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A Field Validation of Dam Indexing Methods in Mississippi

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ABSTRACT

Indexing methods are applied to dam inventories throughout the United States to assist in prioritizing resources to maintain aging dam structures. Three published indexing methods and one proposed method were applied to 24 dams through Mississippi. The majority of dams in Mississippi have little to no information concerning the performance records or design specifics of a given dam. Field assessments were conducted to determine the physical condition of each dam, identify potentially deficiencies at dams, and calculate a consequence in the event of a dam failure. The results of the four indexing methods will be compared and advantages and disadvantages will be identified for each method.

DEDICATION

To Roy Skinner,

The Greatest Man I will ever know.

ABBREVIATIONS

National Dam Inventory (NID)

United State Army Corp of Engineers (USACE)

Federal Emergency Management Agency (FEMA)

Mississippi Department of Environmental Quality (MDEQ)

Risk Indexing Tool (RIT)

Condition Indexing Method (CIM)

Water Resources Vulnerability Assessment Tool (WRVAT)

Geographic Information Systems (GIS)

Vulnerability Assessment of Dams Using Simplifying assumptions (VADUS)

Digital Elevation Model (DEM)

Simplified Condition Indexing Method (SCIM)

Proposed Assessment Method (PAM)

Acknowledgments

I would like to acknowledge Dr. Joel Kuszmaul, Brian Gunter, MDEQ office of Dam Safety, Dr. Robert Holt, and Dr. Louis Zachos for providing insight and guidance throughout this project, the department of Geology and Geological Engineering for the many opportunities throughout my Ole Miss career, and lastly, I would like to acknowledge Lindsey Langsdon for co-piloting my field trips. I would like to thank my family for their support and prayers.

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Chapter 1: Introduction

1.1 Background

Federal dam safety guidelines and mandatory inspections on all dams were implemented in 1977 in response to several major dam failures during the 1960s and 1970s. The number of dam failures and resulting consequences have decreased dramatically as a result of increased regulations, regular inspections, improved technical standards, and increased public awareness (Bowles et al., 1998). The United States Army Corps of Engineers (USACE) maintains the National Inventory of Dams (NID), which classifies a state's dam inventory according to type, purpose, owner type, size, and hazard potential (NID, 2011). Hazard potential is classified into three categories (low, significant, and high hazard) according to the increasing degree of downstream consequences associated with a dam's failure, but this classification does not take into account the current conditions of the dam (FEMA, 2004). New downstream developments, with the associated population and infrastructure growth, increase the hazard potential of a dam. Therefore, hazard classification should be updated on a regular basis.

Mississippi has the sixth largest dam inventory in the United States with 3715 known embankment dams (Figure 1) (NID, 2011). The Mississippi Department of Environmental Quality (MDEQ) is the regulatory agency for the dams in Mississippi. With the current economic conditions, government regulatory agencies are under increased budgetary constraints. The majority of dams in Mississippi are privately owned low hazard dams. Mississippi does not require low hazard dams to be regularly inspected or designed by professionals and little is known about the design and construction of many privately owned dams in the state (MDEQ, 2011). As a dam ages, the structure must be maintained to prevent and reverse deterioration. To manage large inventories of dams, most states throughout the United States utilize ~~a~~ risk-based analysis to systematically identify dams that require maintenance (Harrald et al., 2006).

Traditional risk based assessments require comprehensive field inspection and thorough data analysis of a dam's physical condition and its relationship with the environment (Bowles et al., 1998). When evaluating a large inventory of dams, it is not feasible to commit the budget and time to conduct an analysis on an entire dam inventory. A Simplified Condition Indexing Method (SCIM) was developed by Anderson et al. (2001) to reduce the budget required to evaluate a large inventory of dams. This approach considers the current conditions of the key components of a dam and the impact the conditions have on a potential failure. Four potential failure modes were considered: overtopping, piping, surficial erosion, and mass movement. Failure modes are considered to be the failure-initiating event (Anderson et al., 2001). While all four failure modes must be considered for each case, it is worth noting that the majority of past dam failures in Mississippi have been attributed to piping.

