated damages from this random forest model when all gates were operational with the exception of the targeted gate system were leveraged in the same manner as the coefficients in our simple linear regression model from the previous case study.

While random forests generated the best predictive results, a sample regression tree is shown in Figure 15. This method produced good results and lends itself to relatively easy interpretation of the results and visualization of the interactions between gate systems.

Figure 15. Sample regression tree of Trinity River facilities.



While the output from single cases could be used, it will be important for future work to develop consequence measures that capture the synergy between gates, making the development of a statistical model of the damages as a function of the system important. Further analysis of these experimental results will be conducted in follow-on work. The next section discusses the development of risk and the prioritization of components across the watershed.

4.6 Prioritizing components by risk

Advancing the methodology employed in the Jennings-Randolph Lake case study, the team now incorporates OCA ratings with the likelihood of failure derived from SME input and the estimates of consequences developed from the output of simulation models.

4.6.1 Developing risk scores

The team extended the methodology for risk score calculation by incorporating OCA ratings. The OCA ratings are incorporated as a scaling constant on the risk scores as previously calculated. That is, the following equations define the risk score of a component given an OCA rating when leveraging relative weights in conjunction with consequences at the facility and systems level as well as when using regression model coefficients and consequences at the systems level.

$$\begin{aligned}&[\text{OCA rating scalar}] \times [\text{normalized relative influence of system}]\\&\times [\text{normalized relative influence of system component}]\\&\times [\text{estimated risk due to failure of facility}]\\&= \text{Risk Score of Component Given OCA Rating}\end{aligned} \tag{4}$$

$$\begin{aligned}&[\text{OCA rating sclar}]\\&\times [\text{normalized relative influence of system component}]\\&\times [\text{estimated risk due to failure of facility}]\\&= \text{Risk Score of Component Given OCA Rating}\end{aligned} \tag{5}$$

$$\begin{aligned}&[\text{OCA rating scalar}] \times [\text{Regression coefficient associated with system}]\\&\times [\text{estimated risk due to failure of system}]\\&= \text{Risk Score of Component Given OCA Rating}\end{aligned} \tag{6}$$

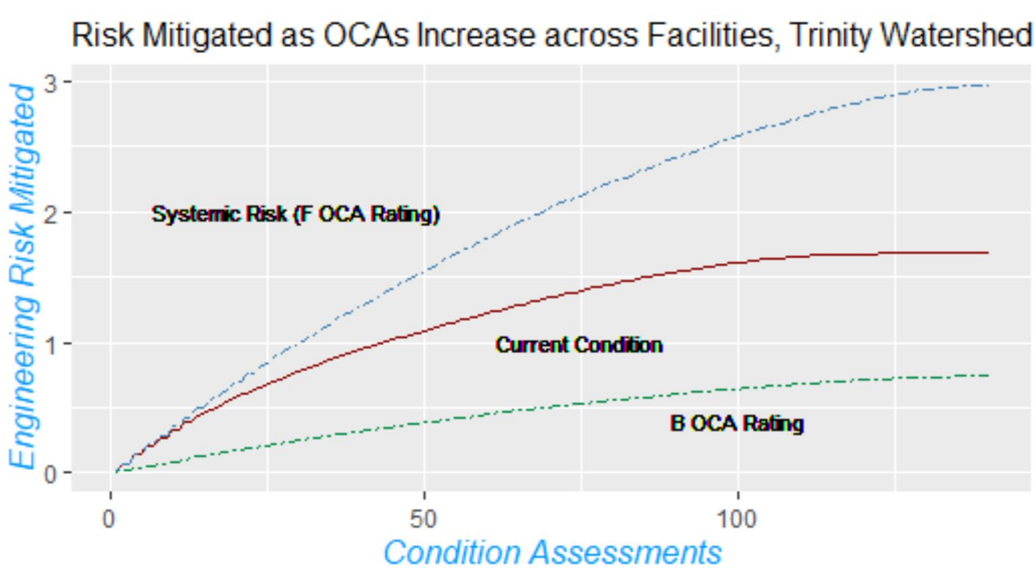
The OCA rating scalar value is determined by a probability function that divides the event space (i.e., [0, 1]) into five equal intervals (one interval for OCA ratings A, B, C, D, and F, respectively). That is, consider all states of the component (i.e., OCA rating conditions) on an equally spaced linear scale with values between 0 and 1, inclusively (Equation 7). Note that should a different probability function or functions be provided, they could be easily incorporated into this framework.

$$\text{OCA rating scalar} = \begin{cases} 0 & \text{OCA rating} = \text{A} \\ 0.25 & \text{OCA rating} = \text{B} \\ 0.5 & \text{OCA rating} = \text{C} \\ 0.75 & \text{OCA rating} = \text{D} \\ 1 & \text{OCA rating} = \text{E} \end{cases} \quad (7)$$

4.6.2 Prioritization

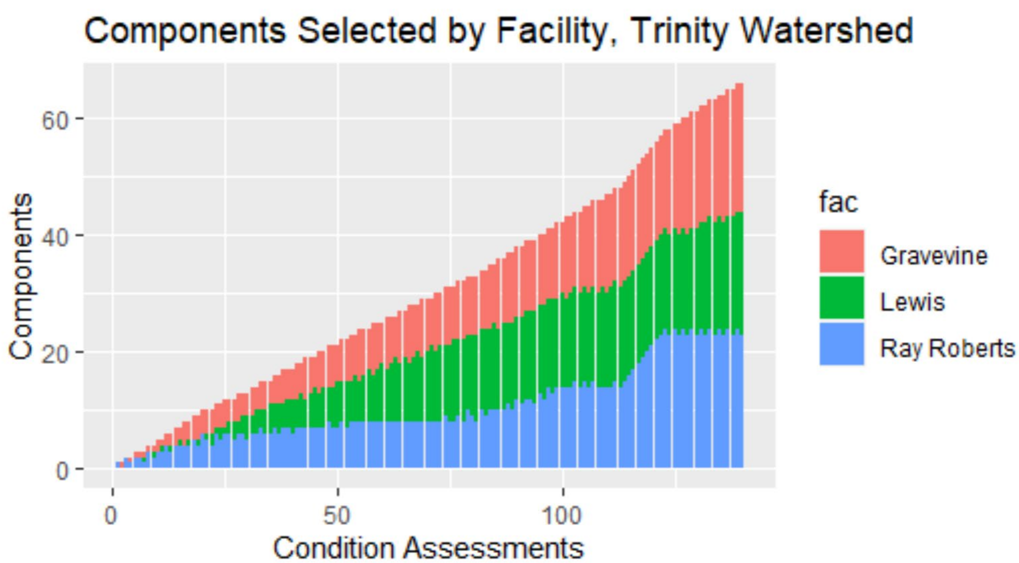
The optimization model formulated in Section 2.6, implemented using the lpsolve package within R statistical programming language, yields the optimal set of components to conduct OCAs on to maximize risk mitigation across the watershed. Figure 16 shows the result of the optimization model that makes use of the engineering risk, where the consequence for each facility is the probabilty that the facility will be operational. The worst case, where each component is assumed to be an F on the OCA rating scale, is shown in the upper line on the graph, a randomly assigned set of OCA values is shown by the red line, and an average case line is shown where each component is assumed to have a B rating.

Figure 16. Engineering Risk (not including consequence) mitigated as OCAs increase across facilities in the Trinity Watershed.



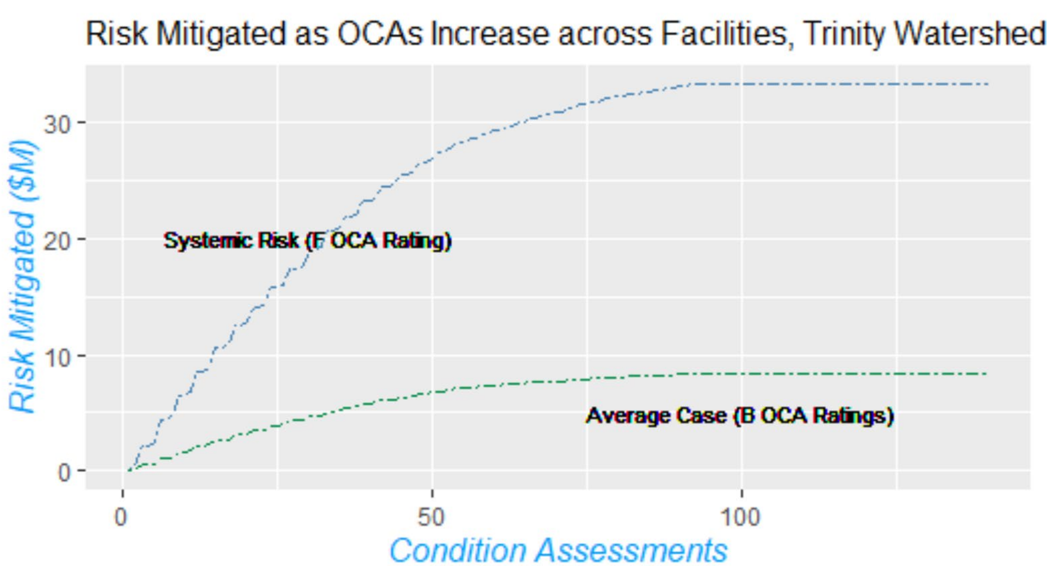
Examining the number of components selected at each facility can provide a sense of the relative importance of each facility to the watershed, as reflected in the SME input relative influence. See Figure 17.

Figure 17. Components selected by facility in the Trinity Watershed.



Incorporating the consequences from the first set of results of the simulation experimentation, Figure 18 shows the risk mitigated as the number of condition assessments increases for the case where every component is assumed to be an F and the average case, where all components are rated as a B.

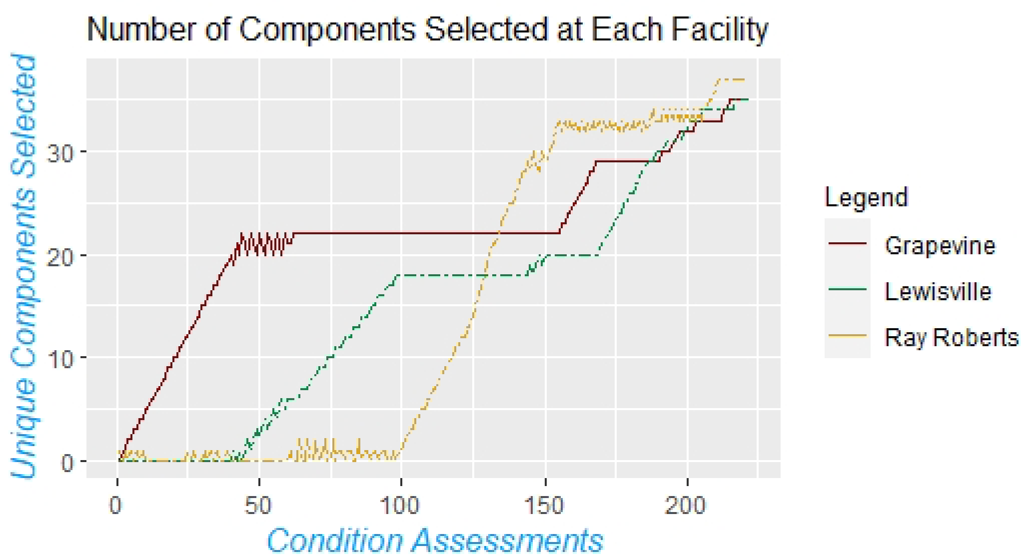
Figure 18. Operational risk (including consequences) mitigated as OCAs increase across facilities in the Trinity Watershed.



