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Risk-Based Prioritization of Operational Condition Assessments: Jennings Randolph Case Study

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

March 2022

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Final report

Abstract

The US Army Corps of Engineers (USACE) operates, maintains, and manages over $232 billion worth of the Nation's water resource infrastructure. Using Operational Condition Assessments (OCA), the USACE allocates limited resources to assess asset condition in efforts to minimize risks associated with asset performance degradation, but decision makers require a greater understanding of those risks. The analysis of risk associated with Flood Risk Management assets in the context of its associated watershed system includes understanding the consequences of the asset's failure and a determination of the likelihood that the asset will perform as expected given the current OCA ratings of critical components. This research demonstrates an application of a scalable methodology to model the probability of a dam performing as expected given the state of its subordinate gates and their components. The research team combines this likelihood with consequences generated by the application of designed simulation experiments with hydrological models to develop a measure of risk. The resulting risk scores serve as an input for an optimization program that outputs the optimal set of components to conduct OCAs on to minimize risk in the watershed. Proof-of-concept results for an initial case study on the Jennings Randolph Dam are provided.

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Preface

1 Introduction

The US Army Corps of Engineers (USACE) operates, maintains, and manages more than $232 billion worth of the Nation's water resources assets. Ensuring the proper functioning of these assets, particularly those associated with Flood Risk Management (FRM), impacts the lives of American citizens daily across the country. USACE personnel perform Operational Condition Assessments (OCAs) on these assets' components at a minimum of every 5 yr[1,2]. The USACE Asset Management community requires an understanding of the current assessment process, and its effectiveness, to identify opportunities to improve the process through focused modernization efforts. This necessitates a holistic review of the current OCA process and the creation of new processes, as required, to systematically develop a transparent, consistent, and traceable risk-based OCA system. To achieve this vision of the OCA system, the following strategic objectives must be addressed:

1. Provide Access to Asset Data.
2. Enhance OCA Conduct and Quality.
3. Determine Asset Risk.
4. Develop OCA Prioritization and Scheduling Framework.

Figure 1 presents a high-level functional decomposition of the OCA system from which the strategic objectives are derived.

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[1] For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248-52, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

[2] For a full list of the unit conversions used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 345-7, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf

Figure 1. OCA strategic objectives; those addressed by this research are highlighted.
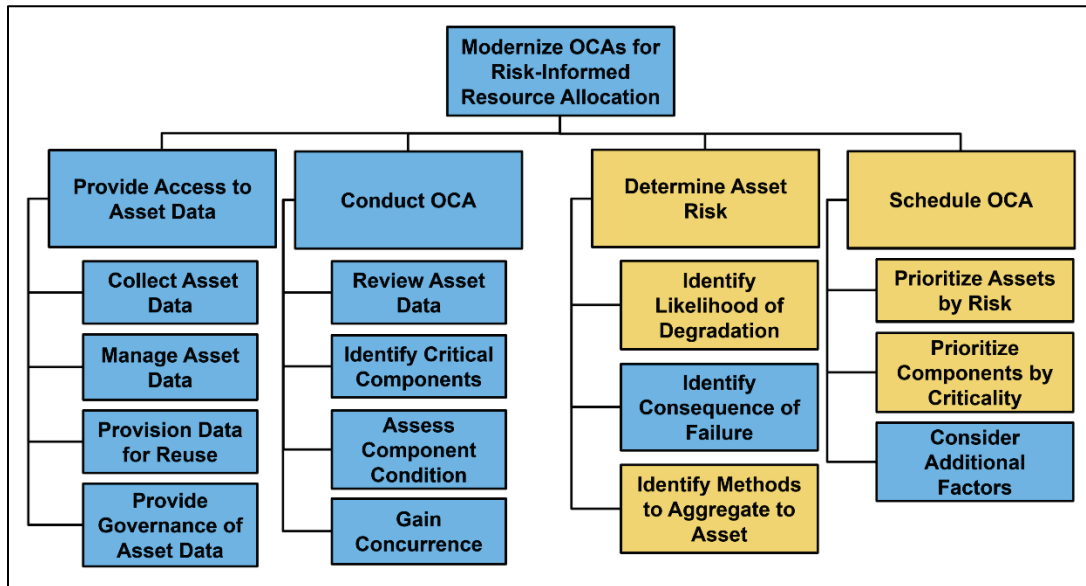
This research develops a methodology to understand how the condition of components impact system performance and how each system impacts the performance of the facility in which they sit. The purpose of this document is to provide an overview of the developed methodology and its application to a case study at the Jennings Randolph Lake (JRL) facility.

1.1 Background

Currently, OCAs are conducted each year without a risk-based prioritization method resulting in the expenditure of resources to assess 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, and the consequence of a systems 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 (Figure 2).

Figure 2. OCA hierarchy.
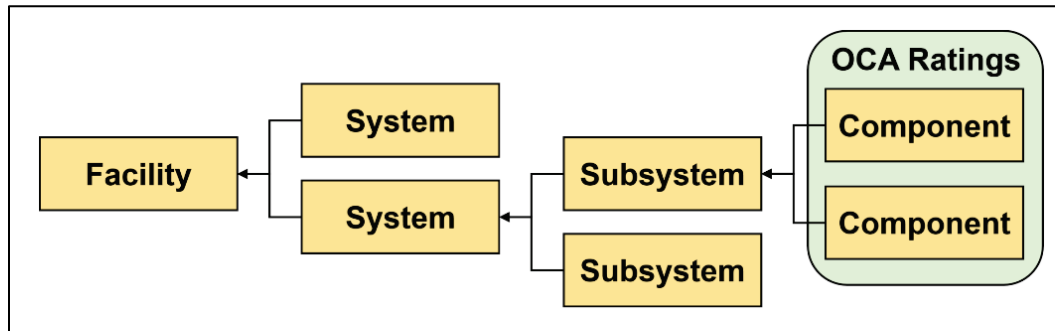
The previous literature review and the results of the JRL facility and Baltimore District staff interviews informed the development of the current methodology and its application (Alt et al. 2021).

1.2   Objective

The objective of this 3 yr effort is to develop an enterprise framework for risk-based prioritization of OCAs. This project will help decision makers understand which FRM facility components require an OCA based on their contribution to overall operational risk and current conditions. Although this project focuses on facilities associated with FRM, the prioritization methodology developed should be generalizable to other business lines in the future. The output of the framework will be (1) the set of FRM facility components across the enterprise that should receive maintenance and OCA scheduling priority to maximize risk mitigation across the enterprise, (2) the uncertainty associated with model results, and (3) an easily understandable presentation of the potential tradeoffs. Figure 3 decomposes the tasks associated with determining asset risk.

Figure 3. Decomposition of the "Determine Asset Risk" function.
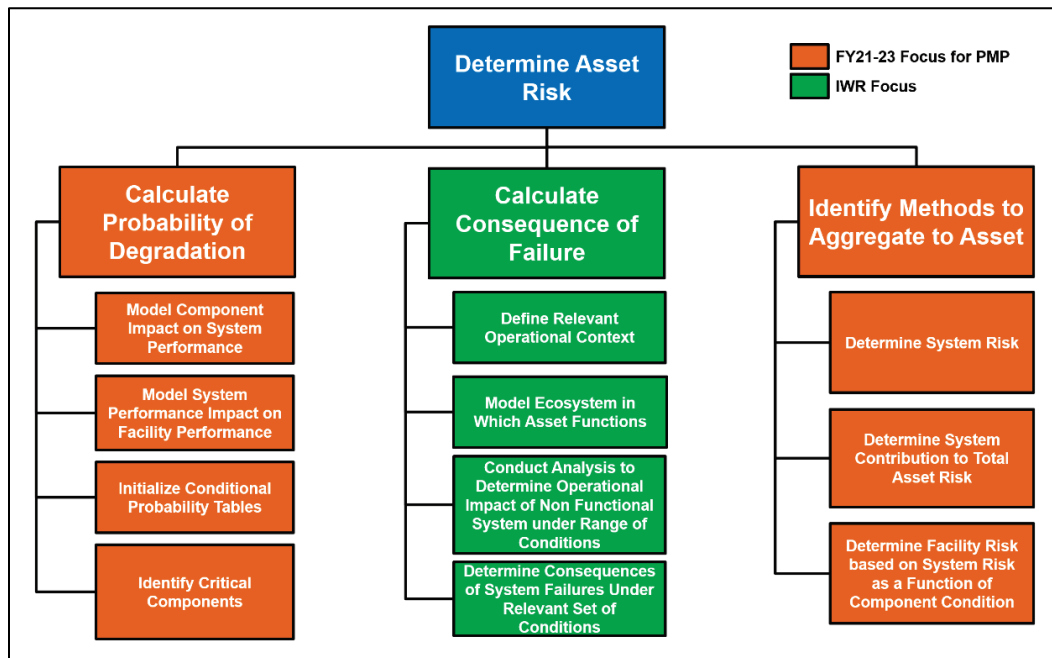
1.3 Approach

The results of the initial literature review informed the development of the candidate methodology, documented in section 2, applied to the first case study. The results of the application of this methodology to the first case study are documented in section 3. Section 4 provides a lead in to the second case study application, ongoing at the time of this report. The two case study watersheds are (1) The North Potomac River Sub-Basin which includes the JRL facility in the Baltimore District and (2) The Elm Fork of the Trinity River Basin which includes the Ray Roberts Lake, Lewisville Lake, and Grapevine Lake Facilities in the Fort Worth District. Data development for each study leveraged existing data sources, such as OCA and Facilities and Equipment Maintenance (FEM) databases and identified gaps in data required to determine the probability of degradation. This required the elicitation of expert input from subject matter experts (SMEs) at each facility using custom web-based tools. To develop consequence data, the research team includes consequence modelers from the Institute for Water Resources (IWR) and the US Army Engineer Research and Development Center (ERDC) Environmental Laboratory. These two teams have collaborated to develop risk scores for the first case study, and these risk scores serve as input into a mixed-integer optimization program that outputs the optimal set of components

requiring OCAs to minimize risk in the watershed. Those results are shown in Section 3.6. The approach is illustrated in Figure 4.

Figure 4. General approach for the execution of the project.
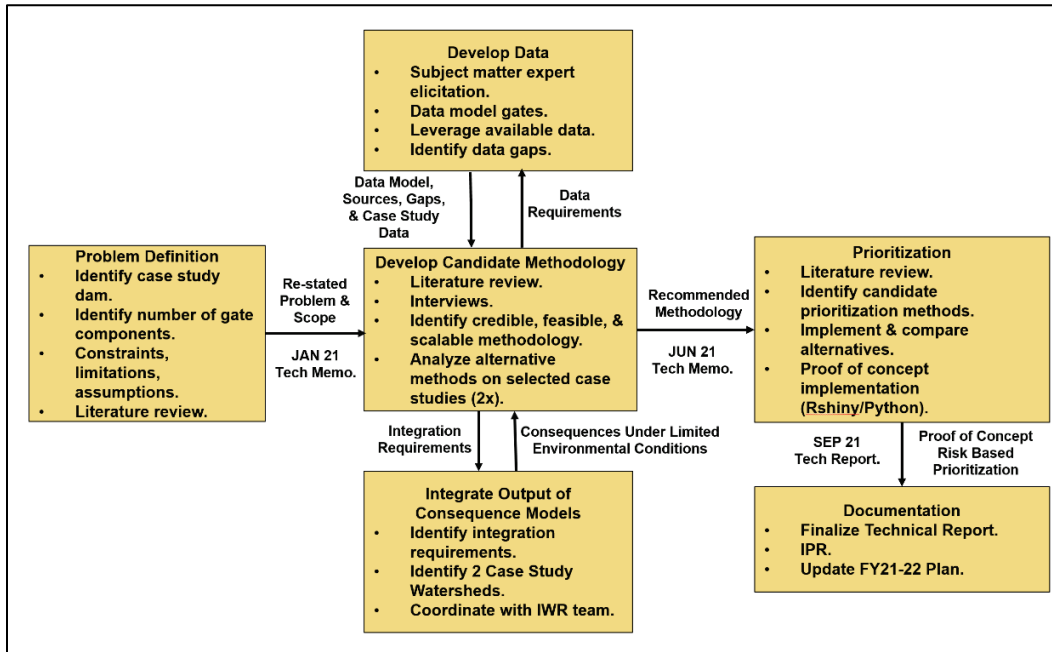
The purpose of this interim report is (1) to document the process, insights, and results from the first case study with the USACE Baltimore District and JRL facility and (2) to introduce the second case study with the USACE Fort Worth District and the associated Trinity River facilities. The next section provides an overview of the developed methodology, results from the first case study, a description of the ongoing second case study, and conclusions.