Kuszmaul et al. (2010) proposed an assessment tool that prioritizes dams by their vulnerability to failure based on MDEQ records. Water Resources Vulnerability Assessment Tool (WRVAT) provides a cost effective technique to prioritize Mississippi's dam inventory according to the user's needs and concerns. WRVAT was developed for a number of purposes, but for dam vulnerability assessment it was intended to provide a GIS-based tool for ranking or prioritizing potentially vulnerable dams in Mississippi. Most importantly, it was intended to emphasize data available using MDEQ records and GIS database layers. There was no component of the method that involved field inspection. WRVAT was applied to dams in Mississippi, providing a ranking of expected vulnerability for each of the dams considered.

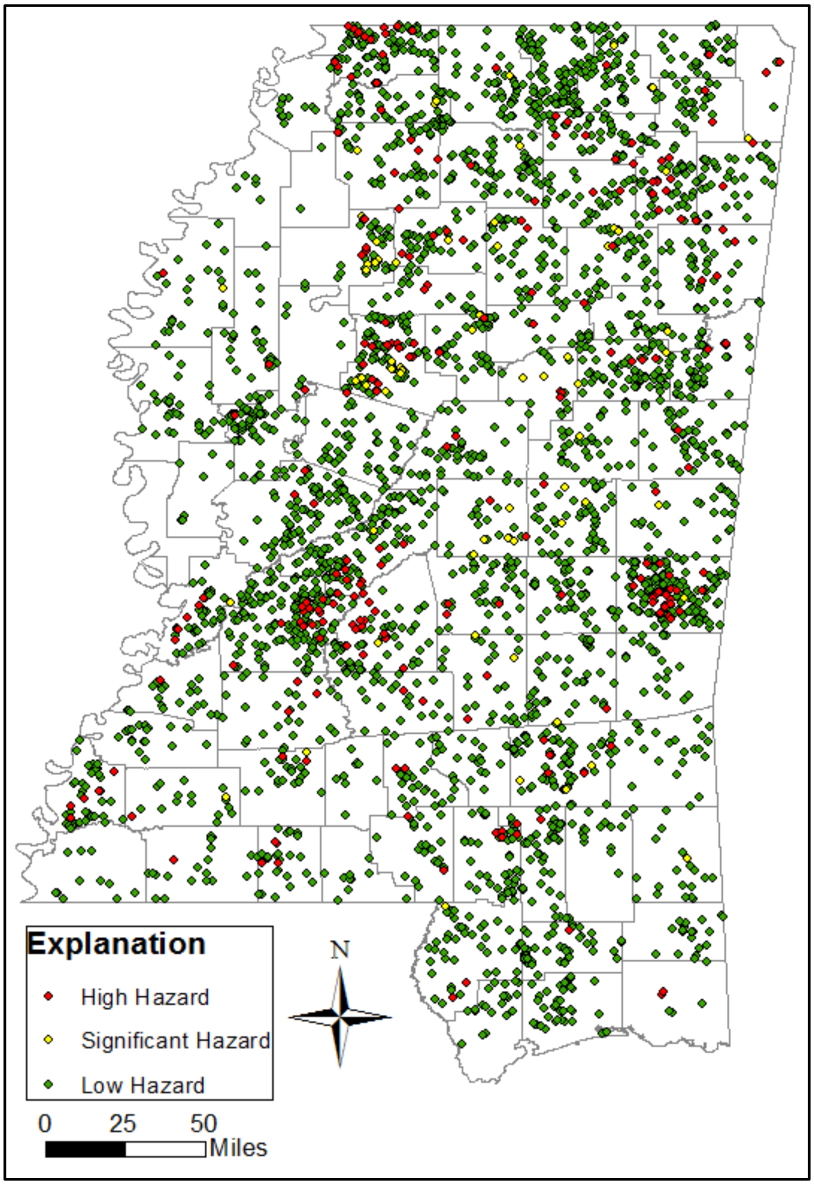

Figure 1.
All dams in Mississippi categorized according to hazard potential.

1.2 Purpose

The objective of this thesis is to compare the results of WRVAT against the results of Anderson's (2001) SCIM and Soetjiono's (2008) dam safety priority ranking (Javanese Method).

A new assessment method (PAM) was developed during this research in an attempt to incorporate a dam's current conditions, the probability of failure, the security presence at a dam, and a consequence factor. Field inspections were conducted at 24 embankment dams throughout Mississippi to collect data on the current conditions of key dam components and the downstream infrastructure that would be vulnerable to a total dam failure (Figure 2).