The results of the prioritization model after incorporating the consequences from the complete set of simulation runs, 1,296 computational experiments, provide similar results. The major difference is the inclusion of the Ray Roberts facility in this larger data set (see Figure 19). In the initial simulation results, these systems and the facility were omitted from the analysis based on SME input. They were assigned a consequence value of $1 in order to retain them in the model. In this larger set of computational experiments, they were represented within the models and estimates of the consequences of their degradation on the watershed generated.

In this case, the results illustrate the importance of modeling the impact of facilities and their systems on the watershed in the presence of other facilities. The system-of-systems interactions can create non-obvious impacts on consequences that might otherwise go unnoticed.

Figure 19. Unique components selected by facility with increasing number of OCAs.



In this initial analysis, the research team made use of estimated consequences experienced when each of the gate systems is the only system in the watershed that is non-operational.

5 Summary and Way Ahead

Modeling the performance of complex facilities with multiple systems, each with many components, requires a flexible and scalable modeling approach that can account for the use of both quantitative and qualitative data. Developing an appropriate conceptual model of a facility and its unique configuration of systems and components requires the input of stakeholders from the districts and facilities under study regardless of modeling approach. Some key outcomes are the following.

5.1 Modeling methodology

This research developed a methodology and supporting tools to identify the probability of degradation of facilities based on the state of their systems and components that leveraged SME input to populate Bayesian networks. These methods provide the ability to update these models with empirical data should it become available.

5.2 Case study 1

The application of the methodology to a single facility within the North Potomac River watershed resulted in the development of several tools to assist in exploring available data from OCA and FEM and to assist in the elicitation of SME input. The team demonstrated the ability to create statistical models of watershed consequences of gate outages from output data generated through the application of a full factorial experimental design to the CWMS models. These consequences combine with probability of degradation values from the Bayesian network to form a risk score for each component of the systems modeled. The team further developed and demonstrated the use of a mixed-integer program to determine the optimal set of components to select for OCAs to maximize risk mitigation in the watershed and packaged it in a simple prioritization tool.

5.3 Case study 2

This case study provided the opportunity to demonstrate this methodology on a more complex sub-basin containing three USACE facilities. The team developed and made use of online SME elicitation tools to facilitate data collection. Due to the increased complexity of the watershed, the consequence generation team enlisted the help of the Hydraulic

Engineering Center. The team is finalizing a prioritization application that stakeholders can access via their browser where they will be able to perform what-if exercises regarding the impact of non-operational gates and components on flood risk, but proof of concept results for a scaled down experimental design are shown.

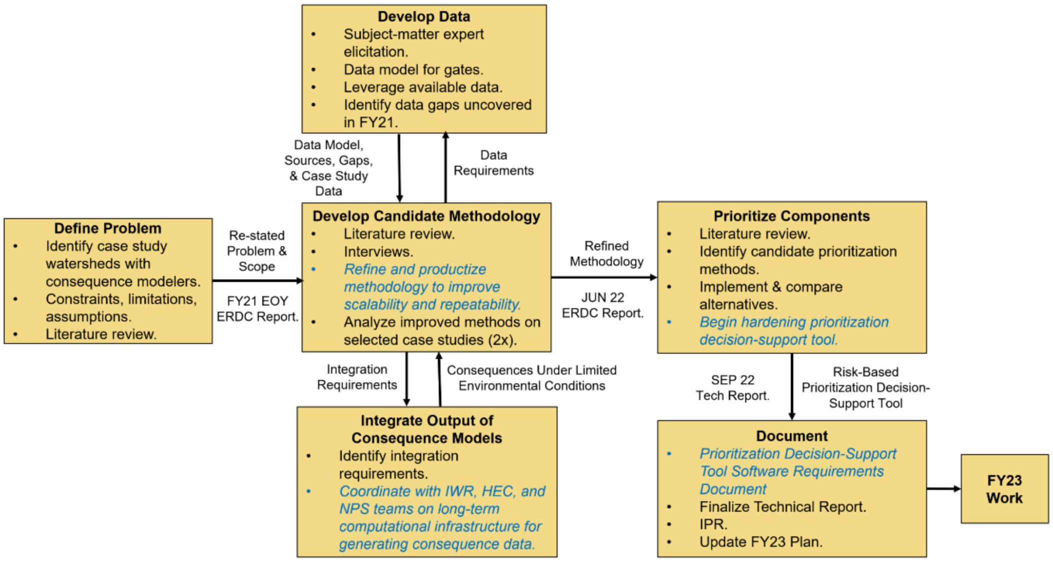
5.4 Way ahead

In FY22, the team has three primary goals:

- Refine the data collection and modeling methodology with a focus on scaling to larger watersheds. This will include considering how to lessen the burden on the SMEs and hardening the current online data collection tools.
- Enhance and evaluate the ability of consequence models to support the modeling and analysis of larger watersheds. This will include collaboration with the Hydraulic Engineering Center in order to establish a long-term computational infrastructure (potentially in an HPC environment) and the Naval Postgraduate School to build efficient designs of experiments.
- Harden the prioritization decision-support tool and refine its requirements to support use at the district level.

These goals are highlighted in Figure 20, which illustrates the project execution approach for Fiscal Year (FY) 2022. In addition to these primary goals, the team also desires to refine the relevant scenario conditions for SME elicitation and refine the methodology to allow for inclusion of appropriate human systems considerations. In FY22, the team will demonstrate these updated methods on larger case studies.

Figure 20. General approach for the execution of the project in FY22.



References

Alt, J. K., W. H. Brown, G. E. Gallarno, and J. P. Richards. 2021. *Risk-Based Prioritization of Operational Condition Assessments: Stakeholder Analysis and Literature Review*. ERDC/ITL SR-21-2.

Brown, W. H., and J. K. Alt. 2021. *Investigating the USACE Operational Condition Assessment Process Current and Future*. ERDC/ITL SR-21-1.

Hassall, K. L., G. Dailey, J. Zawadzka, A. E. Milne, J. A. Harris, R. Corstanje, and A. P. Whitmore. 2019. "Facilitating the Elicitation of Beliefs for Use in Bayesian Belief Modelling." E*nvironmental Modelling and Software*, 122.

HEC IWR USACE. 2017. *HEC-WAT Watershed Analysis Tool User's Manual*. USACE. https://www.hec.usace.army.mil/software/hec-wat/documentation/CPD-88.pdf.

Oehlert, G. W. 2000. *A First Course in Design and Analysis of Experiments*. New York: W. H. Freeman.

Rencher, A. C., and B. G. Schaalje. 2008. *Linear Models in Statistics, 2nd ed*. New York: Wiley-Interscience.

Richards, J., J. Bruhl, J. Richards, and S. Long. 2021. "Improving Mission Assurance Assessments for Resilience of Military Installations." *Natural Hazards Review* 22 (4): 04021036. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000483.

USACE. 2019. *U.S. Army Corps of Engineers Policy for Operational Condition Assessments for USACE Assets*. USACE EC 11-2-218. https://www.publications.usace.army.mil/Portals/76/Users/182/86/2486/EC-11-2-218.pdf?ver=2019-09-04-162858-440.

Appendix A: Terms of Reference

- Facility—In the OCA hierarchy, "projects" are the highest level. For clarity, what is often called "project" in the OCA infrastructure hierarchy is called "facility" in this document.
- System—In the OCA hierarchy, "systems" are the next highest level. Two examples of FRM OCA systems are a "building" or a "spillway gate."
- Subsystem—In the OCA hierarchy, "subsystems" give move specificity to the system level. For example, under the system "building," subsystems could be "maintenance building" or "administrative building." For the system "spillway gate," subsystems could include "tainter gate 1" and "tainter gate 2."
- Component—In the OCA hierarchy, "components" are the lowest level and the level at which OCA ratings are given.
- FRM system—The network of FRM facilities associated with a particular watershed.
- Facility Failure—Due to rarity of facilities being non-operational, facility failure is defined as degraded operations (i.e., uncontrolled release of water from the FRM facility, which may or may not be catastrophic).
- System Failure—Similar to facility failure, system failure is defined as reduced capability to meet designed operational capacity.
- Component Failure—A component is considered to have failed when it has received an OCA score of B– or lower. A rating of B indicates that the component is performing its intended function and that any deficiencies are a result of normal wear. A rating of B– indicates that the component is beginning to show initial signs of the next lower level, and B– is the highest rating at which justification comments are required (USACE 2019).

Appendix B: OCA Rating Scales

Table B-1. OCA rating scale and definitions (USACE 2019).

Rating		Descriptor	Definition	Notes
A	9	Excellent	Component was recently put into service and shows no signs of wear.	Ratings DO NOT require comments.
A–	8	Excellent		
B	7	Good	Component performs its intended function. Any deficiencies are normal wear and not actively progressing at a greater rate than normal wear.	
B–	6	Good		
C	5	Fair	Component has a deficiency that is beginning to affect its performance, operational procedures, and/or maintenance requirements. AND/OR Component is beginning to show a greater rate of change in degradation that has the potential to cause a functional failure.	
C–	4	Fair		Ratings DO require justification comments and will be verified during the assessment.
D	3	Poor	Component has a deficiency that increasingly or moderately affects its performance, operational procedure, and/or maintenance requirements. AND/OR Component has a clear mode of failure due to an advanced state of degradation likely with an accelerating trend.	
D–	2	Poor		
F	1	Failing	Component has a deficiency that substantially affects its performance, operational procedures, and/or maintenance requirements and is approaching complete failure. AND/OR Component is clearly in the final stage of degradation trending toward complete failure (imminent failure).	
CF	0	Completely Failed	Component is completely failed and does not perform its intended function. AND/OR Component is red-tagged.	
Minus OCA Rating Definition				
The minus OCA ratings (A–, B–, C–, and D–) are for components that meet the definition of a particular OCA rating but may be showing initial signs of the next lower OCA rating.				