2   Methodology

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

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). That is

$$P(A|B) = \frac{P(B|A)\,P(A)}{P(B)} \tag{1}$$

where A and B represent events and $P(B) \neq 0$. Bayes theorem, however, is not limited to the conditioning of two events alone and is generalizable. By combining Bayes Theorem and notional information about the relationship between events, it is possible to formulate a Bayesian network. As such, graphical depictions of Bayesian networks are directed acyclic graphs of events in which each network 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*.

While the products of this project will include a Bayesian network model, it is necessary to initialize the conditional probability tables associated with each node in the proposed network. 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.

The research team employs Bayesian networks to develop a model of the facility that captures the relationships between the state of a system and the state of a facility as well as the relationship between the state of components and the state of the system in which they reside. Figure 5 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, $P(F|S_1, S_2, ..., S_n)$.

In this case, the variables at the facility and system level have only two states, fully operational or degraded. Figure 5 also presents an example Bayesian network modeling the probability that a system functions given the state of its components, C_j, where j=1...m and m is the number of components critical to the proper functioning of the system, $P(S_i|C_1, C_2, ..., C_m)$.

Figure 5. 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*.
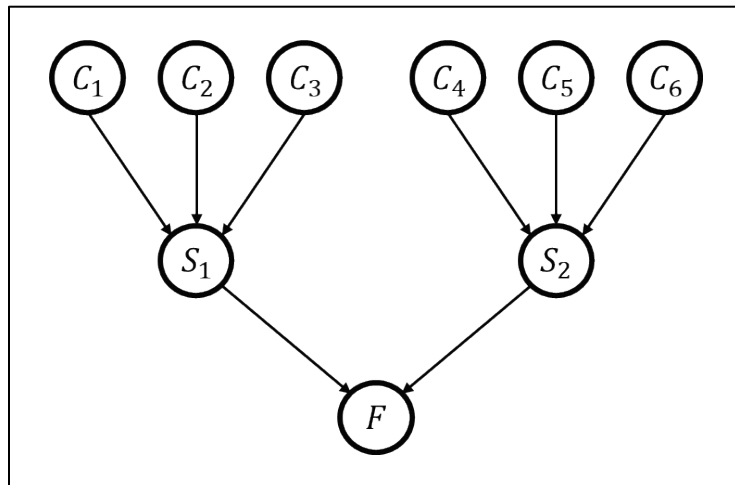
The state of critical components is determined by observation of the component during its most recent OCA. This assessment can take on values *A* through *F*, but the state space can also be reduced to a simple Pass or Fail where an OCA rating of A, A-, B+, or B is a Pass with anything less than a B being a Fail. In the absence of failure or down-time data, the research team used SME knowledge to initialize conditional probability tables required to use this model for inference.

The research 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 that have no points of interaction/integration. Figure 6 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 JRL. 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.

Figure 6. Exploratory Data Analysis Tool screenshot of the OCA and FEM hierarchies of the JRL facility. (https://oca-eda.erdc.dren.mil/dashboard/)
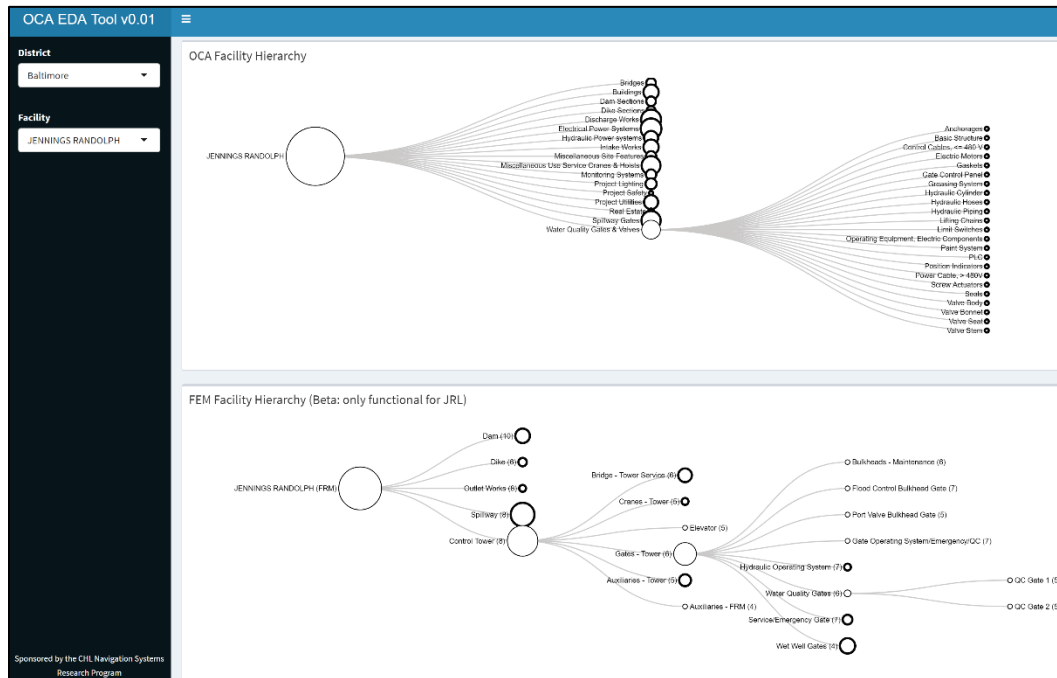
2.2 Initializing conditional probability tables

To decrease the burden on SMEs, this research leverages the technique presented by Hassall et al. (2019). Hassall et al. initialize conditional probability tables by eliciting the relative influence of parent and child nodes within the proposed Bayesian network. First, this study uses SME input to determine critical components within the key gate systems. Next, SMEs identify the relative influence of the critical components for each key gate system under assessment. Last, the SMEs assess the relative influence of the key gate systems to operational status of the JRL facility during *normal* and *flood* operating conditions.

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 characterized as either positive, negative, or *other*. If the

parent node changes to a higher state, this causes the child node to enter a higher state. Similarly, if the parent node changes to a lower state, this causes the child node to enter 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

$$P_{ij} = \begin{cases} \dfrac{j-1}{n_i-1} & \text{if Parent } i \text{ has a positive relationship with the child node} \\[2mm] \dfrac{n_i-j}{n_i-1} & \text{if Parent } i \text{ has a negative relationship with the child node} \\[2mm] \dfrac{ord[j]-1}{n_i-1} & \text{if Parent } i \text{ has an other relationship with the child node} \end{cases} \quad (2)$$

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

$$w_i = \frac{rw_i}{\sum_{j=1}^{m} rw_j} \quad (3)$$

Then the initial probability for the kth combination of parent states is given by

$$Initial\ Prob_{\{k\}} = \frac{\sum_i w_i P_{i\{k\}}}{\sum_i w_i} \quad (4)$$

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

In contrast to methods that direct SMEs estimate probabilities for specific combinations, the method developed by Hassall et al. (2019) allows for a

drastic reduction in the number of SME evaluations as well as provides a starting point for further refinement. For example, given a system with eight components, each of which can take on two different states, if the SME were asked to directly quantify a particular combination of states, this would require $2^8 = 256$ evaluations to initialize the conditional probability table (CPT). In this case, Hassall's method reduces the number of evaluations for initializing the CPT to as few as eight evaluations by quantifying the relative relationship between components. 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 (SME) elicitation methodology

For the collection of expert opinion of 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 was done to place the elicitation into a specific setting and ask relative value judgements with the intent to generate relative comparisons that will be used to calculate the conditional probabilities. The research team conducted SME elicitation in two stages: individual elicitation and group consensus, as shown in Figure 7.

Figure 7. SME elicitation process.
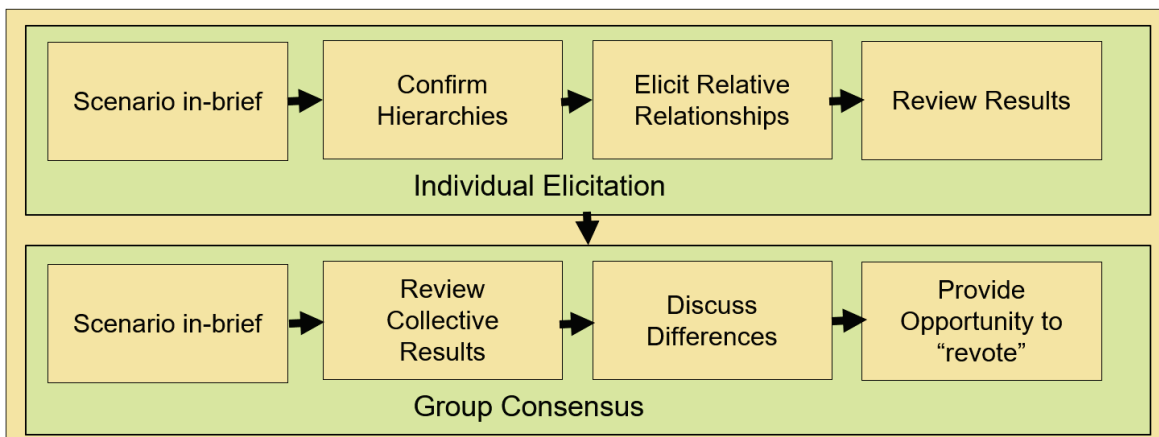
Stage 1 Individual Elicitation

1. Prior to the SMEs providing their input, a facilitator first briefed them on the following scenario to place the elicitation into a specific setting. The relative influence of the systems on the facility was considered under two operating conditions: (1) under a high water/flood event that necessitates the operation of flood control gates to control the output of water so as to not overtop the dam and (2) under normal operations where water is released by water quality and/or service gates (the full script is contained in Appendix B).

2. During an individual elicitation session, one expert stated that some facility systems are more critical than others in a flood situation as opposed to normal operating conditions. This led the research team to establish two rating scenarios: a flood scenario and a normal operating conditions scenario. The experts stated that the relative influence of the gate system differs by scenario (e.g., spillways gates are very important in a flood scenario but not at all important in normal operating conditions). However, they also stated that the relative influence of components to system functioning did not differ by scenario. Therefore, the experts rated the relative influence of systems to the facility for both scenarios, but they rated the relative influence of components to systems with no regard for scenario.

3. The facilitator confirmed the OCA system and component hierarchies by asking SMEs to verify those identified in the OCA database for the facility were correct.

4. The facilitator elicited the relationships between components to systems to facility by asking SMEs to assign relative influence for each system on the facility and each component on the system. Additionally, the facilitator asked the SMEs to identify common terms used by the experts when describing the likelihood a system or component is operating as intended.