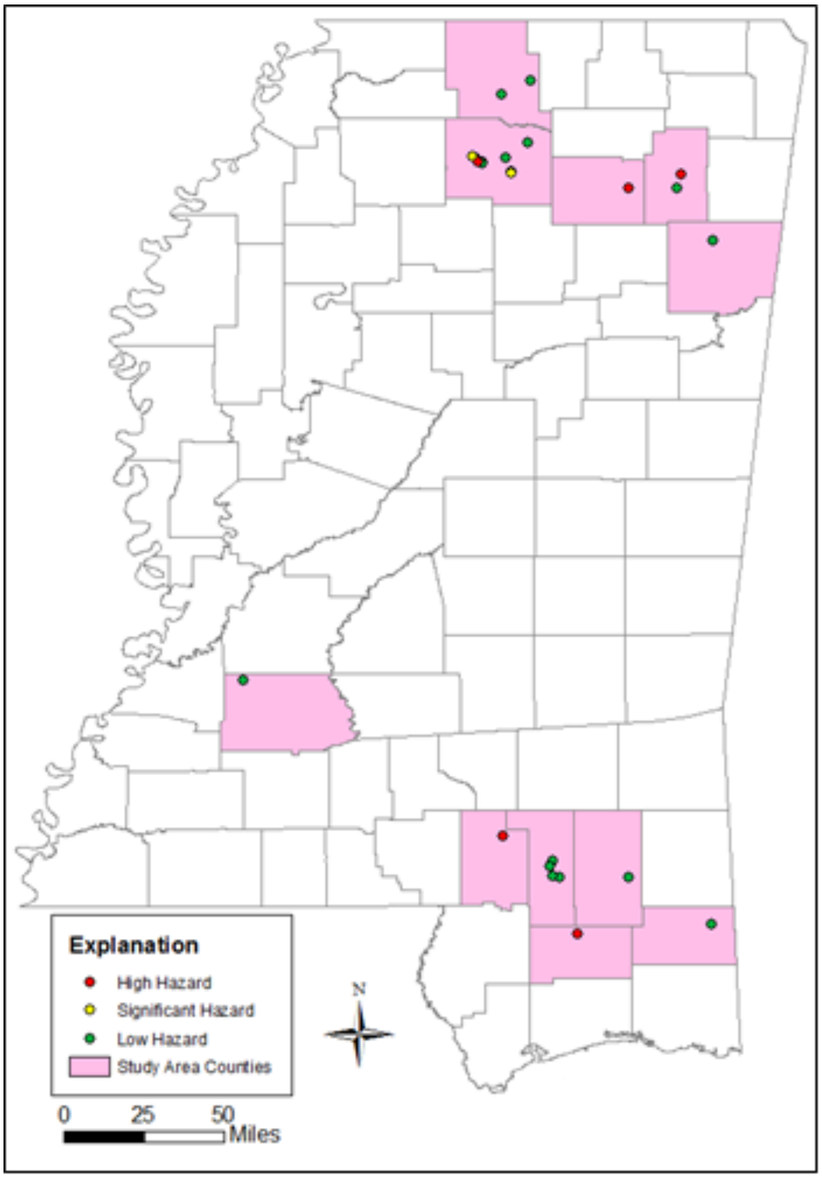

Figure 2.
Dams selected for this study.

Chapter 2: Data Collection

2.1 Dam Selection

To ensure that the selected dams were representative of the Mississippi dam inventory, dams were selected based on the following criteria: complete MDEQ records, hazard potential, accessibility, owner type, purpose, and location. Large federally owned dams, navigation purpose dams, and small dams (< 25 ft. height) not in the MDEQ inventory were excluded from potential dams visited for this report. Owners granted access to dams included in this study on the conditions that the dams would remain anonymous and that the structural integrity of the dams would not be compromised during fieldwork (Appendix A). If the severity of conditions/deficiency of a dam were believed to have the potential to cause a dam failure, evidence would be reported to MDEQ.

2.2 Field Assessments

To effectively maintain safe condition of a dam, routine visual assessments or inspections must be conducted to reduce the probability of a major failure (Fell et al., 2005). Inspections of low hazard dams in Mississippi are the responsibility of the dam owner. Significant and high hazard dams are required by MDEQ to have formal, informal, and periodic inspections to ensure the safety of the dam and protect against the consequences of a dam failure (MDEQ, 2011).