Appendix C: CPT Initialization Methodology

The methodology that is proposed by Hassall et al. (2019) uses the SME elicited relative influences and direction of the relationship between the parent and child nodes to initialize conditional probability tables within the Bayesian network. The relationship between the parent and child node can be characterized as either positive, negative, or “other.” If the parent node changes to a higher state, this causes the child node to enter into a higher state. Similarly, if the parent node changes to a lower state, this causes the child node to enter into a lower state. The “other” relationship occurs when neither a positive nor a negative relationship exists between the states of the parent and child nodes. In this instance, the relationship between the parent and child node states is defined within a relative framework. For the purposes of this case study, two states are considered for all components and systems—sufficiently operating and insufficiently (degraded) operating. Thus, when a parent node is operating sufficiently it will have a positive relationship with the child node, indicating that it has a greater chance of also being in a sufficient operating condition. Conversely, if a parent node is insufficiently operating it will have a negative relationship with the child node, indicating a greater change of the child node being in insufficient operating condition. Mathematically, Hassall et al. define P_{ij} as the score to the jth state of the ith parent given by

$$P_{ij} = \begin{cases} \dfrac{j-1}{n_i - 1} & \text{if Parent } i \text{ has a positive relationship with the child node} \\ \dfrac{n_i - j}{n_i - 1} & \text{if Parent } i \text{ has a negative relationship with the child node} \\ \dfrac{ord[j]-1}{n_i - 1} & \text{if Parent } i \text{ has an other relationship with the child node} \end{cases}$$

where n_i is the number of states of parent i and $ord[j]$ denotes the ordered index of state j. Next, the relative influences are normalized and the normalized influence is used in conjunction with the aforementioned score to calculate an initial probability. That is, the normalized influence of parent i, w_i, is calculated using the m elicited relative weights, rw_i, by the equation

$$w_i = \frac{rw_i}{\sum_{j=1}^{m} rw_j}$$

Then the initial probability for the *k*th combination of parent states is given by

$$\text{Initial Prob}_{\{k\}} = \frac{\sum_i w_i P_{i\{k\}}}{\sum_i w_i}$$

where $\{k\}$ is the kth combination of parent states, with $P_{i\{k\}}$ denoting the associated score of parent i for combination k.

Appendix D: Risk Determination Methodology

In order to determine the amount of risk realized given the current condition of the system, this research can make use of the information stored in the Bayesian network. This will provide a more nuanced estimate of the impact of a set of components' current conditions, as recorded using the A–F rating scale of the OCA process, on the risk carried by the facility and the system. The team can first determine the probability that a system, S_j, is in a degraded condition, D, given the conditions of its components, $P(S_j = Degraded|C_1 \dots C_n)$—this is pulled directly from the conditional probability table for the system. The research can combine this with the facility consequences, Con_f, attributable to the system, I_j, to provide the current system risk, R_j.

$$R_j = Con_f I_j P(S_j = D \mid C_1 \dots C_n)$$

The team assumes, for now, that the OCA process provides the state of each component with no uncertainty, but that assumption could be removed in future iterations. If the team wants to understand the current contribution of each component's state to the current system risk, then it could make use of the conditional probability table to provide a value for an updated probability statement and repeat the calculation above. This could be done systematically to understand the risk associated with each component and each OCA rating and store this information for future use.

In order to update the facility risk profile based on the current state of the systems, the team could make use of the probability that the system is degraded based on the condition of its component, $P(S_j = D|C_1 \dots C_n)$. Since the states of systems are discrete, one approach would be to employ a threshold, $t, P\left(S_j = D\middle|C_1 \dots C_n\right) > t$, to determine when the system is in a degraded state. This approach would then make direct use of the conditional probability tables to determine the probability that the facility was in a degraded state based on the condition of its systems, $P\left(F_f = D\middle|S_1 \dots S_j\right)$. Using this information, the overall risk for the facility, R_f, could be updated, $Con_f P\left(F_f = D\middle|S_1 \dots S_j\right)$.

Another approach might be to make use of the updated probability of a system being degraded based on the state of its components directly—rather than as a simple lookup.

Recall that $P(F|S_1 \dots S_j) = \frac{P(F, S_1, \dots S_j)}{P(S)}$

And that $P(F, S_1, \dots S_j) = P(F|S_1, \dots S_j)P(S_1) \dots P(S_n)$

The team can pull the $P(F|S_1 \dots S_j)$ from the existing conditional probability table and make use of the new $P(S_1) \dots P(S_n)$ to determine a new value for the numerator and make use of the updated values for *P(S)* in the denominator. With this information, the team can update the probability that the facility is degraded given the state of the systems and combine with consequences as previously discussed.

$$R_f = Con_f P(F_f = D | S_1 \dots S_j)$$

Alternatively, the team might make use of conditional probabilities to directly calculate the probability that a facility is in a degraded state.

$$P(F = D) = P(F = D | S_1 = D)P(S_1 = D) + \dots P(F = D | S_j = D)P(S_j = D)$$

Here the team makes use of the conditional probabilities from the facility CPT and the updated values for the probability of a system being in a failed state and combine with the consequences as before.

Appendix E: Single Facility Case

In this case, the team formulates the model to maximize the risk mitigated by the selection of a limited number of condition assessments, with the following sets and indices defined.

Index

- i Component, *1…n*
- j System, *1…m*

Data

- $Risk_{i,j}$ Risk of component i in system j
- *OCABudget* The total number of OCAs available
- $NumOCA_{i,j}$ The number of OCAs required to complete an OCA on all like type components

Variables

$X_{i,j}$ Binary decision variable for each component i in system j

Formulation

$$\max \sum_{i,j} X_{i,j}\, Risk_{i,j}$$

Constraints

$$\sum_{i,j} X_{i,j} NumOCA_{i,j} \leq OCABudget$$

This model would provide the set of components at a single facility that provide the maximum risk reduction within the watershed.

Appendix F: Subject Matter Elicitation Materials

Table F-1. List of respondents to the subject matter expert elicitation.

Respondent	Role	Location
William (Kent) Dunlap	Operations Project Manager	District
Mark Sissom	Operations Division	District
Joshua Pickering	Geotechnical Engineer	District
James (Jim) McClain	Water Management	District
Terry Bachim	Chief Maintenance Section	District
Marie Loftin	Asset Management Program Manager	District
Christopher Bryan	Asset & Maintenance Manager	District
Todd Stowe	Flood Risk Management	District
Nicholas Wilson	Lead Natural Resource Manager	Facility (Lewisville & Ray Roberts)
Robert Jordan	Lake Manager	Facility (Lewisville & Ray Roberts)
John Mathney	Lake Manager	Facility (Grapevine)

OCA data elicitation instructions

We thank you so much for your time in assisting us with this research project and appreciate the opportunity to receive your expert input on the relative influence of systems on the facility and components on the systems. The input will be extremely helpful in our understanding of the USACE Elm Fork Lakes facilities of the Trinity River Basin.

Setting the stage on the expert elicitation

This will be a two-step process. Step one is collection of individual opinions on the relative influence of specific systems and their components on the operations of the facility. Step two is a group meeting to discuss similarities and differences and come to consensus on those relative influences.

The first step in our structured elicitation is to ask you to assign a numerical value reflecting your assessment of the relative influence of the specified gate systems and components as identified in the OCA hierarchy for each of the facilities (Grapevine Lake, Lewisville Lake, and Ray Roberts

Lake). To align with the Corps Water Management System (CWMS) consequence modeling effort being conducted with the Environmental Lab (EL)/Institute for Water Resources (IWR), we are going to look at each of the facilities at two levels: how specific gates influence the operation of the entire facility and how the individual components identified in the OCA influence each of their associated systems.

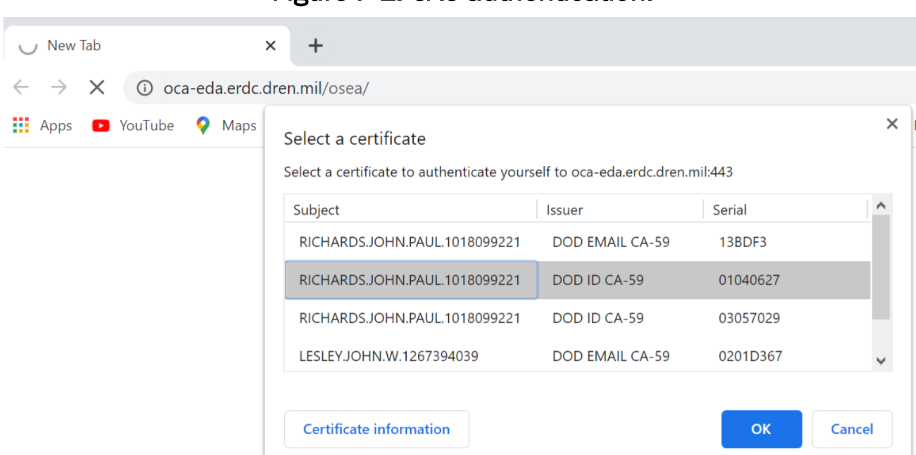
Since the CWMS model takes into account both service discharge and water quality low flow gates, we will ask for the relative influence of these gates on the operation of the facility, both under normal conditions and under high water conditions. Additionally, the CWMS model provides life loss and monetary consequences due to damage to structures from water release at various lake levels. The model does not consider other factors at this time (such as loss of fish, etc.).

For the district-level personnel, we ask that you complete an assessment for each of the three facilities (Grapevine Lake, Lewisville Lake, and Ray Roberts Lake). For operations or maintenance personnel from a specific facility, we ask that you complete only the assessment for your particular facility.

Data collection

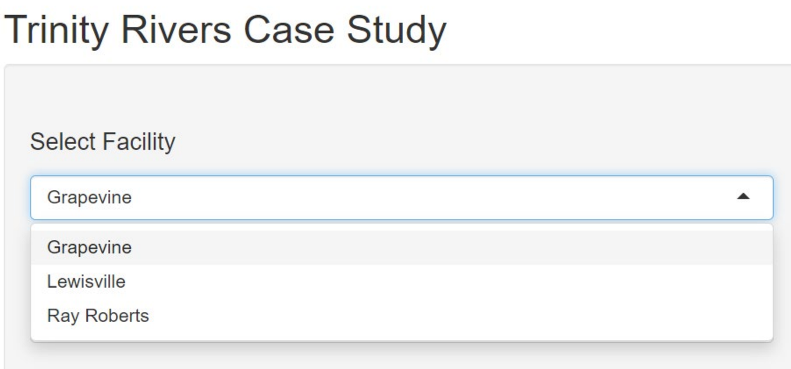
Go to the link https://oca-eda.erdc.dren.mil/osea/ (Chrome is the recommended browser) and log in using your CAC using the non-email certificate when prompted (Figure F-1).

Figure F-1. CAC authentication.



There is a tab for each facility for which we are collecting data (Figure F-2).