5. The research team consolidated the SME input, processed the data to determine the mean and spread of relative influence values, and reviewed results in preparation for group discussions. The relative influences solicited during the individual elicitation sessions are recorded separately within comma-separated values (CSV) files. After an elicitation session finishes, interviewer notes from the event are consulted to ensure the proper relative influences were recorded, and any necessary updates to the CSV are then made. After all SMEs have been consulted, then their responses are aggregated into a singular

table and exported as a CSV file for analysis in preparation for the Delphi session.

Stage 2 Group Consensus

1. Prior to the SMEs providing their input, a facilitator first briefed them on the scenario to place the elicitation into a specific setting (full script is contained in Appendix B).
2. The group reviewed and discussed the aggregated results, looking at the means and the spread. The SMEs were provided their input prior to the group session so they could see their relationship to the mean.
3. The group discussed similarities and differences in their assignment of the relative influence values and came to consensus on a value for each of the gate systems on the facility and the components on the systems.
4. Finally, the experts were provided the consensus relative influence values and asked to indicate their level of agreement with the consensus ratings for each system/component using a Likert scale as well as the opportunity to *re-vote* (i.e., to provide differing values).

Following the group session, the consensus relative influences are added to the CSV files that contain data for the system and component-levels. The consensus values are then normalized and used to instantiate the conditional probability table.

To facilitate distributed SME elicitation and reduce the burden on SMEs, the research team developed a set of web-based applications hosted on the ERDC Cloud Computing Environment. Following computer access card authentication, the user is provided access to an interactive application that allows them to make use of sliders to adjust the relative influence of systems on a facility or components on a system along with graphical displays of the system or facility under study.

An initial session is held to explain the overall scenario and give instructions to the SMEs on how to use the application and understand the visualizations (Figure 8) to collect their individual expert opinions.

Figure 8. Screenshot of the SME elicitation tool used for data collection in the Trinity River Case Study. (https://oca-eda.erdc.dren.mil/osea)
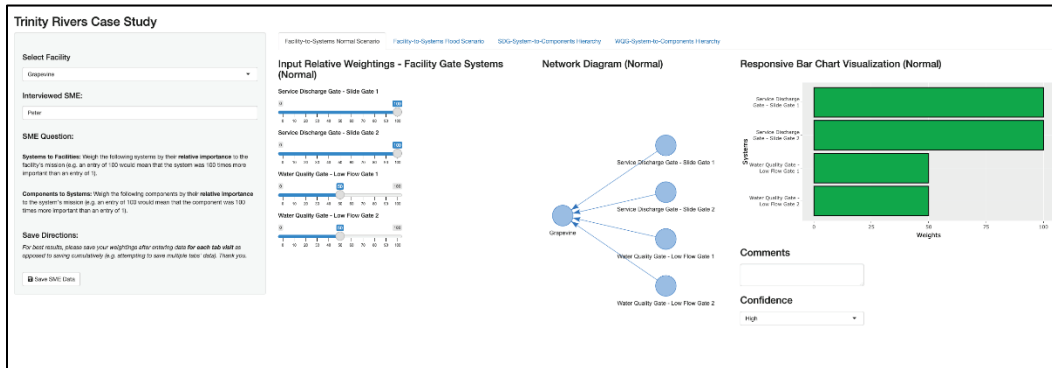
To facilitate the Delphi session, a second application reads in the results of the first round of elicitation from all SMEs and provides a visual of the spread of the input as well as comments from SMEs associated with their previous input. Sliders are set to the median value observed in the previous round, and SMEs are asked to adjust as appropriate (Figure 9). Group discussions can be held to discuss and generate consensus.

Figure 9. Screenshot of the group session application used to gain consensus on system and component relative influence weights.
(https://oca-eda.erdc.dren.mil/delphi)
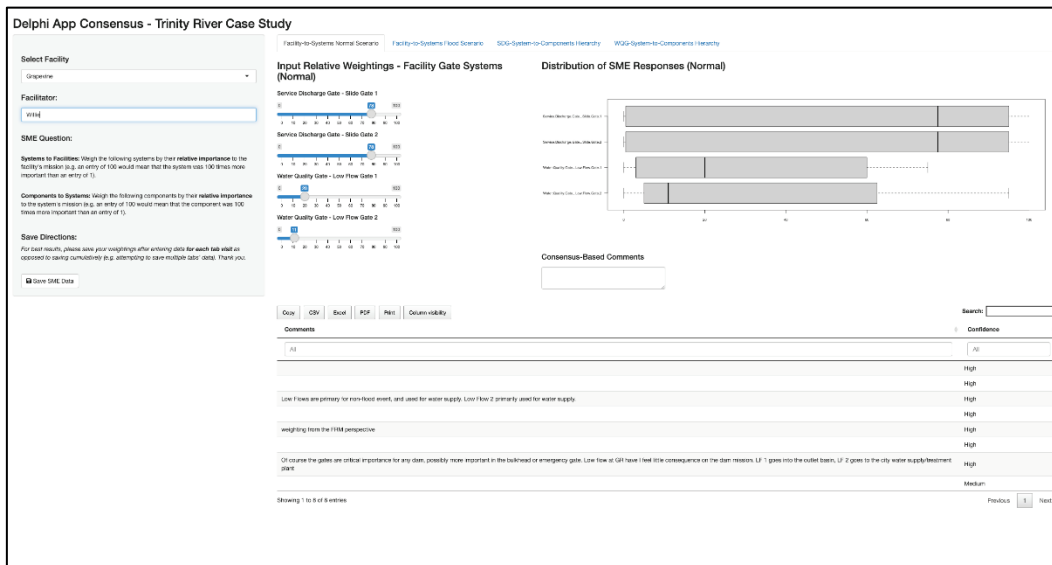
2.4   Consequence development

To generate consequences associated with engineered systems that operate as part of a watershed's FRM System, team members from the IWR made use of simulation models developed using the Hydrologic Engineering Center (HEC) Watershed Assessment Tool (HEC-WAT) (HEC IWR USACE 2017). The models allow for the representation of facilities, engineered systems, down to the gate level, within a watershed system.

2.4.1   HEC-WAT software

HEC-WAT takes precipitation events stored as HEC Data Storage System data records, produces stream flows using the HEC Hydrologic Modeling System (HEC-HMS), calculates reservoir releases using the HEC Reservoir System Simulation (HEC-ResSim), estimates unsteady flood stages using the HEC River Analysis System software, and computes flood damages ($) and life loss using the HEC Flood Impact Analysis software.

2.4.2   Scenario configuration

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. The modelers must also define the environmental conditions under which all experiments will be conducted.

2.4.3   Experimental design

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 a simulation that is feasible to execute within the computational budget of the effort based on the complexity of the system being modeled (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 might 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. Note that if the computational budget and time allow, environmental input variables could be included in the design of experiments as well.

2.4.4 Statistical modeling

Using the consequences generated from each model run as the response variable and each combination of inputs as the independent variables, multivariate statistical modeling methods can be employed to generate a meta-model or surrogate model that provides 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 predicts consequences in dollars as a function of the state of each of the gate systems modeled, the independent variables. While many multivariate methods could be used, if the research team focuses on a multivariate regression model, of the form, $\hat{y} = b_0 + b_1 X_1 + \cdots + b_n X_n$, then the research team can interpret the coefficients of the regression model as the contribution of the gate system to the overall consequences (Rencher and Schaalje 2008). Note that the research 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 research 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 combine 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. The research team considers two cases: (1) consequences only available at facility level and (2) consequences developed through designed computational experiments at gate level.

2.5.1 Case 1: Only facility consequences available

Given the facility, *f*, the systems that compose the facility, *s*, and the components that make up the systems, *c*, the research team can construct a hierarchy that can be used as the basis for a Bayesian network 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 will provide an understanding of the relationships between the systems and the facility's performance and the components and their respective system's performance. The research team will use this SME-elicited information to populate the conditional probability tables. Using this

information, the research team can understand the relative importance of each system to its facility and each component to its system. Initially, given consequences at the facility level, the research team can make use of this information in combination with the relative influence to determine each systems contribution to the overall facility risk and treat this as an upper bound on the risk associated with that system. This could be interpreted as the risk associated with a particular system's failure to function as part of the facility. The research team can apply the same logic at the system-to-component level, where the team can make use of the upper bound on the consequences at the system level and the relative influence of the components on the functioning of the system to determine an upper bound on the risk associated with that component. 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.

2.5.2 Case 2: Consequences resulting from designed experiment

When available, the results of a designed experiment that systematically varies the state of the gate systems and collected 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. This allows the research team to then determine the upper bound on the risk associated with the state of a given gate (system) and then apply the same logic used in Case 1 to map risk down to the component level.

2.5.3 Inference based on state of components

Once the facility model is instantiated as a Bayesian network, and its conditional probability tables initialized, inference about the probability of the facility's operational state based on the condition of its systems and components can be conducted.

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 research 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.

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

The research 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 research 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.

To update the facility risk profile based on the current state of the systems, the research 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, $t, P(S_j = D|C_1 \dots C_n) > t$, 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, $P(F_f = D|S_1 \dots S_j)$. Using this information, the overall risk for the facility, R_f, could be updated, $Con_f P(F_f = D|S_1 \dots S_j)$.

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 research 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 research team can update the probability that the facility is degraded given the state of the systems and combine with consequences as previously discussed.

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

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

$$P(F = D) = P(F = D|S_1 = D)P(S_1 = D) + \cdots P\left(F = D\middle|S_j = D\right)P\left(S_j = D\right)$$

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

2.6   Prioritization model

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 research team formulates the problem as a mixed integer program that seeks to maximize the risk mitigated through the selection of components. To address practical considerations with the execution of condition assessments, the research 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 research team considers two formulations initially: (1) case of a single facility; (2) case with multiple facilities in a single watershed.

2.6.1   Case 1: Single facility

In this case, the research 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.

2.6.2 Case 2: Multiple facilities in the same watershed

In this case, the research team used the model to maximize the risk mitigated by the selection of a limited number of condition assessments across a set of facilities within a watershed. The research team first defined 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.
- NumOCAi,j,l   The number of OCAs required to complete an OCA on all like-type components at a facility.

<u>Variables</u>

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

<u>Formulation</u>

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

<u>Constraints</u>

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

This model would provide the set of components across all facilities that provide 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 were appropriate.

2.7 Summary

This section provided an overview of the methodology, as well as variations on the methodology, that was developed for use in the first case study. 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 overview of the application of this methodology to the JRL facility, the first case study.

3 Case Study: Jennings Randolph Lake (JRL) Results

This section provides an overview of the application of the developed methodology to the JRL case study and a discussion of the results.

3.1 Overview

The first case study for employing these methods was the North Potomac Watershed, where three dams work in series: Mt. Storm, Savage River, and Jennings Randolph. However, the research team focused its efforts on Jennings Randolph because it is the only one managed and operated by the US Army Corps of Engineers (USACE). Jennings Randolph contains three gate systems: spillway gates (5), water quality gates (2), and service discharge gates (2). Figure 10 presents the Jennings Randolph Dam in the context of the North Potomac Watershed.