MDEQ's *Inspection of Embankment Dams,* dam inspection evaluation procedures (NRC, 1983), and a field checklist (Fell et al., 2005) were used as a guide to develop a field inspection checklist to efficiently collect data for all of the prioritizing methods (Appendix B). Anderson's Condition Factors (CF) were the focus of the dam inspections (Table 1).

Physical Condition	
Spillway Obstruction (CF1)	Embankment Piping (CF6)
Loss of Freeboard (CF2)	Foundation Piping (CF7)
Low Level Outlet Condition (CF3)	Mass Movement of Embankment (CF8)
Spillway Erosion (CF4)	Mass Movement of Foundation (CF9)
Embankment Material (CF5)	

Table 1.
The physical condition factors that can lead to a failure of a dam (Anderson et al., 2001).

The probability of a current condition contributing to the associated failure mode was estimated during a dam's visit (Appendix C). Structural deficiencies, recreation areas, personnel presence, gates, fences, evidence of animal activity, and malicious activity were also noted.

The downstream area vulnerable to a dam failure was calculated using the automated program, VADUS (Vulnerability Assessment of Dams Using Simplifying assumptions). The program requires a digital elevation model (DEM), a flow direction grid, the Land Use Classification Dataset, location of the dam, and height of the dam. Delineations of the flooded area terminate when the average height of water in a cross-section is less than 1 foot (Gunter, 2009). VADUS provides a conservative worst-case scenario of the downstream area vulnerable to flooding as a result of a dam failure. The term conservative is applied to this method because of the following observations: 1) overtopping failure mode, 2) the height of the reservoir is equal to the dam height, 3) downstream structures (buildings, trees, roads, and culverts) do not alter the flow direction, 4) VADUS does not process flow through flat terrains well, 5) calculated vulnerability area is dependent of the user's interpretation, and 6) the output can extend several miles downstream.

The interpreted area and dam locations were loaded into an Apple iPad 3G and used as a map reference while in the field. Houses, businesses, emergency responders (hospitals, police and fire departments, military bases), etc. were noted and marked using the Google Maps application (Figure 3).