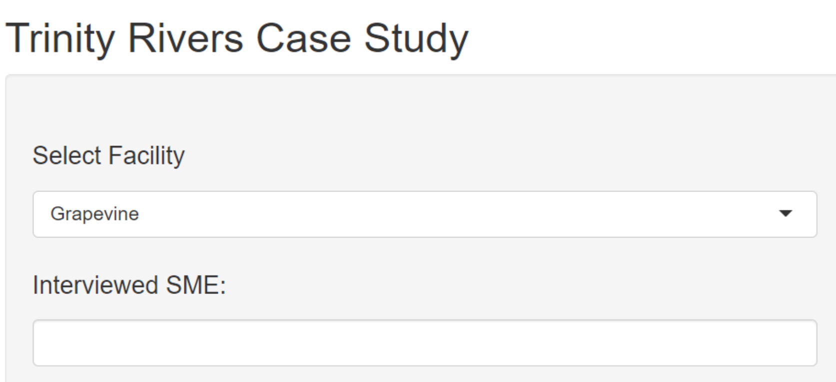
Figure F-2. Select Facility.



For the district-level personnel, we ask that you complete an assessment for each of the three facilities (Grapevine Lake, Lewisville Lake, and Ray Roberts Lake). For operations or maintenance personnel from a specific facility, we ask that you complete only the assessment for your particular facility. Pick the dropdown for the appropriate facility.

After you select the appropriate facility from the dropdown menu, please put your first and last name in the Interviewed SME block (Figure F-3).

Figure F-3. Type name.



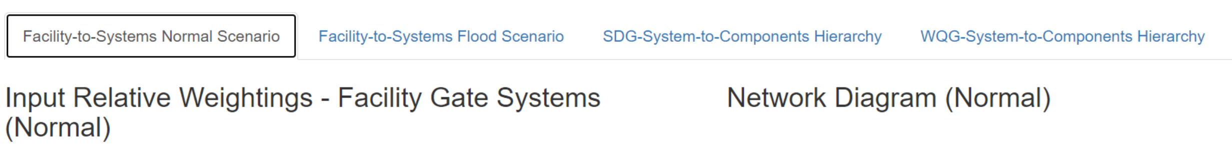
Once you type in your name, the rest of the data collection fields populate (Figure F-4):

Figure F-4. Overall page view.

For the data collection using the online data collection tool, there are four tabs for each facility that we request you fill out.

Tab 1: The relative influence of the gate systems to the facility under normal operating conditions (Figure F-5).

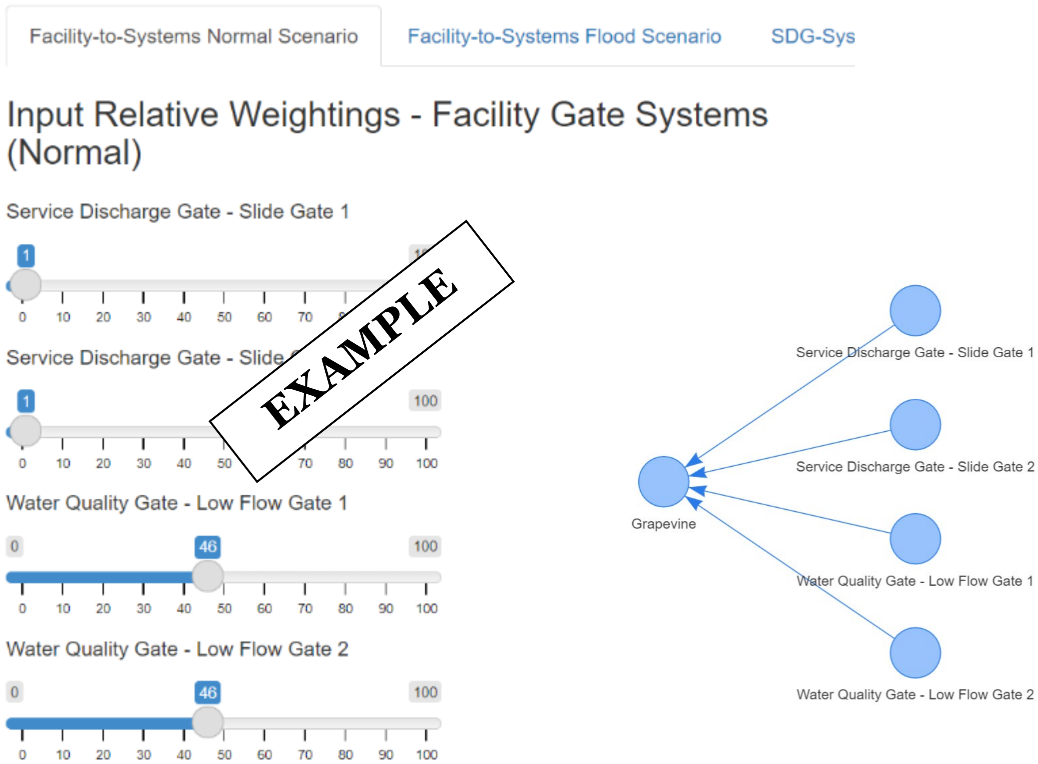
Figure F-5. System relative influence (normal).



We ask you to consider the gate systems-to-facility relationship under **normal operations** where water release is controlled by normal operation of the gates to control water flow, lake levels, water temperature, and associated environmental conditions.

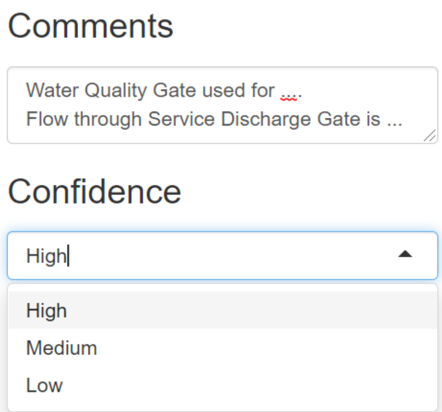
1. To start off, which system has the **least** influence/impact on the operations of the facility under normal conditions? **Set that system at 1** using the slider bar. Verity that the assumption that gates of same type have same influence (Figure F-6).

Figure F-6. Verify that like-type gates have same relative influence (normal).



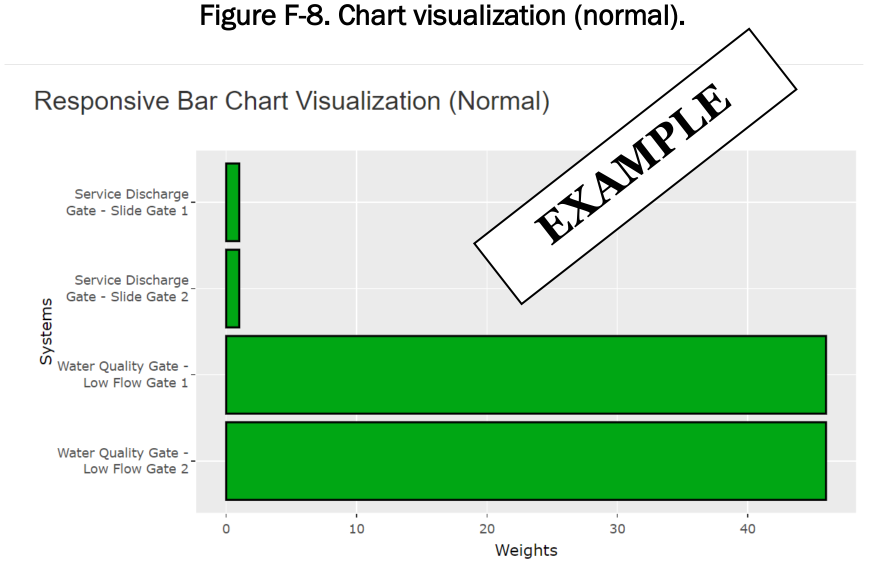
2. Which system has the **greatest** influence/impact on the operations of the facility under normal conditions? Verity that the assumption that gates of same type have same influence.
3. Since the least influential system was set at 1, indicate how much greater you would say the influence of this system is than the least influential (7, 37, 100...times). The scale you utilize is up to your discretion. Input that value using the slider. Verity that the assumption that gates of same type have same influence.
4. **Systems may be assessed the same relative influence**, but for systems with the same influence, confirm that they both are equally important/influential. There is no forced distribution of the relative influence; the values are up to you.
5. You may include any free text comments that might help with describing your assignment of the relative influence for that system in the free text box on the right-hand side of the page.
6. Use the dropdown menu to indicate your level of confidence (high, medium, or low) in your overall assignment of the relative influence for the systems on the facility (Figure F-7).

Figure F-7. Provide comments (normal).



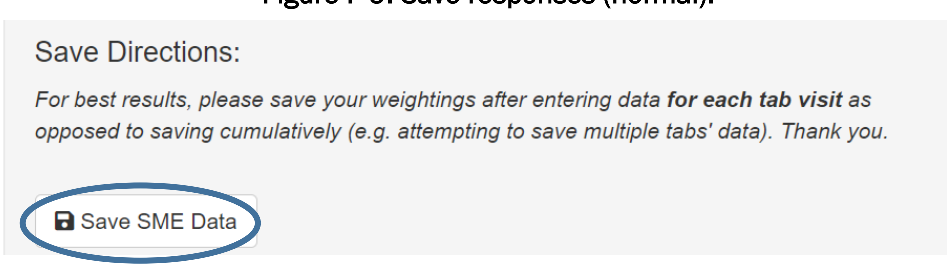
7. Review the bar graph to confirm the relative influence numbers align with their thought process (Figure F-8). Does the relative scale agree with how you visualize the relative influence?

Figure F-8. Chart visualization (normal).



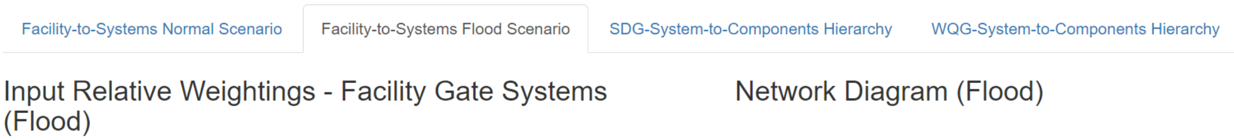
Don't forget to save your work before moving to the next tab (Figure F-9)!

Figure F-9. Save responses (normal).



Tab 2: The relative influence of the gate systems to the facility under flood operating conditions (Figure F-10).