Figure 10. North Potomac watershed. Each circle represents a dam as documented in the National Inventory of Dams, with the orange circles representing dams on which an OCA is conducted. The bright orange circle in this figure is the JRL.
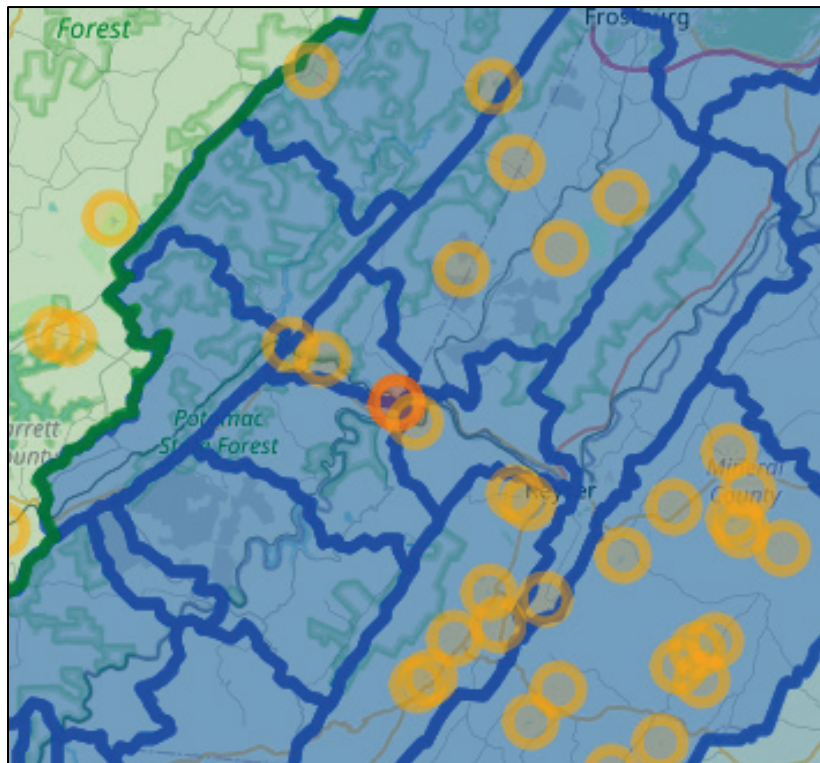
3.2   Data exploration

In the OCA hierarchy, JRL decomposes into 17 unique major systems, with unique 76 sub-systems, and 175 unique components types. Also, the USACE maintenance tracking system, FEM, contains a similar hierarchy along with maintenance actions and criticality scores that indicate the likely impact of the asset's failure on the facility's operation. These scores, or a similar construct, possess the potential to assist in managing the complexity of the problem. The Corps Water Management Systems (CWMS) models also help to define the hierarchical structure of the dam.

Constructing the Jennings Randolph hierarchy was challenging because of differences in structure and nomenclature among these three datasets. The OCA data contains spillway gates and water quality gates, with their corresponding components; the CWMS models contain spillway gates, water quality (QC) gates, and flood gates; and the FEM hierarchy contains all three gate systems without any underlying components. Because this project centers on OCA, the research team used the OCA hierarchy. This presented a few challenges. The differences in nomenclature had to be reconciled by talking to Jennings Randolph staff. Additionally, the absence of service gates in the OCA data forced the research team to build its component list by comparing data across datasets and across like-type facilities in the OCA hierarchy.

Once these systems and components were established, the research team sought to verify the hierarchy with Jennings Randolph staff and found that in addition to errors in the service gate components, there were also errors in the spillway gate and water quality gate components that were copied directly from the authoritative OCA hierarchy (Figure 11). These errors and the differences between datasets highlight the need for a common, accurate asset hierarchy among these and other datasets.

Figure 11. Errors in the JRL OCA hierarchy.
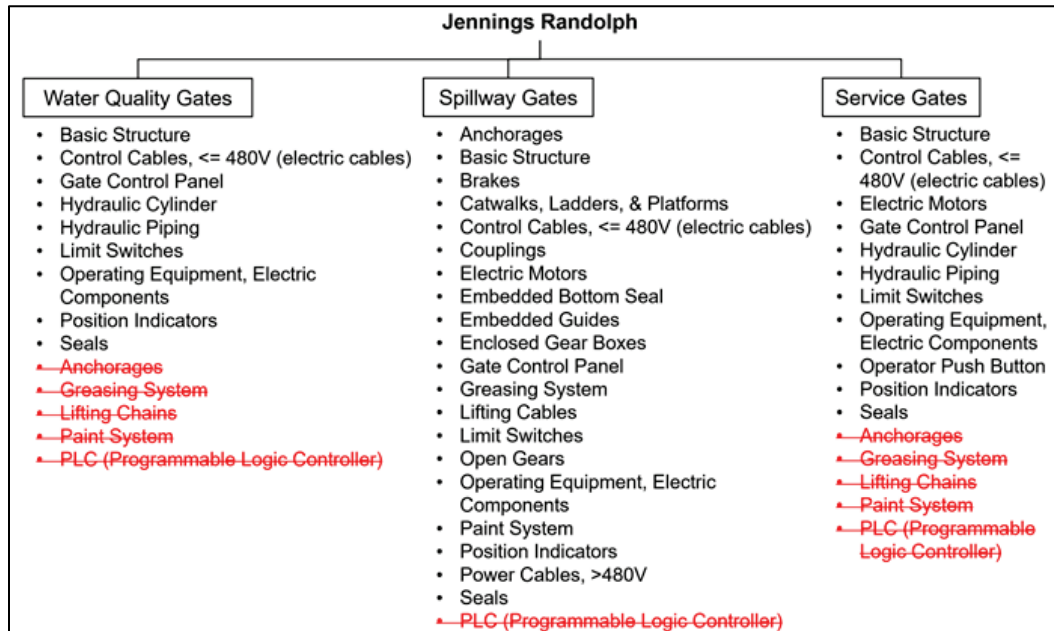
3.3 SME elicitation

The research team conducted the SME elicitation for the JRL as laid out in section 2.3. The USACE Baltimore District identified four SMEs for this case study based on their knowledge and experience with both the dam and flood risk management operations. Two SMEs sit at the district level and are involved in operational condition assessments and flood risk management, and the other two SMEs sit at the actual facility and are involved in its day-to-day operations. Four individual sessions were conducted, one with each SME as well as two group sessions. The research team used the SME spreadsheet elicitation tool outlined in section 2.3.2 to collect the individual data, send that data back out for review, and provide the data and framework for the group discussions. The research team spent approximately 3 hr of contact time with each SME between the individual and group sessions.

3.3.2 Results

The initial individual SME discussions conducted through the modified Delphi method highlighted the need to clearly identify the operating scenarios for the facility since scenarios may change the relative influence of the systems on the facility. Specifically, discussion revealed that flood

conditions increase the relative influence of the spillway gates, which have minimal influence under normal operating conditions since no water runs through them. Under normal operating conditions, the JRL operates solely with the water quality and service gates.

Another insight from the sessions was the benefit of the elicitation process to the JRL facility and Baltimore District staff. The experts stated that the group discussion helped with the shared understanding of the facility condition, maintenance, and operation. Additionally, when the facilitator sought confirmation on the OCA hierarchy, the research team found that some of the components listed in the OCA data do exist at the facility. Discovering this discrepancy greatly improved the quality, but it also benefitted the JRL facility and Baltimore District staff in identifying some errors in the authoritative OCA data.

The spread for the individual SME assignment of relative influence for the system to facility for the two differing operational scenarios, flood and normal operations, at the JRL is shown below (Figure 12). This spread indicates disparate views of the level of relative influence of these systems between the SMEs or a difference in how they interpreted the scenarios.

Figure 12. Case Study 1 individual results for relative influence of systems to facility under flood conditions.
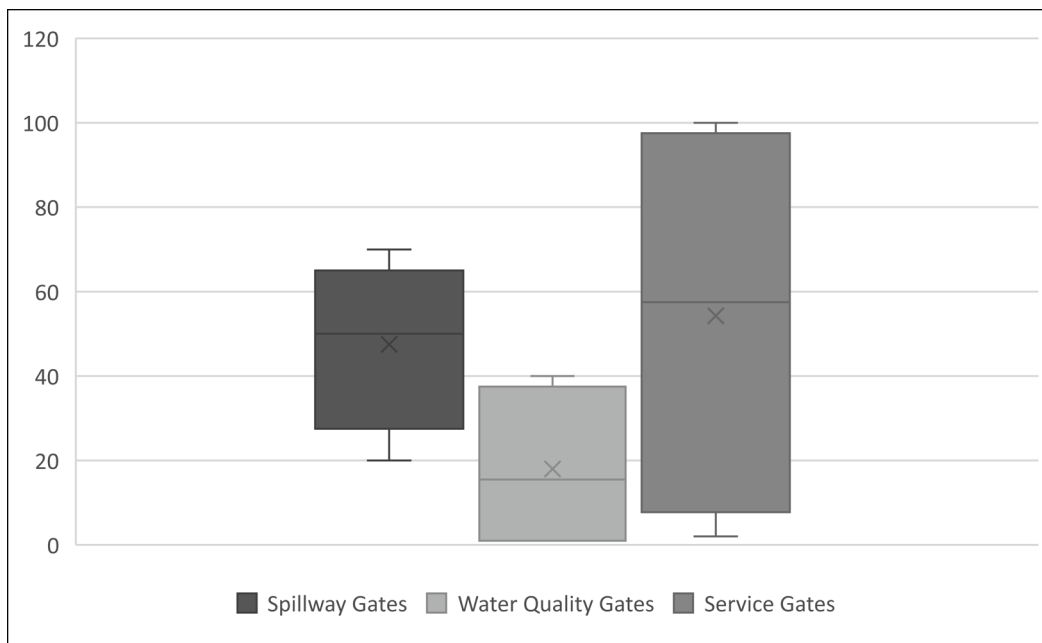
The following data are demonstrative of how the group sessions allow the SMEs to discuss the scenarios and their assignment of the relative influence of each of the systems on the facility under these scenarios. Table 1 shows the individual SME values and the mean values.

Table 1. Aggregated individual elicitation relative influences from Case Study 1 for the relative influence of systems to facility.

System	SME1		SME2		SME3		SME4		Mean	
	Flood	Normal	Flood	Normal	Flood	Normal	Flood	Normal	Flood	Normal
Spillway Gate 1	70	50	20	1	50	50	50	1	47.5	25.5
Spillway Gate 2	70	50	20	1	50	50	50	1	47.5	25.5
Spillway Gate 3	70	50	20	1	50	50	50	1	47.5	25.5
Spillway Gate 4	70	50	20	1	50	50	50	1	47.5	25.5
Spillway Gate 5	70	50	20	1	50	50	50	1	47.5	25.5
Water Quality (QC) Gate 1	40	30	1	10	1	50	30	100	18	47.5
Water Quality (QC) Gate 2	40	30	1	10	1	50	30	100	18	47.5
Service Gate 1	90	80	2	2	25	1	100	80	54.25	40.75
Service Gate 2	90	80	2	2	25	1	100	80	54.25	40.75

The Delphi session resulted in the following values for relative influence at the system-level for both operational scenarios (Table 2). Note that the Delphi session drove discussion that resulted in values other than the median values. This demonstrates the value of the discussions.

Table 2. Consensus relative influences from Case Study 1 for the relative influence of systems to facility.

SYSTEM	CONSENSUS	
	Flood	Normal
Spillway Gate 1	100	1
Spillway Gate 2	100	1
Spillway Gate 3	100	1
Spillway Gate 4	100	1
Spillway Gate 5	100	1
Water Quality (QC) Gate 1	1	75
Water Quality (QC) Gate 2	1	75
Service Gate 1	20	70
Service Gate 2	20	70

Finally, the process produced excellent consensus. All SMEs indicated that they agreed or strongly agreed with all the group consensus assigned values of relative influence for each of the systems on the facility and for all the components on each of their respective systems. 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 amongst the SMEs for the assignment of relative influence at the end of the process.