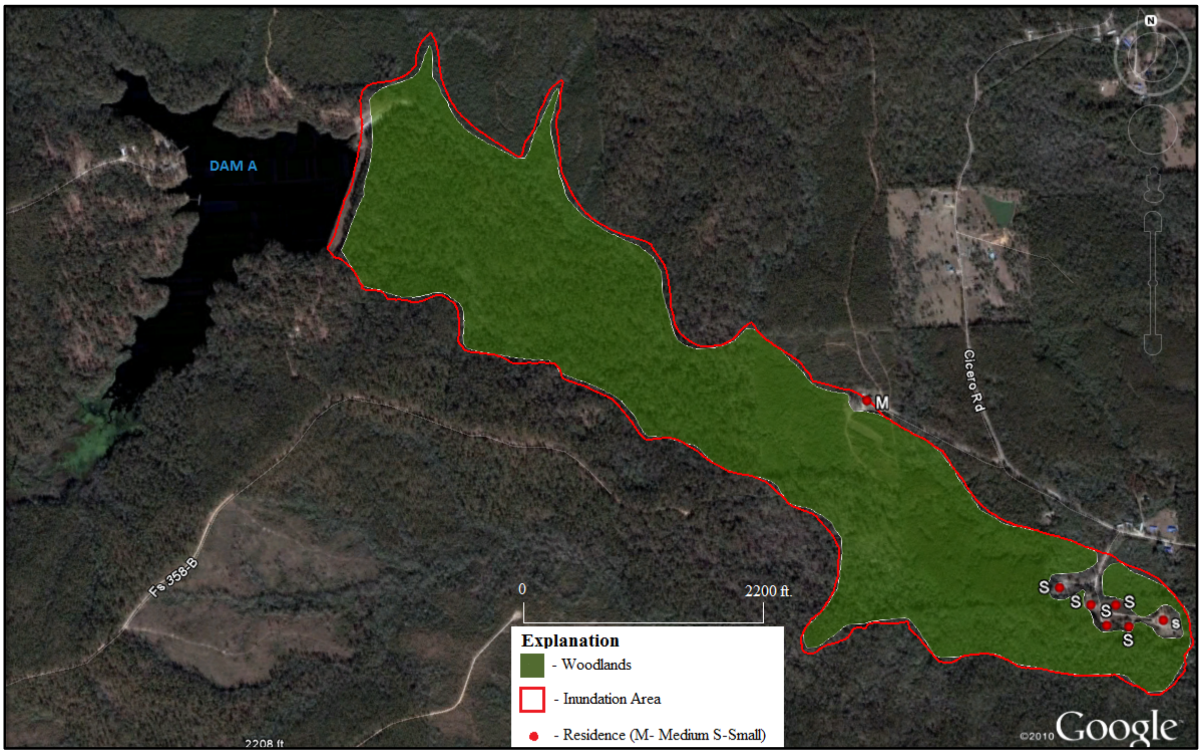

Figure 3.
Dam A inundation area with land use marked (Google, 2011).

2.3 Site Assessment

Data collected during fieldwork was organized according to the different indexing methods requirements. MDEQ allowed access to their database to ensure all information required for the purpose of this study was available.

Some areas within the VADUS assessment area were not accessible to the public. To account for these areas, satellite imagery was reviewed to mark any structures that were missed during fieldwork. Lengths of roads and rails, and areas of farmland within each VADUS assessment area were also determined using satellite imagery. The combination of fieldwork and data using satellite imagery provides a sufficient estimate of the consequences downstream of a dam failure.

Chapter 3: Prioritization Methods

3.1 Overview

There are two major approaches to systematically prioritize dams in an attempt to identify "high-risk" dams within the inventory. A condition indexing approach is based solely on the physical conditions of the dam through on-site inspections. The USACE and MDEQ uses a CIM to cost effectively evaluate dams that require maintenance (Anderson, 2001) (MDEQ, 2011). Alternatively, risk based analysis is widely used to identify the probability of an adverse event occurring at a dam as a result of physical deficiencies or security against outside threats. Risk indexing is not an accurate measure of the risk associated with a dam, but does indicate the potential for failure and the subsequent consequences (Harrald et al., 2006). Assessing the security risk of a dam is extremely difficult because of the uncertainty of predicting the likelihood of an attack on individual dams. Security-based assessments provide reducing strategies to detour a successful attack on a dam. The largest dams with the highest consequence are assumed to be at the highest risk, but this does not account for reckless activities at smaller dams. WRVAT and PAM consider threat based security assessment but take into account different variables to determine threat.

The methodologies of SCIM, the Javanese Method, WRVAT, and PAM will be introduced and applied to Mississippi dams selected for this study. Results and Components of each method will be compared and analyzed to determine the validity of each method as it is applied to Mississippi in later chapters.

3.2 Simplified Condition Indexing Method (SCIM)

3.2.1 Overview

To merge the most desirable aspects of CIM and risk based analyses, Anderson et al. developed a SCIM. Three components are combined to determine a risk index of a dam's key components: (1) The vulnerability (V) of a dam to failure and the associated consequence (C) determine the importance (I_{dam}) of the dam within the inventory, (2) the relative importance (RI_j) of key components (Table 2) of a dam, and (3) the current conditions of a dam and how the conditions affect the performance of the dam. A total risk index (IR_{TOT}) is the sum of all key components total risk associated with its current conditions. A dam inventory is prioritized according to the importance of a dam and the total risk at the associated dam.

3.2.2 Importance

The vulnerability function is the product of the mean value of the following three characteristics: time invariant characteristics (Intrinsic (I)), time variant characteristics (Extrinsic (E)), and design characteristics (D). Each factor is scaled between 1and 10 as described in Appendix D.

$$V = \frac{I_1+I_2+I_3+I_4}{4} \times \frac{E_1+E_2}{2} \times \frac{D_1+D_2}{2} \qquad [1]$$

The MDEQ database heavily relies on variables to define height (I_1), dam type (I_2), foundation type (I_3), reservoir storage capacity (I_4), and dam age (E_1). Seismic hazard (E_2) was determined using USGS seismic acceleration maps. Design conditions, spillway capacity (D_1), and slope stability (D_2)-were rated according to suspected conditions unless analyses were present in the database. The consequence of a dam failure is classified by the hazard potential (H). For this study, H was ranked according to parameters proposed by Anderson (1999) using data from the consequence study previously discussed (Appendix D).

$$I_{Dam} = V \times H \qquad [2]$$

3.2.3 Physical Conditions and Prioritization

Anderson's method proposes a quick dam investigation that focuses on the key components of a dam that affect the overall performance (Table 2). The 9 condition factors are ranked from 10 to 1 based on field observations (Appendix E). If there was no indication of deficiencies of physical conditions, the value of 10 was assigned. The probability of four potential failure modes ($P[M_i|F]$) were considered using the results of an 1998 USCOLD (United States Committee on Large Dams) study on failures (Table 2). These probabilities of failure modes are estimates without knowing specific information about a dam. ($P[M_i|F]$) assumes that a failure has already occurred at a dam.