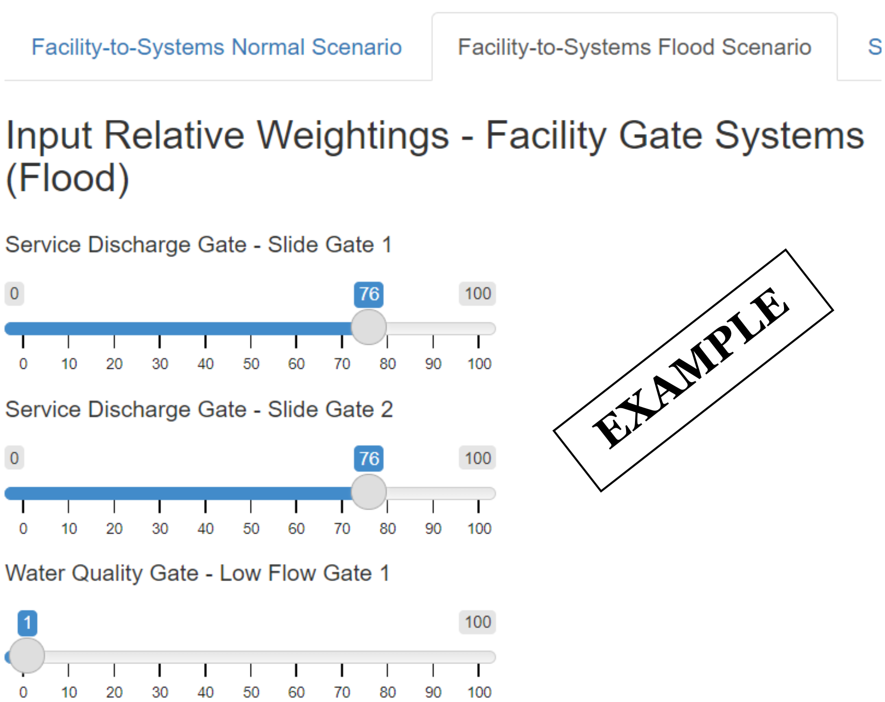
Figure F-10. System relative influence (flood).



Next, we are interested in how you would weigh the relative influence of each of the gate systems on the operational status of the facility under **high water/flood emergency operations**. Utilize the same process for Question 1 for the influence of the systems on the facility under a high water/flood event that necessitates the operation of gates to control the output of water so as to not overtop the dam and input the relative influence values using the sliders.

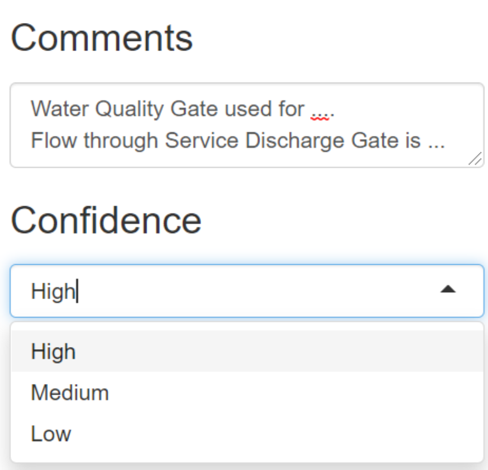
1. To start off, which system has the **least** influence/impact on the operations of the facility under flood conditions? **Set that system at 1** using the slider bar (Figure F-11). Verity that the assumption that gates of same type have same influence.

Figure F-11. Verify that like-type gates have same relative influence (flood).



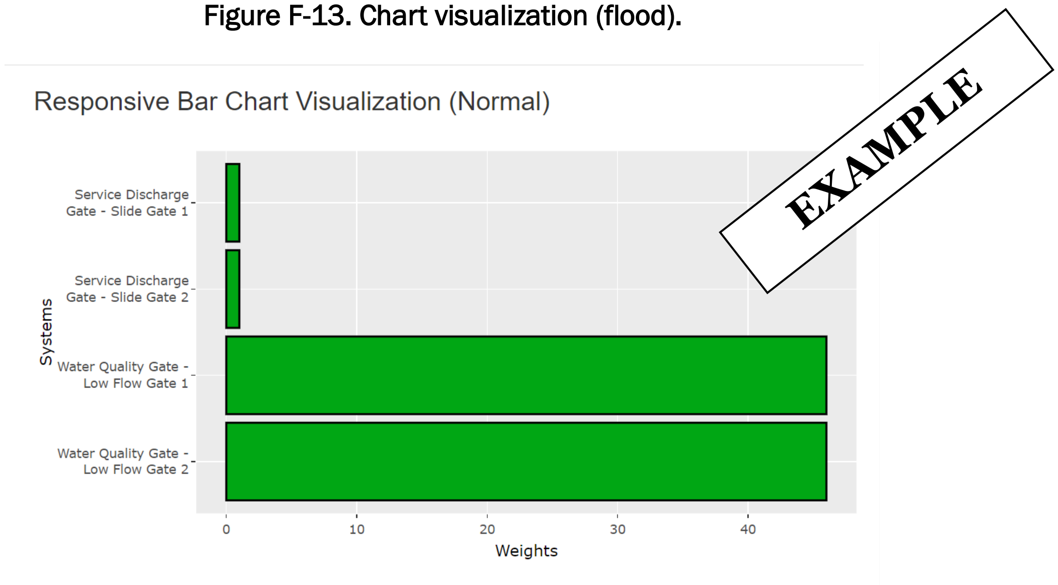
2. Which system has the **greatest** influence/impact on the operations of the facility under flood conditions? Verity that the assumption that gates of same type have same influence.
3. Since the least influential system was set at 1, indicate how much greater would you say the influence of this system is than the least influential (7, 37, 100…times)? The scale you utilize is up to your discretion. Input that value using the slider. Verity that the assumption that gates of same type have same influence.
4. **Systems may be assessed the same relative influence**, but for systems with the same influence, confirm that they both are equally important/influential. There is no forced distribution of the relative influence, the values are up to you.
5. You may include any free text comments that might help with describing your assignment of the relative influence for that system in the free text box on the right-hand side of the page.
6. Use the dropdown menu to indicate your level of confidence (high, medium, or low) in your overall assignment of the relative influence for the systems on the facility (Figure F-12).

Figure F-12. Provide comments (flood).



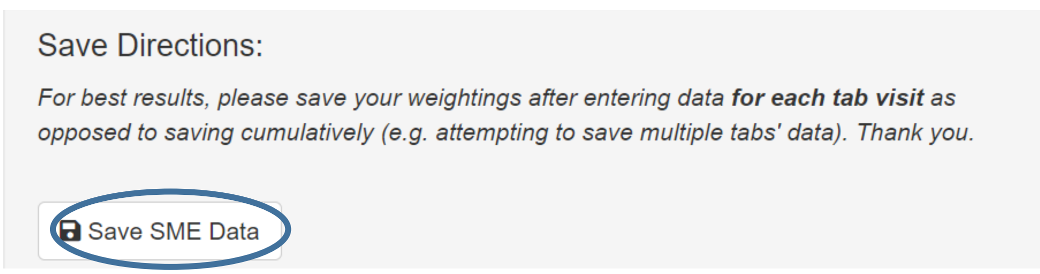
7. Review the bar graph to confirm the relative influence numbers align with their thought process (Figure F-13). Does the relative scale agree with how you visualize the relative influence?

Figure F-13. Chart visualization (flood).



Don't forget to save your work before moving to the next tab (Figure F-14)!

Figure F-14. Save responses (flood).

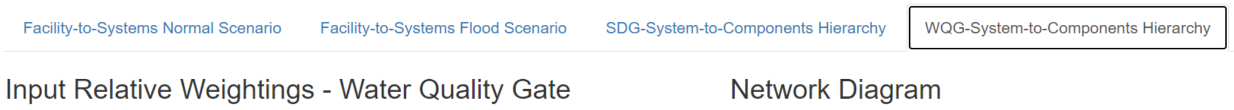


Tab 3: The relative influence of the components of the Service Discharge Gate to the gate system to under normal operating conditions (Figure F-15).

Figure F-15. Service discharge gate relative influence.

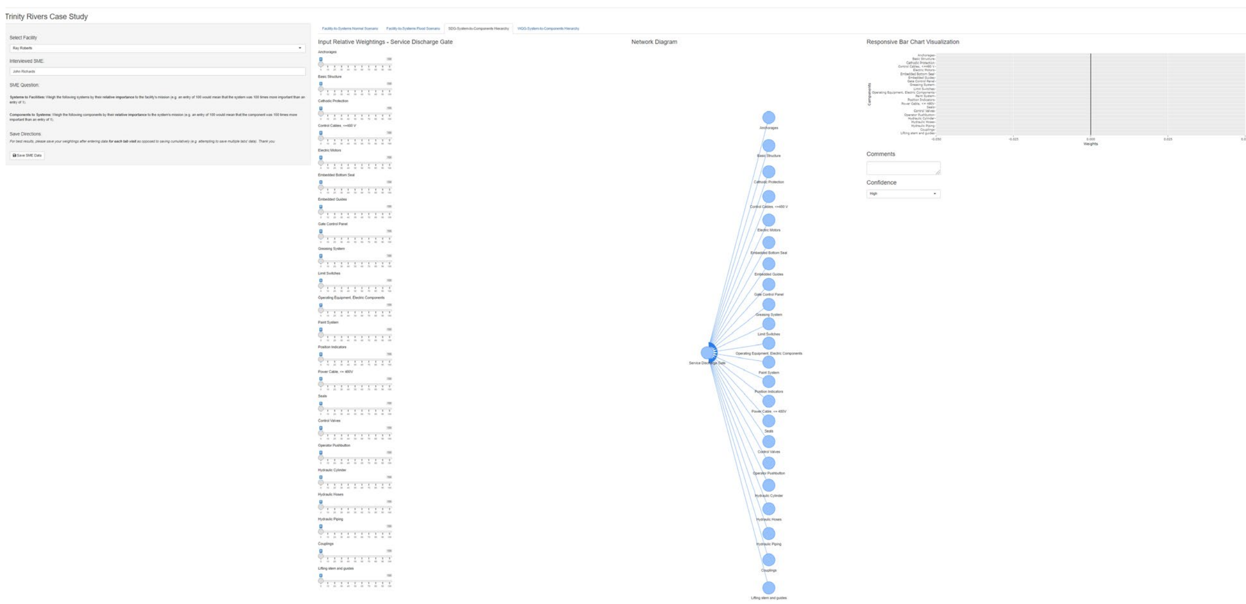
Tab 4: The relative influence of the components of the Service Discharge Gate to the gate system to under normal operating conditions (Figure F-16).

Figure F-16. Water quality gate relative influence.



Now for each of the types of gate systems, we would like you to indicate your assessment of the relative influence of each of the component's impact on the operation of its associated system under normal operations (Figure F-17). Please note that due to the number of components in a system, you may need to scroll down to see them all!

Figure F-17. Component relative influence.



It is assumed that all the gates for each type of gate system operate identically and consist of the same components (in other words, all the Service Discharge gates at the facility have the same components).

The assignment of the relative influence of the components on the system follows a similar process as for the relative influence of the systems on the facility.

1. To start off, which component has the least influence/impact on the operations of the system under normal conditions? Set that component at 1 using the slider bar.
2. Which component has the greatest influence/impact on the operations of the system under normal conditions?

3. Since the least influential component was set at 1, indicate how much greater would you say the influence of this component is than the least influential (7, 37, 100…times)? The scale you utilize is up to your discretion. Input that value using the slider bar.
4. How would you then rate the influence of the next highest component (and on down the line)? Input these values using the slider bar until all components have a relative influence value. Multiple components may be assessed the same relative influence, but for components with the same influence, confirm that they both are equally important/influential. There does not need to be a forced distribution of the relative influence across the system.
5. If you think a component is not physical present of a part of the specified system, leave the value at 0.
6. You may include any free text comments in the box on the right-hand side that might help with describing your assignment of the relative influence for that component.
7. Use the dropdown menu to indicate your level of confidence (high, medium, or low) in your overall assignment of the relative influence for the components on the system.
8. Review the bar graph to confirm the relative influence numbers align with their thought process. Does the relative scale agree with how you visualize the relative influence?