3.4   Initializing Bayesian networks

The relative influence information collected during the SME elicitation was leveraged to populate the conditional probability tables required to instantiate the Bayesian network model following the methodology laid out by Hassall et al. (2019). Figure 13 illustrates how the JRL facility decomposes into the gate systems under consideration in Case Study 1.

Figure 13. Diagram of facility to system levels for JRL.
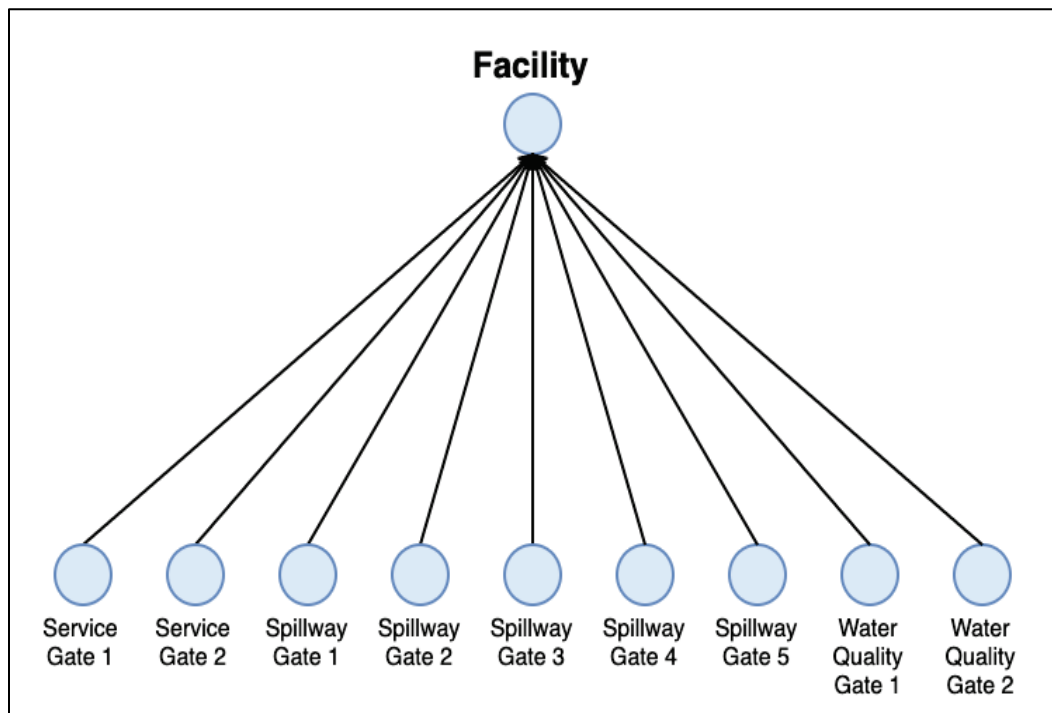
Continuing the case from section 3.3 above, the research team then normalized these values between 0 and 1 (Table 3).

Table 3. Normalized consensus relative influences from Case Study 1 for the relative influence of systems to facility.

SYSTEM	NORMALIZED CONSENSUS	
	Flood	Normal
Spillway Gate 1	0.1845	0.0034
Spillway Gate 2	0.1845	0.0034
Spillway Gate 3	0.1845	0.0034
Spillway Gate 4	0.1845	0.0034
Spillway Gate 5	0.1845	0.0034
Water Quality (QC) Gate 1	0.0018	0.2542
Water Quality (QC) Gate 2	0.0018	0.2542
Service Gate 1	0.0369	0.2373
Service Gate 2	0.0369	0.2373

The conditional probability tables are initialized via the method of Hassall, et al. (2019) as described in section 2.2.

Using these normalized weights, and given an assumption of two states for system operational capability, the research team generated the conditional probability tables for the system level. The rows of this table give the probability of facility failure given particular conditions for the facility gate systems, as is illustrated below. The calculation of individual scores and the creation of a conditional probability were scripted in the R programming language to allow for automated construction of conditional probability tables.

Now that the research team has the data prepared and the conditional probability tables populated, the research team can make use of this information for inference about the state of the facility. In the following example, the research team determines the probability that the facility is operational given the state of its gates, $P(F=O|S_1,S_2,...,S_9)$.

$$P(F = O \mid 1,0,0,0,0,0,0,0,0,0)_{FLOOD} \approx \frac{\sum_i w_i \, P_{i\{1,0,0,0,0,0,0,0,0,0\}}}{\sum_i w_i}$$

$$\approx 0.1845 * \left(\frac{2-1}{2-1}\right) + \sum_{i=2}^{5} 0.1845 * \left(\frac{1-1}{2-1}\right)$$

$$+ \sum_{i=6}^{7} 0.002 * \left(\frac{1-1}{2-1}\right) + \sum_{i=8}^{9} 0.0369 * \left(\frac{1-1}{2-1}\right)$$

$$\approx 0.1845$$

That is, if only spillway gate #1 is operational at the Case Study 1 facility, there is only an 18% chance of that facility being operationally sufficient to handle a 100 yr flood event.

To make use of this information in the determination of risk, the research team must combine the probability that the facility is operationally sufficient to handle a 100 yr flood event with the consequences to the watershed if the facility is incapable of handling a 100 yr flood event. The next section discusses the development of consequences using the CWMS models.

3.5   Developing consequences

3.5.1   Scenario configuration

To determine a gate outage method, an initial test was set up for an already existing HEC-WAT model in the North Branch Potomac basin, which contains one USACE dam, Jennings Randolph. The 24 hr, 100 yr precipitation event was used in this initial test of the Jennings Randolph dam. The basin average and spatial distribution of this 24 hr, 100 yr event were estimated using National Oceanic and Atmospheric Administration (NOAA) Atlas frequency analysis gridded data (https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_gis.html). The NOAA Atlas data were summarized into total basin and sub-basin precipitation depths. Historical Livneh gridded precipitation data were used to estimate the areal reduction of the NOAA Atlas basin and sub-basin 100 yr event averages (https://psl.noaa.gov/data/gridded/data.livneh.html).

It was also necessary to disaggregate the 24 hr total precipitation into hourly values to run through the HEC-WAT model. The most extreme front-loaded temporal distribution (most precipitation falling with first 6 hr of event) was selected from the NOAA Atlas 14 precipitation temporal distributions. A front-loaded hyetograph was chosen to mimic a situation where the peak inflow occurs early in the event, blowing out

selected gates, causing uncontrolled outflow from the reservoir for a large portion of the event. Once the precipitation event(s) and their temporal distribution were defined, they were input to the HMS model within the HEC-WAT model. Figure 14 shows the hourly distribution of precipitation for the 24 hr, 100 yr test event.

Figure 14. Hourly distribution of precipitation for the 24 hr, 100 yr test event run through the North Branch Potomac basin. Each line represents the hourly precipitation at a sub-basin within the larger North Branch Potomac basin. The overall basin average precipitation was 5.4 in.
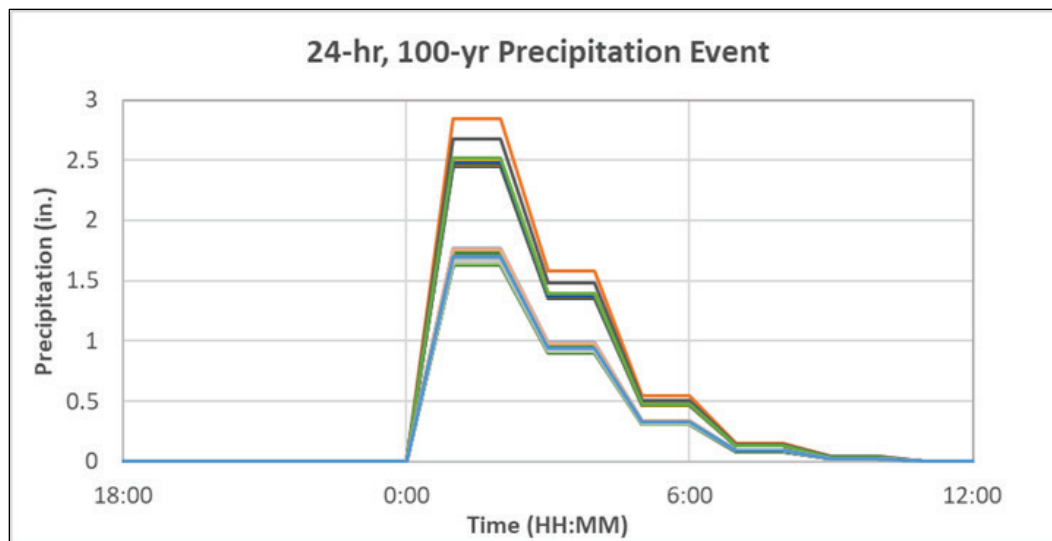
Once the precipitation event was defined, the gate outage scenarios were selected and modeled in HEC-ResSim. After some initial testing, a gate outage was defined as a gate that has blown out (i.e., breaks and floats down the river, leaving a hole in the dam for uncontrolled flow) at the time of peak inflow. This initial definition of a gate outage was selected as it was found to be the most damaging type of outage when (1) looking at an isolated event and (2) evaluating consequences based on downstream damages and life loss.

3.5.2 Experimental design

The research team used a full factorial design that explored all combinations of gates functional status. A total of 54 gate outage alternatives were defined for the Jennings Randolph Dam, which represent all possible combination of the two water quality, two flood, and five tainter gates located in the dam. All 54 alternatives were run through the North Branch Potomac HEC-WAT model to determine

downstream flood damages ($) and life loss associated with each gate outage combination.

These were the initial assumptions:

- Gate failure occurs at peak inflow to reservoir or reservoir system.
- Gate failure occurs as gate blow out (i.e., uncontrolled flow out of gate area).
- The non-USACE dams in the system were assumed to be operating normally under all Jennings Randolph gate outage alternatives.

3.5.3   Analysis of results

Using the data generated by the designed experiment, the research team employed multiple regression to develop a statistical model of consequences based on status of the gates. The model predicts the magnitude of consequences in the watershed based on the setting of the gates, operational or non-operational, and allows the research team to identify the contribution of each gate to the consequences to the watershed — the primary objective of this modeling effort. The research team made use of the R statistical programming language to conduct the analysis (R Core Team 2021). The modeling team explored the inclusion of interaction and higher order terms in the model, but the model performance was not improved enough to justify the added complexity and impact on interpretation. The resulting model accounted for 95% of the variance in the response and satisfied appropriate assumptions (Rencher and Schaalje 2008).

The research team can make use of this model to provide estimates, with confidence intervals, of the consequences to the watershed of various combinations of gate states. The research team can also make use of the model to estimate magnitude of the consequences for each gate at the facility. The consequences for each gate state with associated standard errors are included in Figure 15. Note that for each gate type, number of gates operational is indicated by the trailing number on each label. Quality control gates were represented as a single gate in the model. Figure 15 also shows that the number of consequences avoided is highest when all five tainter gates are operational. If all gates of all types are non-operational, then the consequences realized would be equivalent to the intercept.