Failure Mode	Prior Conditional Probability
Overtopping	0.49
Piping	0.32
Mass Movement	0.09
Surficial Erosion	0.10

Table 2.
The probability of a failure mode (USCOLD, 1999)

The probability of each condition factor's (CF) likelihood of causing the associated failure mode ($P[C_j|M_i]$). The relative importance (RI_j) is the probability that each CF would initiate the sequence of events leading to failure (Figure 4).

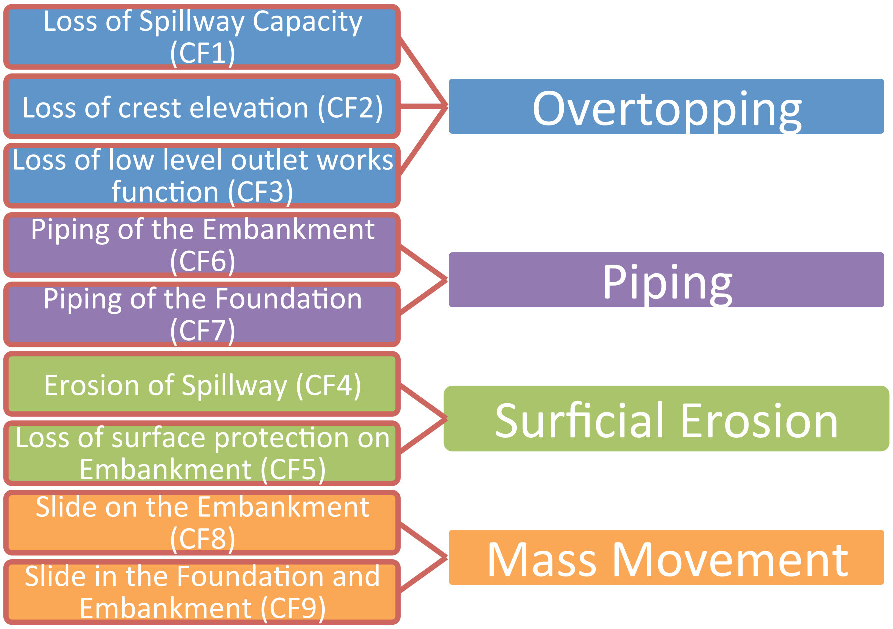

Figure 4.
The condition factors that can lead to failure type.

Relative importance of each condition is the product of the subjectively assigned condition probability, the probability of failure mode, and the importance of a dam.

$$\mathrm{RI_j} = \sum_{i=1}^{4} \sum_{j=1}^{9} \mathrm{P}\left[\mathrm{C_j}|\mathrm{M_i}\right] \times \mathrm{P}[\mathrm{M_i}|\mathrm{F}] \times \mathrm{I_{Dam}} \qquad [3]$$

Zero relative importance of a physical condition does not imply zero risk. It means there was no indication of poor conditions or that the relative importance of that condition is of lesser importance than others. The risk index of the observed CF and the relative importance of each condition can be summed to determine the total risk of a dam's likelihood to fail.

$$\mathrm{IR_{TOT}} = \sum \left(\mathrm{RI_j} \times \frac{(10 - \mathrm{CF_j})}{10} \right) \qquad [4]$$

Prioritizing dams within an inventory is the product of the total risk of the dam and the importance of that dam. The total risk index is an indication of potential severity of the structural deficiencies compromising the performance of a dam (Appendix F).

$$PR_{DAM} = I_{DAM} \times IR_{TOT} \qquad [5]$$

The prioritization equation emphasizes the significance of a dam's vulnerability, hazard potential, and the effects of the current condition on the overall performance. Results of SCIM applied to study dam inventory are summarized in Appendix G.