Don't forget to complete both component to systems tabs (SDG-System-to-Components Hierarchy and WQG-System-to-Components Hierarchy) and save your work before moving to the next tab!

Reminder, if you are at the District level or in a position that interacts with more than one of the facilities (Grapevine, Lewisville, and Ray Roberts), please complete an assessment each facility using the dropdown menu and following the same procedures outline above.

Thank you for your time and effort! We greatly appreciate your input into this project and look forward to the upcoming group meeting to discuss the results and consensus.

Any questions or concerns, please contact John Richards at john.p.richards@erdc.dren.mil or Willie Brown at Willie.H.Brown@erdc.dren.mil.

Subject matter expert elicitation consensus discussion script

Good afternoon. We thank you so much for your time in assisting us with this research project. We appreciated your individual assessment of the relative influence of systems on the facilities and components on the systems.

The next step in our structured elicitation is to discuss the results and try to come to consensus on the relative influence for the various systems and components. Depending on how the discussion goes, we anticipate this may take an additional session.

If you don't mind, I'd like to record this session with your permission.

I would like to start with the Facility to System Relative Influences for all three facilities (Grapevine, Lewisville, and Ray Roberts) for both the normal and flood operations. There was consistency in both scenarios for all three facilities that the service discharge gates had a higher relative influence than the water quality gates on the operation of the facility. There is some amount of dispersion as to the actual amount of that relative influence I'd like to talk through today.

One note, as we go through this process, you will have an opportunity to review the results of today's discussion and indicate your level of agreement with the group consensus, from strongly agree down to strongly disagree. I'll go over that feedback at the end of the session but wanted you to be aware of that ability to provide that feedback.

Facility-System Flood Operations tab

Here are the results from your feedback on relative influence on flood operations for the Grapevine Facility. You all indicated that the Water Quality Gates would have the least influence, but had varying degrees of influence, as show in the box and whisker plot to the right of the screen.

[Need to explain rating system! Some had zeros. Some didn't use 1 for lowest influence.]

To provide consistency, we'd like to set the relative influence of the water quality gates at 1 so we can base the service discharge gates off that system. Now, there was some difference between the two gates. As I'm not familiar with this facility, is it a valid assumption that they operate the same and would have the same relative influence or not? If so, we'll assign the gates the same relative influence of 1.

Now, with the water quality gates assigned a relative influence of 1, how much greater is the relative value for the service discharge gates? In other words, would their relative influence be (7, 37, 100) times greater than the water quality gates? And is it safe to assume they carry the same relative influence on the normal operation of the Grapevine Lake?

Save data each tab!

Facility-System Normal Operations tab

To provide consistency, we'd like to set the relative influence of the water quality gates at 1 so we can base the service discharge gates off that system. Now, there was some difference between the two gates. As I'm not familiar with this facility, is it a valid assumption that they operate the same and would have the same relative influence or not? If so, we'll assign the gates the same relative influence of 1.

Now, with the water quality gates assigned a relative influence of 1, how much greater is the relative value for the service discharge gates? In other words, would their relative influence be (7, 37, 100) times greater than the water quality gates? And is it safe to assume they carry the same relative influence on the normal operation of the Grapevine Lake?

Let's do the same for Lewisville and Ray Roberts.

Save data each tab!

Go through the entire facility first?

Before we go through the same exercises with the relationships of the components to the gate systems, I want to ask if you identified any components that we need to clarify if they are present in the system or not. By the way, this has been helpful to us to realize that there may be OCA data that needs to be updated. We also realize that not everyone (including us) has an intimate knowledge of the facility and either may have not felt comfortable assigning relative influence, or may have assigned influence for something that may not actually present. So that is why we want to clean up the component list before moving forward.

For Grapevine, the only component that someone assessed with 0 relative influence was the anchorages.

Service Discharge Gate—Component tab

Let's start with the service discharge gates. You can see that the spread on some of these was pretty large. The components with the lowest average influence were the paint and PLC. Is there agreement that these components have the lowest influence? If so, set their relative influence at 1. Are they both equally influential, or does one have more influence than the other? Any other components with the same relative influence?

The lifting cables were rated as having the highest relative influence at 97.5. Is there agreement that these have the highest influence?

1. If we set the least influential system at 1, how much greater would you say the influence of this system is than the least influential (7, 37, 100…times)?
2. How would you then rate the influence of the next highest system (and on down the line)?
3. For components with the same influence, confirm that they both are equally important/influential.

Water Quality Gate—Component tab

Let's now move on to the water quality gates for Grapevine. You can see that the spread on some of these was pretty large. The component with the lowest average influence was the anchorages. Is there agreement that these components have the lowest influence and if so, set their relative influence at 1? Any other components with the same relative influence?

The Operating Equipment, Electric Cables and Power Cable <= 480V were rated as having the highest relative influence at 90. Is there agreement that these have the highest influence?

1. If we set the least influential system at 1, how much greater would you say the influence of this system is than the least influential (7, 37, 100…times)?

2. How would you then rate the influence of the next highest system (and on down the line)?
3. For components with the same influence, confirm that they both are equally important/influential.

Use Low Flow Gate or Water Supply Gate Instead of Water Quality Gate.

Thank you for your assistance. I'll send a follow up email asking for the following:

Step 1: For each of the Facility to System Consensus rankings below, click in the yellow box and select your level of agreement with the ranking and relative influence: (strongly agree, agree, neither agree nor disagree, disagree, strongly disagree).

Step 2: For each of the System to component rankings below, make any changes to your relative influence in the yellow boxes. Changes are not required (i.e., if you feel comfortable with your original relative influence values, use them again). The spreadsheet will update the rankings for you.

Individual SME elicitation results

System to Facility (Flood Condition)

Figure F-18. Grapevine Lake.

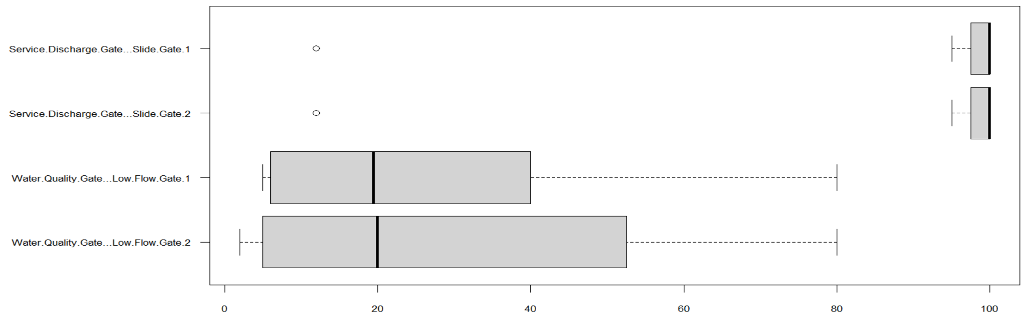


Figure F-19. Lewisville Lake.

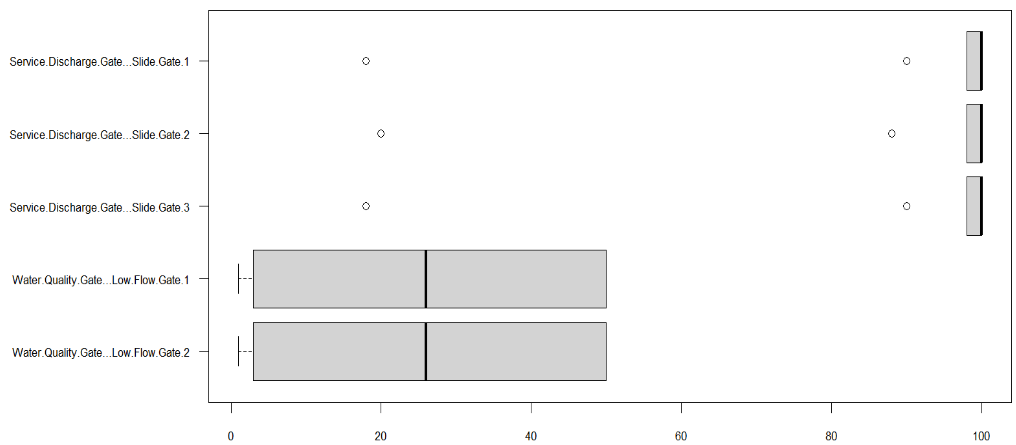
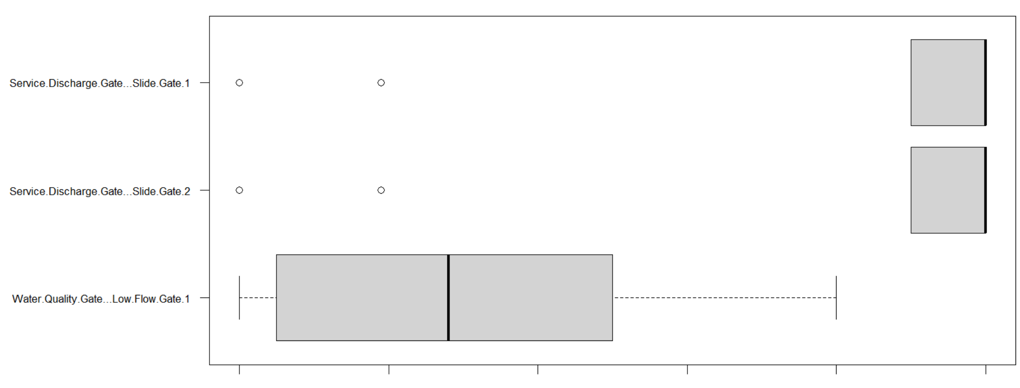


Figure F-20. Ray Roberts Lake.



System to Facility (Normal Condition)

Figure F-21. Grapevine Lake.

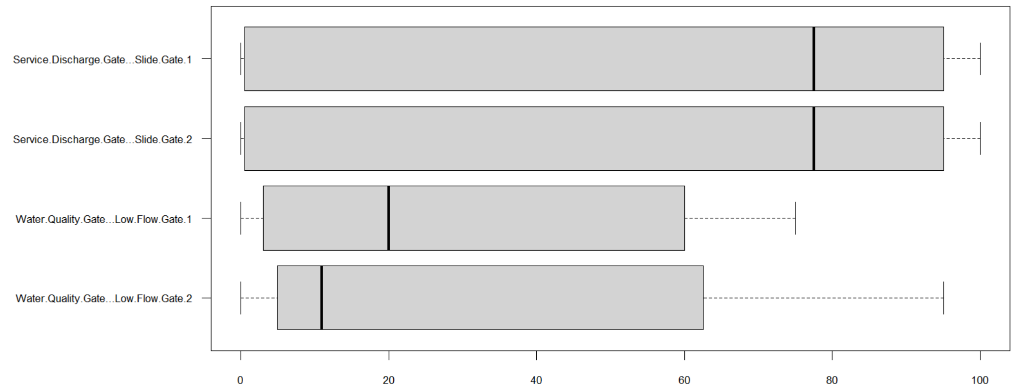


Figure F-22. Lewisville Lake.