Figure 15. Coefficients of regression model with confidence interval.
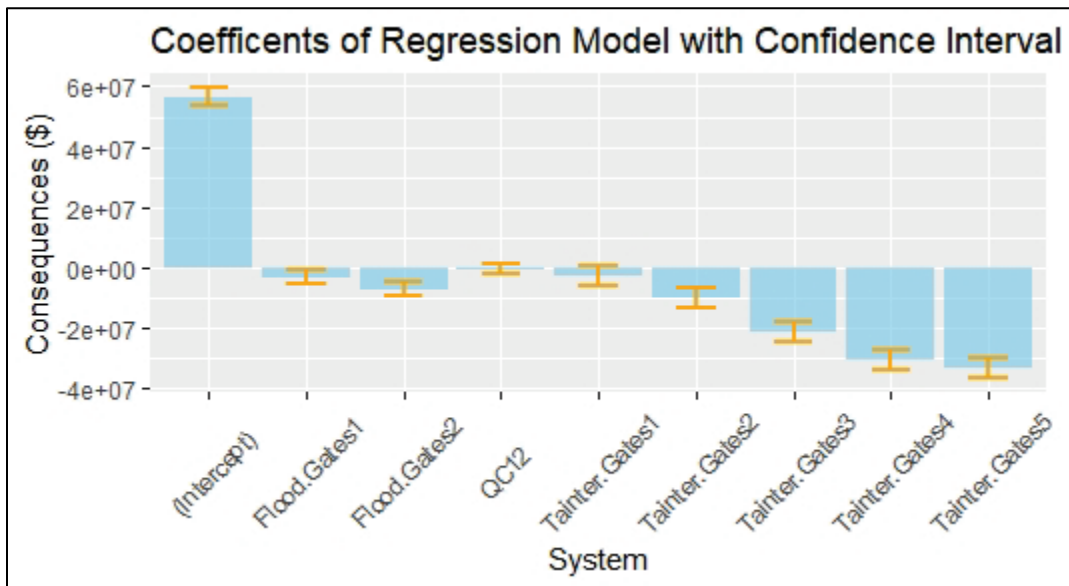
3.5.4   Insights

Under the conditions explored through the designed experiment, the state of the tainter gates had the greatest impact on consequences, followed by flood gates and then quality control gates. Note that the scenario conditions explored were representative of the "flood" scenario used as a prompt for SME elicitation. When the research team compares the normalized relative weights provided by experts for each of the gate systems to the coefficients generated by the statistical model, the research team finds that they are strongly correlated (0.99), indicating agreement between the experts and the model. This opens the possibility of making use of SME input to gage the relative importance of systems to a facilities operation combined with consequences at the facility level as a credible approach for those facilities where detailed CWMS models might not yet exist. This has implications for the scalability of this approach.

3.6   Prioritizing by risk

To employ prioritization frameworks, such as the optimization models described in section 2.6, the research team must combine the likelihood of failure derived from SME input with estimates of consequences developed from the output of simulation models.

3.6.1 Developing risk scores

The research team examines two cases for developing risk scores: (1) where consequences are available only at the facility level; (2) where consequences are available at the gate level.

3.6.1.1 Case 1: Facility consequences

Using SME-elicited relative weights, the research team can understand the relative importance of each system to its facility and each component to its system. Initially, given only consequences at the facility level, the research team can make use of this information in combination with the relative influence to determine each systems contribution to the overall facility risk and treat this as an upper bound on the risk associated with that system. This yields a set of weights associated with both normal and flood conditions (Figure 16).

Figure 16. Comparison of normalized gate system relative influence weights by scenario.
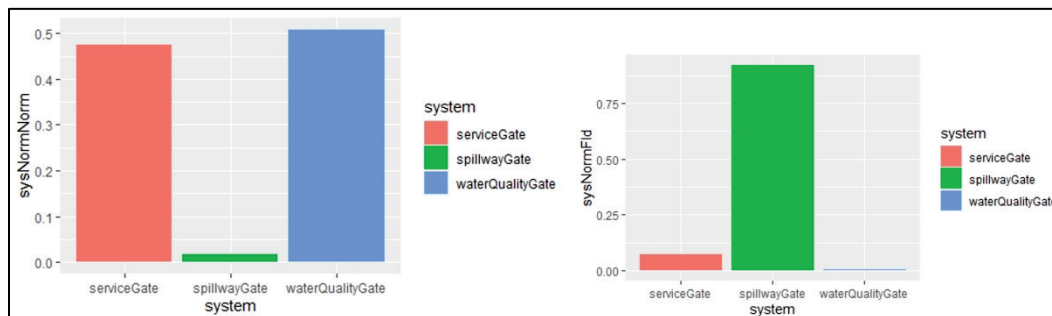
The research team can then make use of these weights combined with the facility estimated consequences (Figure 17) to develop an upper bound on the consequences associated with each system (accounting for the number of each type of system and spreading the consequences out in a linear manner).

Figure 17. Illustrative example of risk mitigation calculation, where risk is the probability of degradation multiplied by facility consequences (in this case, $100,000).

System 1			System 1					
Component Name	Normalized Relative Influence		Comb.	C1	C2	C3	P(Degradation)	Risk
Component 1	$1/8 \approx 0.125$		1	1	0	0	0.125	12.5
Component 2	$4/8 \approx 0.5$		2	0	1	0	0.5	50
Component 3	$3/8 \approx 0.375$		3	0	0	1	0.375	37.5
			4	1	1	0	0.625	62.5
			5	1	0	1	0.5	50
			6	0	1	1	0.875	87.5
			7	1	1	1	1	100

The research team can then use the normalized relative weights of the components of each system to determine the risk associated with each component (Figure 18).

Figure 18. Example of normalized relative weights and risk associated with each component of the Water Quality (QC) Gate #1.

SYSTEM	NORMALIZED RELATIVE WEIGHTS
Spillway Gate 1	0.0034
Spillway Gate 2	0.0034
Spillway Gate 3	0.0034
Spillway Gate 4	0.0034
Spillway Gate 5	0.0034
Water Quality (QC) Gate 1	0.2542
Water Quality (QC) Gate 2	0.2542
Service Gate 1	0.2373
Service Gate 2	0.2373

WATER QUALITY (QC) GATE		
COMPONENT	NORMALIZED RELATIVE INFLUENCE	RISK ($)
Basic Structure	0.166	3,398,758
Control Cables, <=480V (electric cables)	0.166	3,398,758
Gate Control Panel	0.155	3,172,175
Limit Switches	0.002	45,317
Operating Equipment, Electric Components	0.166	3,398,758
Position Indicators	0.002	45,317
Seals	0.011	226,584
Hydraulic Cylinder	0.166	3,398,758
Hydraulic Piping	0.166	3,398,758

3.6.1.2 Case 2: Leveraging results of gate level design of experiments

In this case, the risk calculation starts with gate-level estimates of the consequences associated with each system of the facility (Figure 19) and makes use of the relative weights elicited for the components to arrive at their contribution to system risk.

Figure 19. Example of regression coefficients and risk associated with each component of the Water Quality (QC) Gates.

REGRESSION MODEL COEFFICIENT	VALUE
Tainter (Spillway) Gate 1	2,982,197
Tainter (Spillway) Gate 2	10,121,459
Tainter (Spillway) Gate 3	21,343,254
Tainter (Spillway) Gate 4	30,973,696
Tainter (Spillway) Gate 5	33,625,995
Water Quality (QC) Gates 1 & 2	713,839
Service (Flood) Gate 1	3,611,850
Service (Flood) Gate 2	7,576,948
Intercept	-56,575,505

WATER QUALITY (QC) GATE		
COMPONENT	NORMALIZED RELATIVE INFLUENCE	RISK ($)
Basic Structure	0.166	118,497
Control Cables, <=480V (electric cables)	0.166	118,497
Gate Control Panel	0.155	110,645
Limit Switches	0.002	1,428
Operating Equipment, Electric Components	0.166	118,497
Position Indicators	0.002	1,428
Seals	0.011	7,852
Hydraulic Cylinder	0.166	118,497
Hydraulic Piping	0.166	118,497

With the use of a statistical model to generate these estimated consequences, the research team can also provide an estimate of the uncertainty. For the purposes of this case study, the research team makes use of only point estimates but plans to incorporate uncertainty into future work.

3.6.2 Initial prioritization

With the estimated risk scores for each component determined, the research team can make use of the optimization model formulated in section 2.6 and implemented using the lpsolve package within R statistical programming language to determine the optimal set of components to conduct OCAs on to maximize risk mitigation.

An illustrative example of the mixed integer program output is provided in Table 4. In this table, the red cells indicate component selection under the "Flood" decision frame, tan cells indicate component selection under the "Normal" decision frame, and green cells indicate component selection.

Table 4. Illustrative example of mixed integer program output with a maximum budget/restriction of 24 OCA selections.

KEY:	
COMPONENT PRIORITIZE IN "NORMAL" DECISION FRAME	
COMPONENT PRIORITIZED IN "FLOOD" DECISION FRAME	MAXIMUM OCAs SELECTED
COMPONENT PRIORITIZED IN BOTH DECISION FRAMES'	24

	Component	Selected
SPILLWAY GATES	Anchorages	
	Basic Structure	
	Control Cables, <=480V (Electric Cables)	red
	Electric Motors	
	Gate Control Panel	
	Lifting Cables	
	Operating Equipment, Electric Components	red
	Power Cable, > 480V	
	Brakes	
	Couplings	red
	Enclosed Gear Boxes	red
	Open Gears	
WATER QUALITY (QC) GATES	Basic Structure	tan
	Control Cables, <=480V (electric cables)	tan
	Gate Control Panel	tan
	Limit Switches	
	Operating Equipment, Electric Components	tan
	Position Indicators	
	Seals	
	Hydraulic Cylinder	
	Hydraulic Piping	tan
SERVICE (FLOOD) GATES	Basic Structure	
	Control Cables, <=480V (electric cables)	tan
	Electric Motors	tan
	Gate Control Panel	
	Seals	
	Operating Equipment, Electric Components	tan
	Hydraulic Cylinder	
	Hydraulic Piping	green
	Position Indicators	
	Limit Switches	
	Operator Push Button	red
RISK MITIGATED: FLOOD (IN MILLIONS $ U.S.)		12.51
RISK MITIGATED: NORMAL (IN MILLIONS $ U.S.)		8.63

The difference in decision frame relative influence of each system on the facility is demonstrated by the output data, with only one system component overlapping between decision frames. Namely, the "Flood" decision frame emphasizes the "Spillway Gates" as most important, "Service/Flood Gates" as moderately important, and "Water Quality (QC) Gates" as least important. The "Normal" decision frame, in this case, inverts system importance and, consequently, the choice of system components for OCA assessment.

3.6.3 Sensitivity analysis

Illustrative results are presented to indicate differing component selection and risk mitigation when using two SME-elicited decision frames — "Normal" operating conditions and "Flood" operating conditions (Table 5 and Figure 20). Assuming that component selection is for all similar type gates within the facility, appropriate *penalties* were applied to each component. That is, a spillway gate component would have its selection cost multiplied by five since there are five spillway gates at the facility. Similar penalties were applied to components from the two water quality gates and two service gates.

Table 5. Results of optimization model to maximize risk mitigation. Components-level selections are made across three gates systems at the facility. Red cells indicate components selected by the SME in the "Flood" scenario, yellow cells indicate components selected by the SME in the "Normal" scenario, and green cells indicate components selected by both scenarios.