3.3 Javanese Dam Safety Methodology

Soetjiono modified Anderson's SCIM to rank the safety of embankment dams in Java, Indonesia. Dams were ranked according to the susceptibility of failure as a result of natural events. Hazard potential was kept consistent with the H used for SCIM but does not greatly impact the results. The dam's safety rank (N) is a preliminary evaluation of the risk of a dam to fail.

$$N = \left(\frac{I_{DAM} - IR_{TOT}}{I_{DAM}}\right) \times 100 \qquad [6]$$

The computation of priority rank of dam safety classifies dams that are satisfactory ≥ 75 and unsatisfactory < 54. Results are summarized in Appendix H.

3.4 WRVAT Assessment

WRVAT is an ArcGIS™ based tool developed to manage a statewide database of dams by "quickly" assessing a dam's Vulnerability (V). Kuszmaul et al., 2010 applied Anderson's vulnerability [1] as the Intrinsic vulnerability (I) of a dam's likelihood to fail and included an Extrinsic vulnerability (E) that considers the external threat of intentional and/or unintentional damage and a more detailed Consequence (C) factor to calculate vulnerability.

$$V = (I + E) \times C \qquad [7]$$

This assessment method does not require dam inspections but relies on an updated dam database, population data, and land use data to accurately prioritize dams requiring maintenance. If all information is current, WRVAT offers the most cost effect technique to prioritize a dam inventory.

Extrinsic vulnerability factor is the sum of three forms of external threat: (1) intentional harm to a dam by humans, (2) harm caused by animal activity, and (3) harm caused by a negligent dam owner.

$$E = E_1 + E_2 + E_3 \qquad [8]$$

Scores are based on past findings reported to the regulatory agency (MDEQ). The data available for the study inventory did not completely address all three terms. These terms were ranked based on field observations using suggested scores in Kuszmaul et al., 2010 (Appendix I).

The consequence of a dam failure was determined using the program VADUS. Census tract data, primary roads, secondary roads, universities, hospitals, and prisons within the VADUS assessment area were equally weighted to estimate the downstream population and infrastructure at risk of a potential dam failure. A summary of WRVAT results is located in Appendix I.

3.5 Proposed Assessment Method (PAM)

An additional method proposed and applied in this study in an attempt to combine SCIM's risk index [4], WRVAT's intrinsic vulnerability [1], an extrinsic vulnerability factor that accounts for the security presence at a dam, and a consequence factor (discussed earlier).

$$V = (\rho_I I + \rho_E E + \rho_R IR_{TOT}) \times C \qquad [9]$$

Multiplicative factors are applied to the intrinsic, extrinsic, and risk index terms, allowing the user to modify the importance of these variables (Table 3).

Variables	User Defined Values
Intrinsic Factor (ρ_I)	0.32
Extrinsic Factor (ρ_E)	0.33
Risk Factor (ρ_R)	0.35

Table 3.
The user defined variable used for this study

This method produces a detailed assessment of the study inventory that can be modified based on the user's judgment. It is not feasible to apply this method to a large inventory of dams because of the time required to thoroughly investigate the consequence error.

3.5.1 Extrinsic

Extrinsic vulnerability is defined by replacing (E_1) in the WRVAT calculation [8]. Animal activity (E_2) and owner neglect (E_3) are determined during fieldwork.

$$E = \frac{C_R}{A_D} + E_2 + E_3 \qquad [10]$$

The likelihood of a human successfully harming a dam was defined by the ratio of the likelihood of an attack on a dam (C_R) over the accessibility of the components of the dam (A_D) (Tables 4 and 5). The likelihood that a dam will be attacked is defined by the rank of the calculated consequence factor within the study inventory (Martella et al., 2010).

Likelihood of an Attack (C_R)	Score
Consequence is in the top 25%	3
<25% but >75%	2
Bottom 25%	1

Table 4.
The likelihood of an attack scoring table.

Security Measures (A_D)	Score
Unrestricted accessibility	1
Restricted accessibility	2
Security presence	3

Table 5.
The accessibility scoring table

The accessibility of a dam was determined by the security measures in place at the dam facility. Restricted accessibility score was warranted by the presence of locked gates blocking vehicular access (Bowen et al., 2010). The security at a dam was not consistent with the ownership type. The likelihood ratio can account for some of the variance in determining the threat of a human damaging a dam. High consequence dams are more likely to attract more determined bad actors. The uncertainty associated with assessing the security risk of a dam is difficult to account for because the actions and the magnitude of damage by a bad actor cannot be quantified. (Appendix K).