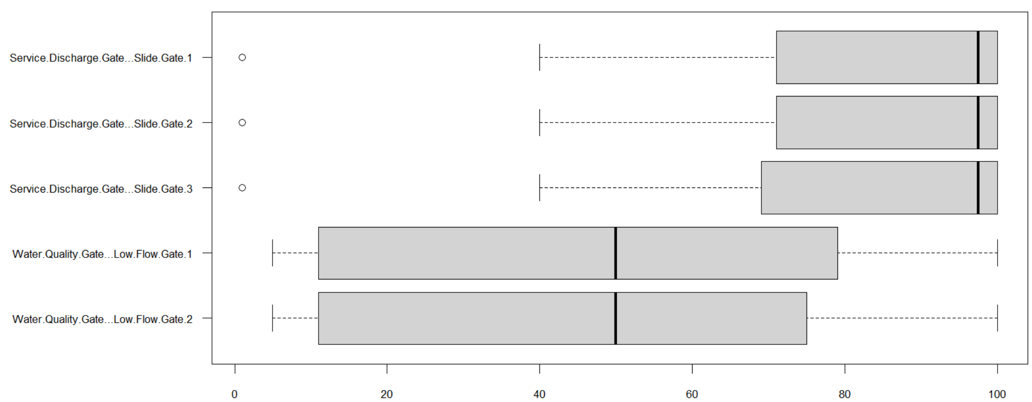
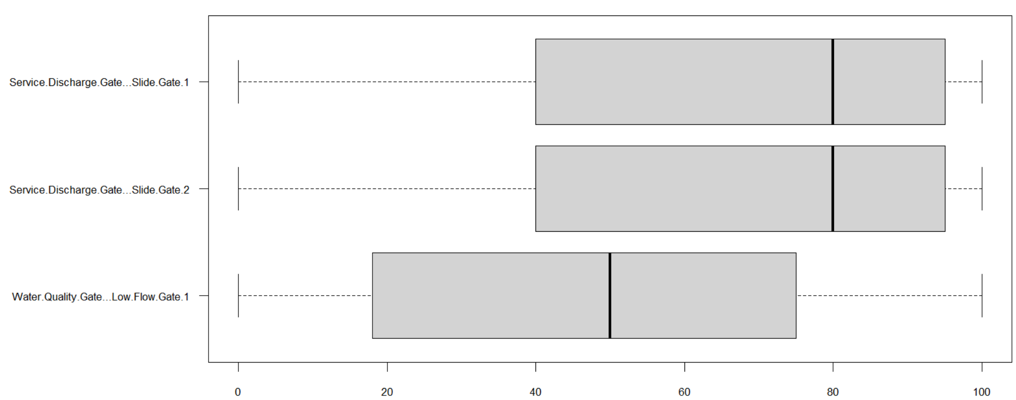


Figure F-23. Ray Roberts Lake.



Service Discharge Gates

Figure F-24. Grapevine Lake.

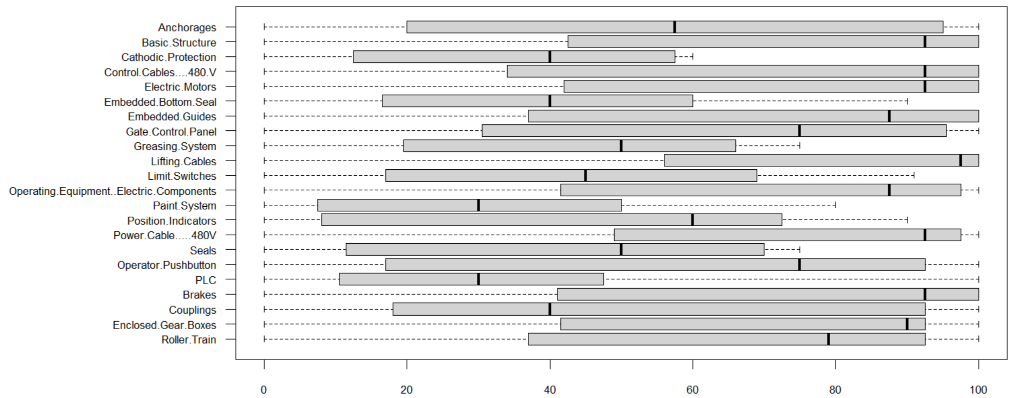


Figure F-25. Lewisville Lake.

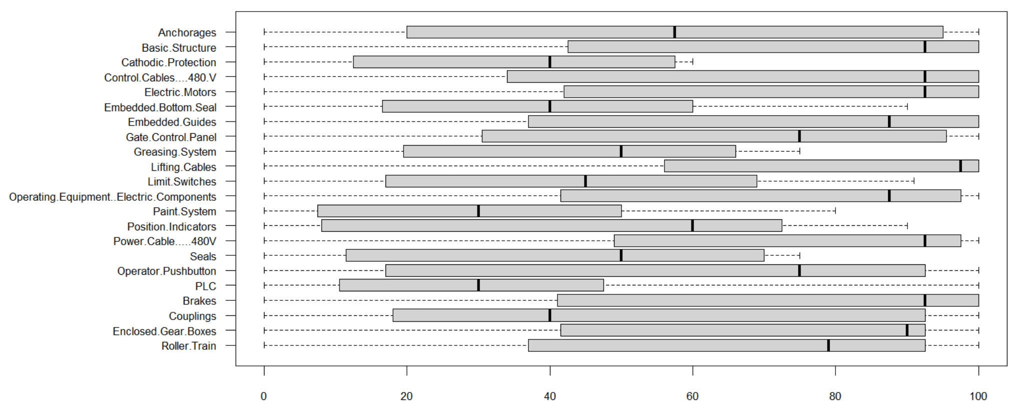
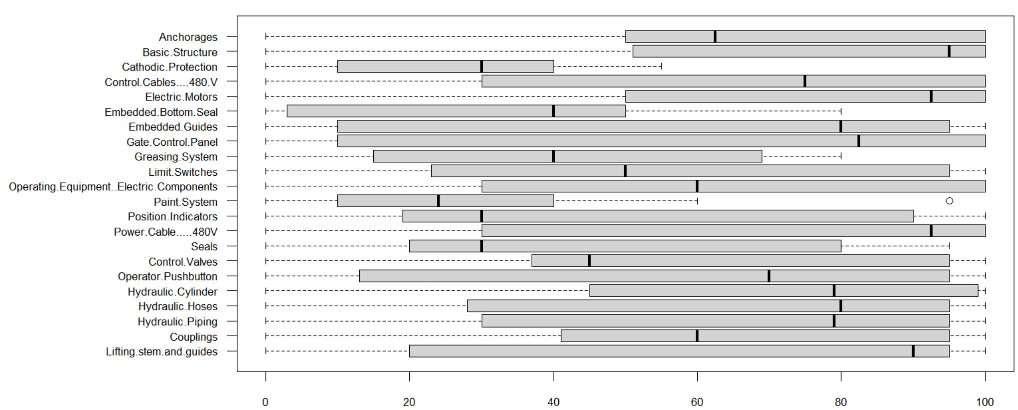


Figure F-26. Ray Roberts Lake.



Water Quality Gates

Figure F-27. Grapevine Lake.

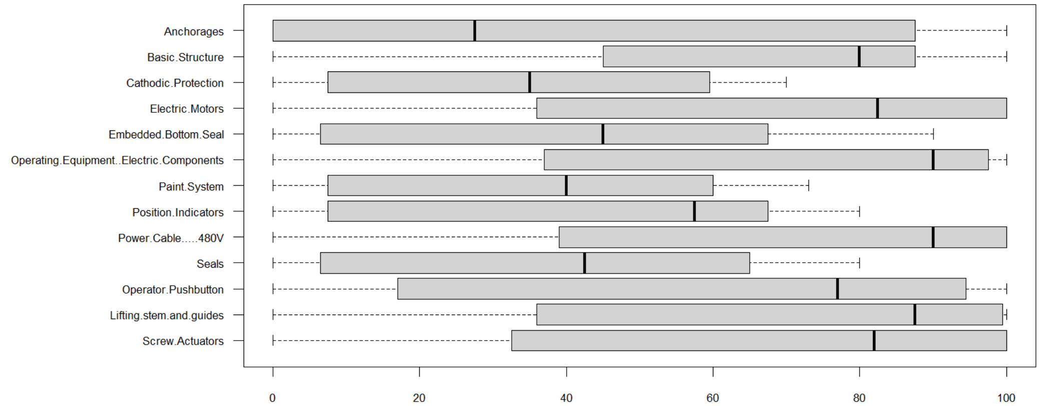


Figure F-28. Lewisville Lake.

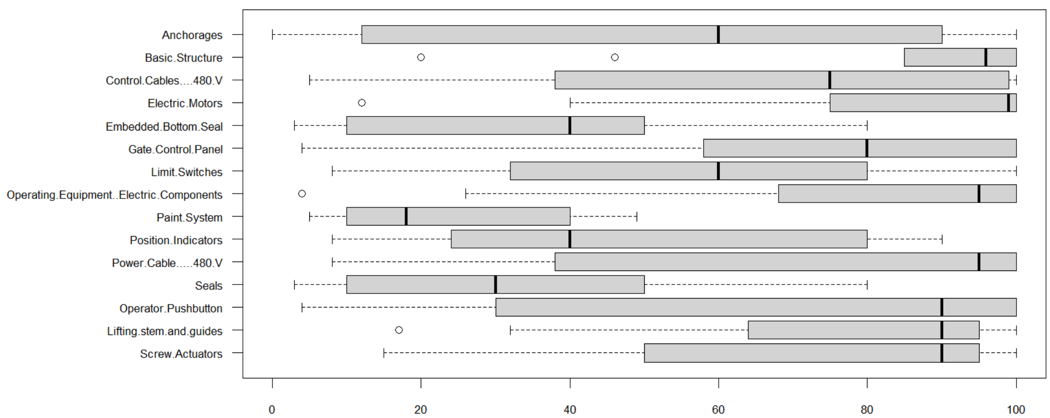


Figure F-29. Ray Roberts Lake.