Figure 20. Risk mitigated by scenario with increased condition assessments. Far more resources are required to mitigate the maximum amount of risk in the "Flood" scenario as compared to the "Normal" scenario.
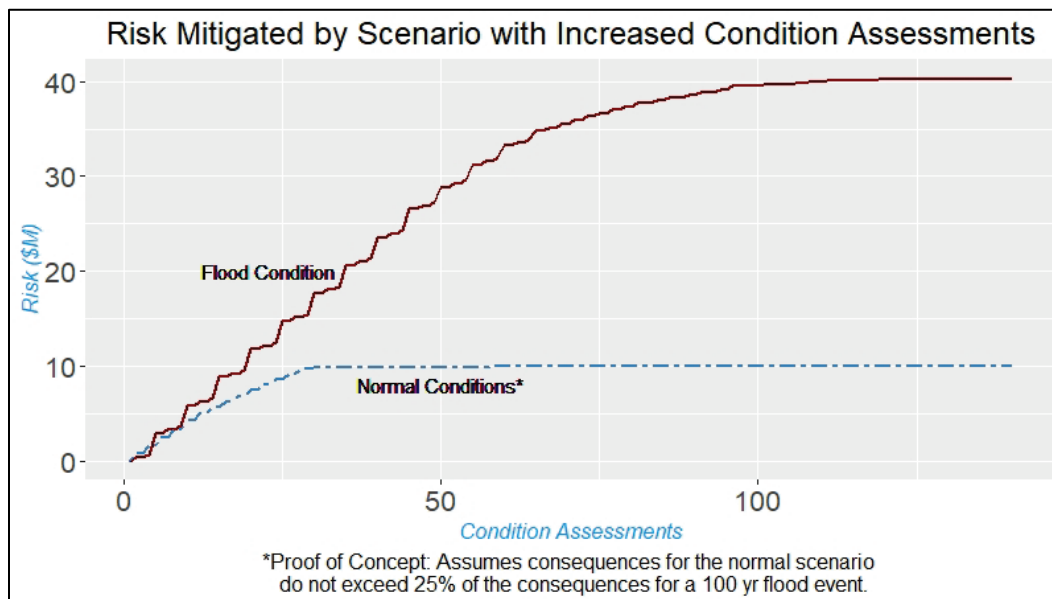
To mitigate risk in a resource-constrained environment, this approach allows decision makers to identify the optimal set of components to invest in. There are 57 components identified in the OCA database across the three gate types (service, water quality, and spillway) at JRL. This methodology determined that if resources are constrained and not all the components are able to be assessed, risk can still be mitigated with a small subset of components. In this case, while the "Flood" scenario prioritized the spillway gates (in accordance with the weights given by SMEs), with more components in the spillway gates, the mitigated risk is lower per selected component. These results contrast with the "Normal" scenario that prioritized the water quality and service gates, giving them greater impact on mitigated risk per component selected due to a smaller number of components in those systems. Exploration of the decision trade space confirms that the choice of scenario greatly affects decision-making capabilities and influences risk mitigation for smaller numbers of OCAs. The mitigated risk under the "Normal" scenario, however, greatly outpaces the mitigated risk under the "Flood" scenario despite the prioritization of less essential component. To appropriately reflect the risk mitigation under the "Normal" scenario, a scaling factor was introduced to penalize the total risk mitigated by maintaining systems and components prioritized under normal operating conditions. For the results presented in Figure 20, the research team used a notional scaling factor of 0.25 for

the "Normal" scenario. This resulted in the risk mitigation under the "Normal" scenario plateauing after approximately 30 OCA selections; however, the risk mitigated for the same number of components selected under the "Flood" scenario decision frame does not start to plateau until there are over 100 OCA selections. Figure 20 also illustrates the lower resource burden in achieving near maximal risk mitigation for the "Normal" scenario versus the "Flood" scenario, though the decreased resource burden comes with a decreased ceiling for mitigated risk. Ultimately, this approach allows decision makers to identify the optimal set of components to allocate their resources against to mitigate risk in a given scenario.

3.7   Summary of Jennings Randolph Lake (JRL) case study

The research team conducted the proof-of-concept case study on a section of the North Potomac watershed, including the JRL, Mt. Savage, and Mt. Storm facilities. This section of watershed was selected to facilitate collaboration with the IWR and leverage its existing CWMS models. Since the Mt. Savage and Mt. Storm facilities are not USACE facilities, the research team does not have access to their component information. They are therefore modeled at a lower resolution, with no representation of gate system or their impact on the flow of water. The third facility, JRL, a USACE facility, has detailed system and components data available within the OCA and FEM data. The environmental conditions explored within the CWMS models are also limited to a manageable data set to prove the methodology.

4   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. In the absence of empirical failure 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. OCA data and FEM data provide the two primary sources of component and system assessment and maintenance data to develop the conceptual model of the facility, the condition of its components, and to determine events that occur at the facility over time, but challenges exist in integrating these two data sources. Therefore, the research team relied on SME elicitation to understand the data and the relationships between the components and systems and between systems and facility. Some key outcomes are the following:

- Modeling Methodology. This research developed methodology and support 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.
- Case Study 1. Case study 1 results illustrate the application of the methodology to a single facility within the North Potomac River watershed, which contains one USACE facility: JRL. The research team elicited the relative influence of the gate systems on facility performance and the relative influence of the components on gate systems' performance. Using that information, the research team populated conditional probability tables and combined that data with consequence-of-failure data from the CWMS models to calculate risk scores for each component of the gate systems. For both flood and normal operating conditions scenarios, the research team used a mixed-integer program to prioritize components based on risk. The research team also developed an Exploratory Data Analysis tool to better understand the data and identify data gaps, and USACE employees can access this tool via an internet browser.
- Case Study 2. In collaboration with the IWR, the research team identified the Trinity River sub-basin as the second case study. This

section of the watershed contains three USACE facilities: Ray Roberts Lake, Lewisville Lake, and Grapevine Lake. These facilities have high-quality OCA data, FEM data, and CWMS models. The research team has begun eliciting the relative influence ratings from district and facility personnel as in Case Study 1. However, to improve scalability, the research team developed a data collection tool accessible via an internet browser where SMEs provided their initial system and component relative influence weights. Also, the research team is working with IWR and the HEC to generate consequence-of-failure data. Last, the research team is developing a prioritization application that stakeholders can access via their browser where they will be able perform what-if exercises regarding the impact of non-operational gates and components on flood risk.

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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."
- Sub-system – In the OCA hierarchy, "sub-systems" 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: Subject Matter Expert Elicitation Materials

Stage 1: This data collection tool was generated from the OCA database for the JRL facility used to collect SME answers to Question 1 to verify that the systems and components identified in the OCA database for the facility were correct, assign relative a relative influence for each system on the facility and each component on the system and visualize the differences in the influences (Figure 21), and identify common terms used by the experts when describing likelihood a system or component is operating as intended (Figure 22).

Figure 21. Individual SME data collection tool for Case Study 1 for Questions 1 and 2 (System to Facility Relative Influence).

Figure 22. Individual SME data collection tool
for Case Study 1 for Question 3
(common failure terms).

What are some common terms that are used to describe the likelihood a system is operating as intended? Can you rank order these terms?

TERMS
01. Inoperable
02.
03.
04.
05. Fully Operational

Stage 2: The data collection tool displayed an anonymized summary of the SME input from the individual sessions both numerically and graphically and provided room to collect the consensus values for relative influence (Figure 23). After the consensus data were collected, the experts stated their level of agreement with the consensus ratings and provided any differing ratings using Figure 24.

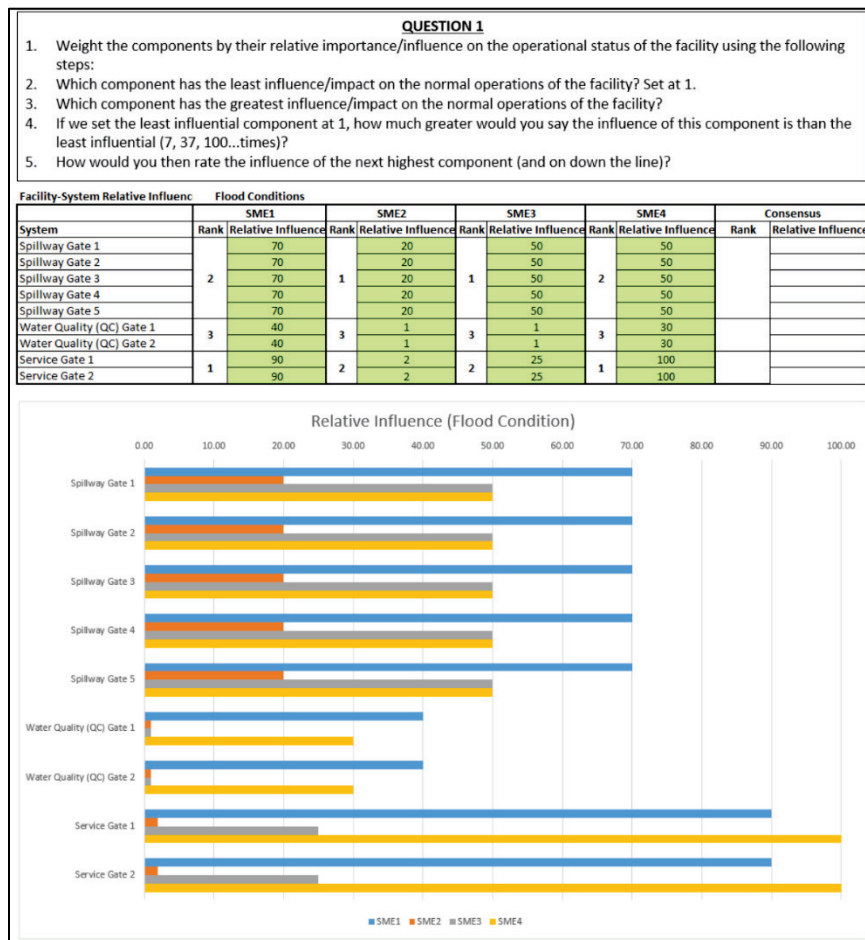Figure 23. Group discussion SME data collection tool for Case Study 1.

QUESTION 1

1. Weight the components by their relative importance/influence on the operational status of the facility using the following steps:
2. Which component has the least influence/impact on the normal operations of the facility? Set at 1.
3. Which component has the greatest influence/impact on the normal operations of the facility?
4. If we set the least influential component at 1, how much greater would you say the influence of this component is than the least influential (7, 37, 100…times)?
5. How would you then rate the influence of the next highest component (and on down the line)?

Facility-System Relative Influenc   Flood Conditions

System	SME1 Rank	SME1 Relative Influence	SME2 Rank	SME2 Relative Influence	SME3 Rank	SME3 Relative Influence	SME4 Rank	SME4 Relative Influence	Consensus Rank	Consensus Relative Influence
Spillway Gate 1		70		20		50		50		
Spillway Gate 2		70		20		50		50		
Spillway Gate 3	2	70	1	20	1	50	2	50		
Spillway Gate 4		70		20		50		50		
Spillway Gate 5		70		20		50		50		
Water Quality (QC) Gate 1	3	40	3	1	3	1	3	30		
Water Quality (QC) Gate 2		40		1		1		30		
Service Gate 1	1	90	2	2	2	25	1	100		
Service Gate 2		90		2		25		100		

Relative Influence (Flood Condition)

Figure 24. SME data collection tool for individual level of agreement and re-vote.

Case Study 1 Individual Session

Good afternoon. We thank you so much for your time in assisting us with this research project. The overall goal of the project is to investigate how the OCA and FEM data may be utilized to inform a risk-based decision process on resource allocation in the maintenance of various USACE facilities.

The JRL is the initial facility we are working with to develop our methodology. The intent of today's discussion is to identify your assessment of the relative influence of the systems and components identified in the OCA hierarchy for the operation of the JRL facility.

To align with the CWMS consequence modeling effort being conducted with the EL and IWR, we are going to look at JRL at two levels, how several specific systems (the spillway, service, and water quality gates) influence the operation of the entire facility, and how the individual components identified in the OCA influence each of their associated systems. Level of operation of the facility based on the operating condition of the system.

Structured elicitation method that will take about 45–60 minutes to gather specific information that will allow the research team to determine relative importance/influence of the systems and components within the facility.

We are interested in how you would weigh the relative influence of each of the gate systems on the normal operational status of the facility with components functional.