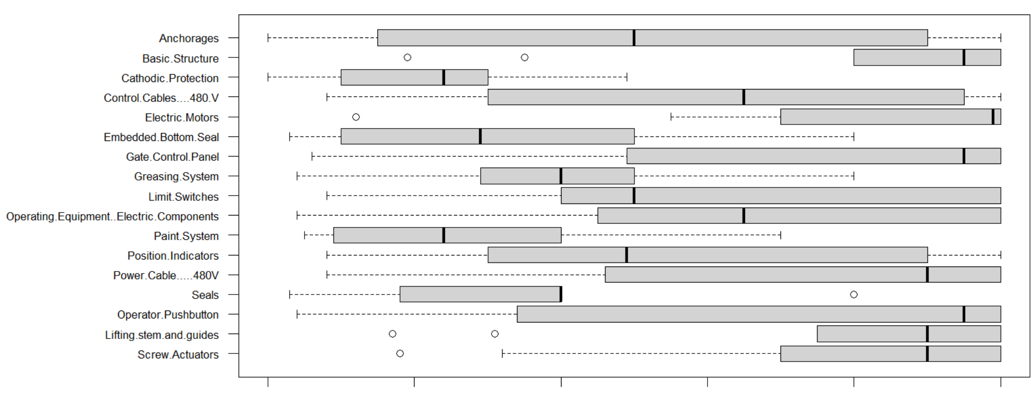
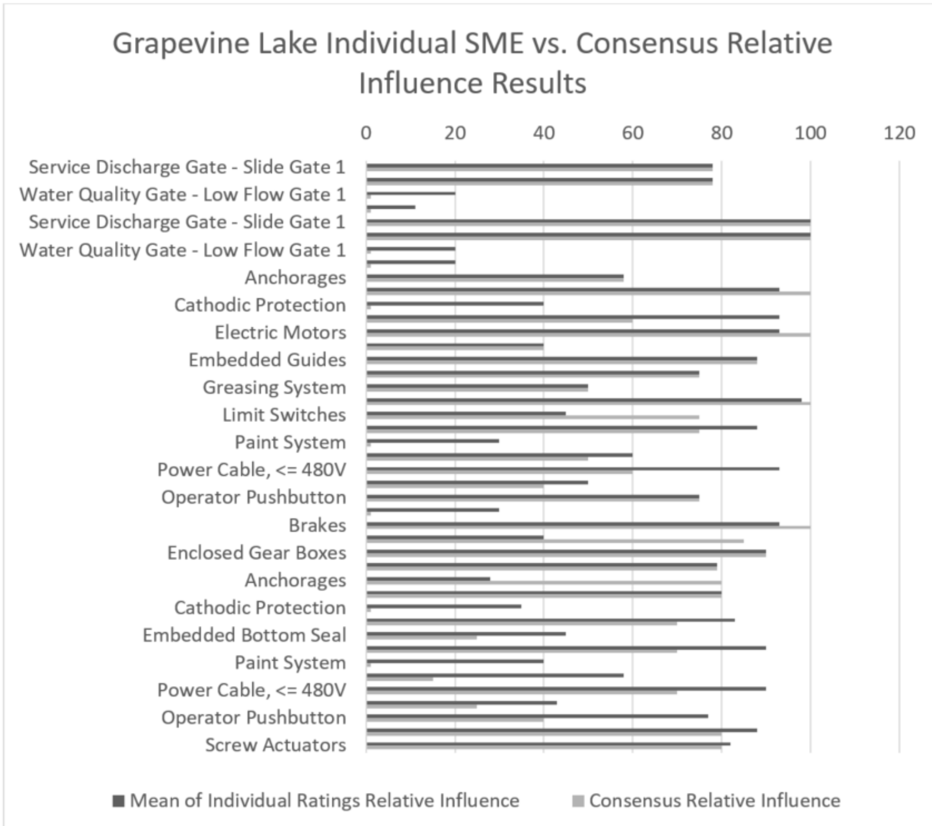


Figure F-30. Case study 2 individual SME vs. consensus relative influence results—Grapevine Lake.



The SME level of agreement responses (Table F-2) indicated that they agreed or strongly agreed with the vast majority the group consensus assigned values of relative influence for each of the systems on the facility and for all of the components on each of their respective systems. Of the 862 total responses for the relative influence of the nine systems to the facility under flood and normal operations, 96.87% were categorized as agree (strongly agree or agree) with only 2.32% categorized as disagree (disagree or strongly disagree). Ten of the 12 scenarios had an agreement level greater than 95%, with only 2 lower, both in the 83-85% range. This denotes a strong level of agreement amongst the SMEs for the assignment of relative influence at the end of the process.

Table F-2. Level of agreement results for case study 2—Trinity River.

Scenario	Responses	Same Relative Influence (%)	Agree (%)	Neutral (%)	Disagree (%)
Grapevine system to facility—normal	4	100.00	100.00	0.00	0.00
Grapevine system to facility—flood	8	93.75	100.00	0.00	0.00
Grapevine service discharge gates	7	99.35	97.40	1.30	1.30
Grapevine water quality (low flow) gates	8	94.23	98.08	0.00	1.92
Lewisville system to facility—normal	7	85.71	94.29	0.00	5.71
Lewisville system to facility—flood	6	93.33	100.00	0.00	0.00
Lewisville service discharge gates	7	95.71	95.71	1.43	2.86
Lewisvile water quality (low flow) gates	6	97.78	97.78	1.11	1.11
Ray Roberts system to facility—normal	6	61.11	83.33	0.00	16.67
Ray Roberts system to facility—flood	7	76.19	85.71	0.00	14.29
Ray Roberts service discharge gates	7	97.40	96.75	1.30	1.95
Ray Roberts water quality (low flow) gates	4	97.06	100	0.00	0.00
Overall		**95.13**	**96.87**	**0.81**	**2.32**

One final observation is that not all eight SMEs provided level of agreement input for every tab that represented a system within each facility to complete the level of agreement assessment (Table F-3). There were 12 total tabs within the data collection tool. The first and the last had the lowest response rate at 33%. This indicates that there was a flaw in the data collection and saving of the data whereby the first and last tab could either be bypassed or not saved prior to leaving the data collection tool. This flaw and the associated guidance/directions will need to be rectified in the next iteration of this process.

Table F-1. Example system-component OCA ratings.

Tab Order	Scenario	Respondents
1	Grapevine system to facility—normal	4
2	Grapevine system to facility—flood	8
3	Grapevine SDG	7
4	Grapevine WQG	8
5	Lewisville system to facility—normal	7
6	Lewisville system to facility—flood	6
7	Lewisville SDG	7
8	Lewisville WQG	6
9	Ray Roberts system to facility—normal	6
10	Ray Roberts system to facility—flood	7
11	Ray Roberts SDG	7
12	Ray Roberts WQG	4

Appendix G: Initializing Bayesian Networks Example

This example details how to calculate the probability that a nine-gate system facility is operational given one gate system has components that are failing (OCA rating of F).

First, one must calculate the probability that a gate system is operational given the condition of its components. That is, if a gate system consists of 10 primary components that received the OCA ratings given in Table 1, then using the normalized subject matter expert elicited relative influences of the system components (Table G-1), the team is able to ascertain the probability that the system is operational.

Table G-1. Example system-component OCA ratings.

System	Component	OCA Rating
Service Gate System 1	Component 1	F
Service Gate System 1	Component 2	D
Service Gate System 1	Component 3	C
Service Gate System 1	Component 4	D
Service Gate System 1	Component 5	B

Combining the component OCA ratings with the normalized relative influence values (Table G-2), it is possible to calculate system-level probability of degradation.

Table G-2. Example system components normalized relative influence.

System	Component	Relative Influence	Normalized Relative Influence
Spillway Gate System 1	Component 1	23	$\frac{23}{40} = 0.575$
Spillway Gate System 1	Component 2	1	$\frac{1}{40} = 0.025$
Spillway Gate System 1	Component 3	3	$\frac{3}{40} = 0.075$
Spillway Gate System 1	Component 4	3	$\frac{3}{40} = 0.075$
Spillway Gate System 1	Component 5	10	$\frac{10}{40} = 0.25$

Appendix H: SMEs for Both Case Studies

Case Study 1—Baltimore District

Julie Fritz, Brian Glock, Barry Holland, Gary Kalbaugh

Case Study 2—Fort Worth District

Terry Bachim, Denny Bays, Christopher Bryan, W. Kent Dunlap, Robert Jordan, Marie Loftin, Jim McClain, James Murphy, Joshua Pickering, Mark Sissom, Todd Stowe, Nick Wilson

Acronyms and Abbreviations

CHL	Coastal Hydraulics Laboratory
CPT	Conditional probability table
CSED	Computational Science and Engineering Division
CWMS	Corps Water Management System
EL	Environmental Laboratory
ERDC	US Army Engineer Research and Development Center
FEM	Facilities and Equipment Maintenance
FRM	Flood Risk Management
FSPD	Flood and Storm Protection Division
HEC-WAT	Hydrologic Engineering Center-Watershed Assessment Tool
HSB	Hydrologic Systems Branch
ISER	Institute for Systems Engineering Research
ITL	Information Technology Laboratory
IWR	Institute for Water Resources
OCA	Operational Condition Assessments
PoF	Probability of failure
SME	Subject matter expert
STS	Socio-technical systems
USACE	US Army Corps of Engineers

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE ***(DD-MM-YYYY)***	**2. REPORT TYPE**	**3. DATES COVERED** ***(From - To)***
11-2022	Final Special Report	

4. TITLE AND SUBTITLE

Risk-Based Prioritization of Operational Condition Assessments: Methodology and Case Study Results

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Jonathan K. Alt, Willie H. Brown, George E. Gallarno, John P. Richards, Jennifer M. Olszewski, and Titus L. Rice

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Information Technology Laboratory
US Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER

ERDC/ITL SR-22-5

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Navigation Systems Research Program
Coastal Hydraulics Laboratory
US Army Engineer Research and Development Center
Vicksburg, MS 39180

10. SPONSOR/MONITOR'S ACRONYM(S)

ERDC-CHL

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

Funding: U4381095, AMSCO: 031391

14. ABSTRACT

USACE operates, maintains, and manages more than $232 billion of the Nation's water resource infrastructure. USACE uses the Operational Condition Assessment (OCA) to allocate limited resources to assess condition of this infrastructure in efforts to minimize risks associated with performance degradation. The analysis of risk associated with flood risk management (FRM) assets includes consideration of how each asset contributes to its associated FRM watershed system, understanding the consequences of the asset's performance degradation, and a determination of the likelihood that the asset will perform as expected given the current OCA condition ratings of critical components. This research demonstrates a proof-of-concept application of a scalable methodology to model the probability of a dam performing as expected given the state of its gates and their components. The team combines this likelihood of degradation with consequences generated by the application of designed simulation experiments with hydrological models to develop a risk measure. The resulting risk scores serve as an input for a mixed-integer optimization program that outputs the optimal set of components to conduct OCAs on to minimize risk in the watershed. This report documents the results of the application of this methodology to two case studies.

15. SUBJECT TERMS

Civil engineering--Planning; Decision making; Engineering—Management; Hydraulic structures; Dams; Risk assessment

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** ***(include area code)***
Unclassified	Unclassified	Unclassified	none	77	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18