Facility-System Tab

The first layer we will discuss is how the spillway, service, and water quality gate systems influence the overall facility operation.

QUESTION 1

We are interested in how you would weigh the relative influence of each of the gate systems on the normal operational status of the facility.

1) So, to start off, which system has the least influence/impact on the normal operations of the facility? Set at 1.
2) Which system has the greatest influence/impact on the normal operations of the facility?
3) 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)?
4) How would you then rate the influence of the next highest system (and on down the line)?

For components with the same influence, confirm that they both are equally important/influential.

Review the bar graph to confirm the relative influence numbers align with their thought process. Does the relative scale agree?

Two scenarios (normal operations vs. high water/flood operations) — would the numbers change?

QUESTION 2

Is the list of systems that support facility operations correct? If not, are there unnecessary systems included? Are there systems that should be added?

Now, for each of the 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. As part of this discussion, we also would appreciate your input on if the list of components that support system operations is correct. If not, are there unnecessary components included? Are there components that should be added?

Spillway Gate-Component Tab

Water Quality-Component Tab

Service Gate-Component Tab

Case Study 1 Group Discussion

Good afternoon. We thank you so much for your time in assisting us with this research project. We appreciated the opportunity to meet with you individually to discuss the relative influence of systems on the facility and components on the systems. The discussions were extremely helpful in our understanding of the JRL facility.

The next step in our structured elicitation. Today, we will go over the results of the elicitation to this point as well as start to come to consensus on the relative influence for the various systems and components. Depending on how the discussion goes, we anticipate this taking an additional session.

Facility-System Flood Operations Tab

Based on your input, we've decided to consider the system to facility relationship in both normal operations and a high water/flood event and how the spillway, service, and water quality gate systems influence the overall facility operation.

QUESTION 1

Here are the results from your feedback on relative influence in flood operations. You all indicated that the Water Quality Gates would have the least influence, but had varying degrees of influence, as show in the bar graph on the left below the table.

To provide consistency, we'd like to set that at 1, so we can base the other gates off that system. Also, since you all indicated that they typically operate in tandem, we'll give the gates the same relative influence of 1. We'll be able to visualize how our consensus on the relative influence in the bar graph to the right.

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.

Now, there was a split between which of the gate systems had the most influence on the facility operations in a flood/high water event. I would like to come to consensus on which has the greater influence, the spillway or service gates, and would like to open up the discussion, but to frame it better, let's assume that the water is high enough in the lake that the spillway gates do need to be activated.

Now let's assign relative values. Since we used 1 for the water quality gates with the least influence, where would we put the relative influence of the xx gates? And the xx gates?

We are interested in how you would weigh the relative influence of each of the gate systems on the normal operational status of the facility.

1. So, to start off, which system has the least influence/impact on the normal operations of the facility? Set at 1.
2. Which system has the greatest influence/impact on the normal operations of the facility?
3. 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)?

4. How would you then rate the influence of the next highest system (and on down the line)?

For components with the same influence, confirm that they both are equally important/influential.

Review the bar graph to confirm the relative influence numbers align with their thought process. Does the relative scale agree?

Facility-System Normal Operations Tab

For the normal operations, we had a bit more dispersion on the rankings of the systems. Let's first come to consensus on the rankings, then we can fill in the relative weights. Again, after today's discussion, you will have the opportunity to indicate your level of agreement with the results of our discussion.

Two of the four of you indicated that the Spillway gates have the least amount of influence on normal operations. Again, this assumes typical, non-flood or high-water events. Does this change the ranking or can we come to consensus?

Three of the four of you indicated Water Quality Gates had the greatest amount of influence on normal operations. Again, this assumes typical, non-flood or high-water events. Does this change the ranking or can we come to consensus?

Now let's assign relative values. If we use 1 for the gates with the least influence, where would we put the relative influence of the xx gates? And the xx gates?

Before we go through the same exercises with the relationships of the components to the gate systems, we found that there were some components 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 by 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.

Water Quality-Component Tab

Let's start with the Water Quality Gates. There is consensus that there are not any lifting chains. Two of the three indicated there is not any paint (stainless steel?). Let's start with those then work through some of the other components.

One each indicated there was not a greasing system, limit switches, anchorages, PLC, or hydraulic piping. Let's come to consensus on these components.

Service Gate-Component Tab

Let's next go to the Service Gates. There is consensus that there are not any lifting chains. Two of the three indicated there is not any paint (stainless steel?), embedded guides, or enclosed gear boxes. Let's start with those then work through some of the other components.

One person each indicated embedded bottom seal, limit switches, anchorages, hydraulic hoses, PLC and Operator Push button.

Spillway Gate-Component Tab

Finally, let's finish up with the Spillway Gates. The only component noted that might not be present is the PLC.

Great, that's a good place to stop for today. We will send out the following spreadsheet

NOTE: The data from the previous group meeting is included in the additional tabs. There is NO work you need to do with those tabs; they are only there for your reference/information. This tab is the only one that we are requesting your input.

We ask you to do 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 with update the rankings for you.

The other tabs will be the results of the past two discussions, but no work will need to be done on those tabs. They are just for your reference.

Appendix C: Experimental Design Table

Number of Gates Operable			WAT Identifier	100 yr Event Consequences	
Water Quality Gates	Flood Gates	Tainter Gates	Stuck OPEN	Damages ($)	Life Loss
0	0	0	Q0F0T0_up	53,052,280	2.58
1	0	0	Q1F0T0_up	53,056,864	2.58
2	0	0	Q2F0T0_up	53,136,968	2.58
0	1	0	Q0F1T0_up	53,230,544	2.58
1	1	0	Q1F1T0_up	53,211,188	2.58
2	1	0	Q2F1T0_up	53,141,420	2.58
0	2	0	Q0F2T0_up	51,419,252	2.56
1	2	0	Q1F2T0_up	51,230,632	2.56
2	2	0	Q2F2T0_up	50,953,452	2.56
0	0	1	Q0F0T1_up	53,051,644	2.58
1	0	1	Q1F0T1_up	53,056,864	2.58
2	0	1	Q2F0T1_up	53,107,768	2.58
0	1	1	Q0F1T1_up	50,595,776	2.55
1	1	1	Q1F1T1_up	50,307,656	2.55
2	1	1	Q2F1T1_up	49,990,416	2.55
0	2	1	Q0F2T1_up	45,534,328	2.54
1	2	1	Q1F2T1_up	45,152,076	2.54
2	2	1	Q2F2T1_up	44,760,804	2.54
0	0	2	Q0F0T2_up	52,266,980	2.56
1	0	2	Q1F0T2_up	48,971,888	2.54
2	0	2	Q2F0T2_up	46,936,708	2.54
0	1	2	Q0F1T2_up	42,885,512	2.54
1	1	2	Q1F1T2_up	42,442,436	2.54
2	1	2	Q2F1T2_up	41,969,048	2.54
0	2	2	Q0F2T2_up	35,461,680	2.52
1	2	2	Q1F2T2_up	35,090,104	2.52
2	2	2	Q2F2T2_up	34,685,232	2.52
0	0	3	Q0F0T3_up	39,528,420	2.54
1	0	3	Q1F0T3_up	38,908,996	2.52
2	0	3	Q2F0T3_up	38,260,588	2.52
0	1	3	Q0F1T3_up	31,188,622	2.45

Number of Gates Operable			WAT Identifier	100 yr Event Consequences	
Water Quality Gates	Flood Gates	Tainter Gates	Stuck OPEN	Damages ($)	Life Loss
1	1	3	Q1F1T3_up	30,672,632	2.45
2	1	3	Q2F1T3_up	30,171,546	2.45
0	2	3	Q0F2T3_up	23,966,202	2.20
1	2	3	Q1F2T3_up	23,869,846	2.20
2	2	3	Q2F2T3_up	23,759,014	2.20
0	0	4	Q0F0T4_up	25,001,124	2.20
1	0	4	Q1F0T4_up	24,475,508	2.20
2	0	4	Q2F0T4_up	24,075,136	2.20
0	1	4	Q0F1T4_up	21,466,772	2.20
1	1	4	Q1F1T4_up	21,237,776	2.20
2	1	4	Q2F1T4_up	21,015,526	2.20
0	2	4	Q0F2T4_up	18,786,698	2.20
1	2	4	Q1F2T4_up	18,774,222	2.20
2	2	4	Q2F2T4_up	18,766,590	2.20
0	0	5	Q0F0T5_up	19,138,378	2.20
1	0	5	Q1F0T5_up	19,055,168	2.20
2	0	5	Q2F0T5_up	18,973,824	2.20
0	1	5	Q0F1T5_up	18,766,292	2.20
1	1	5	Q1F1T5_up	18,766,290	2.20
2	1	5	Q2F1T5_up	18,766,146	2.20
0	2	5	Q0F2T5_up	18,766,100	2.20
1	2	5	Q1F2T5_up	18,766,102	2.20
2	2	5	existing	18,767,204	2.20

Acronyms and Abbreviations

CPT	Conditional probability table
CSV	Comma-separated values
CWMS	Corps Water Management Systems
ERDC	US Army Engineer Research and Development Center
FEM	Facilities and Equipment Maintenance
FRM	Flood Risk Management
HEC	Hydrologic Engineering Center
HMS	Hydrologic Modeling System
IWR	Institute for Water Resources
JRL	Jennings Randolph Lake
NOAA	National Oceanic and Atmospheric Administration
OCA	Operational Condition Assessment
QC	Water quality
ResSim	Reservoir System Simulation
SACE	US Army Corps of Engineers
SME	Subject matter expert
USACE	US Army Corps of Engineers
WAT	Watershed Assessment Tool

REPORT DOCUMENTATION PAGE

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED *(From - To)*
March 2022	Final Report	

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Risk-Based Prioritization of Operational Condition Assessments: Jennings Randolph Case Study	
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)	5d. PROJECT NUMBER
Jonathan K. Alt, Willie H. Brown, George E. Gallarno, John P. Richards, and Titus L. Rice	
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
Information Technology Laboratory US Army Engineer Research and Development Center 3909 Halls Ferry Road Vicksburg, MS 39180-6199	ERDC/ITL SR-22-4

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
Navigation Systems Research Program Coastal Hydraulics Laboratory US Army Engineer Research and Development Center Vicksburg, MS 39180-6199	
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
Funding Account Code U4375151; AMSCO Code 031391

14. ABSTRACT
The US Army Corps of Engineers (USACE) operates, maintains, and manages over $232 billion worth of the Nation's water resource infrastructure. Using Operational Condition Assessments (OCA), the USACE allocates limited resources to assess asset condition in efforts to minimize risks associated with asset performance degradation, but decision makers require a greater understanding of those risks. The analysis of risk associated with Flood Risk Management assets in the context of its associated watershed system includes understanding the consequences of the asset's failure and a determination of the likelihood that the asset will perform as expected given the current OCA ratings of critical components. This research demonstrates an application of a scalable methodology to model the probability of a dam performing as expected given the state of its subordinate gates and their components. The research team combines this likelihood with consequences generated by the application of designed simulation experiments with hydrological models to develop a measure of risk. The resulting risk scores serve as an input for an optimization program that outputs the optimal set of components to conduct OCAs on to minimize risk in the watershed. Proof-of-concept results for an initial case study on the Jennings Randolph Dam are provided.

15. SUBJECT TERMS

Civil engineering—Planning, Decision making, Engineering—Management, Hydraulic structures, Jennings Randolph Lake (Md. and W. Va.), Operations research, 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			Willie H. Brown
Unclassified	Unclassified	Unclassified	SAR	64	19b. TELEPHONE NUMBER *(Include area code)* 601-634-4119