3.5.2 Consequence

The consequence (C) of a dam failure was estimated by the number and type of structures within the VADUS output area that would affect the daily life of the downstream population [11]. Consequence increases as population and downstream development increases (FEMA, 2004). Factors include residential structures (C_1), population (C_2), transportation (C_3), and land use (C_4).

$$C = \rho_1 C_1 + \rho_2 C_2 + \rho_3 C_3 + \rho_4 C_4 \qquad [11]$$

Data was collected for each factor during extensive fieldwork and desk study. The location and size of residential structures were marked and totaled to determine C_1 (Table 7).

# of Houses	Score
1-25	1
26-50	2
51-75	4
76-100	8
>100	16

Table 6.
Ranking scale used to score the C_1 consequence variable.

Population within the vulnerable area is dependent on the size of residential structures within that area. It is assumed that there are more individuals residing in larger residential structures (Table 7).

House Size	# of Residential structures
Large	4.5
Medium	3
Small	2

Table 7.
The assumptions used to estimate the population vulnerable to a dam failure.

This assumption does not accurately represent an exact population count; rather it is a generalized estimation of the population. The population factor was scored based on this assumption (Table 8).

Estimated Population	Score
1-50	1
51-100	2
101-200	4
201-300	8
>300	16

Table 8.
Ranking scale used to score the C_2 consequence variable.

C_3 includes major roads (t_m) (four lane highways vital to the area), secondary roads (t_s) (two lane roads vital to the communities), local roads (t_l) (roads vital to neighborhoods), and railroads (t_r) [12]. The total miles of each variable was determined using satellite imagery and GIS data layers scored respectively using Table 9.

Transportation Ranking	Score
Primary (R_m)	8
Secondary (R_s)	4
Local (R_l)	2
Train Rail (R_r)	1

Table 9.
Ranking scale used to score the C3 consequence variable.

$$C_3 = t_m(R_m) + t_s(R_s) + t_l(R_l) + t_r(R_r) \quad [12]$$

C_4 includes businesses (B), downstream infrastructure (I_d), and unit area of farmland (F).

$$C_4 = B + I_d + F \qquad [13]$$

The number of businesses were scaled and ranked according to Table 10.

# of businesses	Score
1-5	1
6-15	2
16-25	4
>25	8

Table 10.
Ranking scale used to define B.

I_d is defined by the civic infrastructure that provides public services to the community (Table 11). Emergency responders such as police departments, fire departments, and hospitals were ranked highest because of the likelihood that their destruction would impair their ability to maintain order during a failure event. Prisons, universities, and primary schools were also considered, although none were encountered during this study. A unit area of farmland is defined as 100 acres.

Infrastructure	Score
Hospital	5
Police & Fire Departments	
Prisons	2
Primary Schools	
Universities	

Table 11.
Ranking scale to define I_d.

Multiplicative factors are applied to all terms individually. This allows the user the ability to tailor the consequence variable to fit the study purpose (Table 12).

Variables	User Defined Values
Inhabitance Factor (ρ_2)	0.35
Transportation Factor (ρ_3)	0.3
Land Use Factor (ρ_4)	0.25

Table 12.
Multiplicative factors applied to consequence terms.

Consequence ranking is a time dependent variable. Dam failures that occur during different times will incur different degrees of hazard for the factors considered. For the purpose of this study the variability of the time of failure was not accounted for. Consequence results are summarized in Appendix K.

Chapter 4: Results

4.1 Overview

The four discussed methods were applied to this study's dam inventory. For consistency, results of SCIM, WRVAT, and PAM were scaled between 1 and 100. Higher scores for these three methods represent dams at greater risk to fail. Inversely, the Javanese method scores dams that are in the best condition as highest. This section introduces the results of the 4 methods that will be compared and analyzed in following chapters.

4.2 Simplified Condition Indexing Method

Results of SCIM rated Dams V, U, L, E, and F as the dams at the highest risk to fail as results of physical deficiencies (Figure 5). Dams V, U, and L are all younger (< 25 years old) and have suspected inadequate spillways and unstable slopes. A summary of SCIM results is in Appendix G.

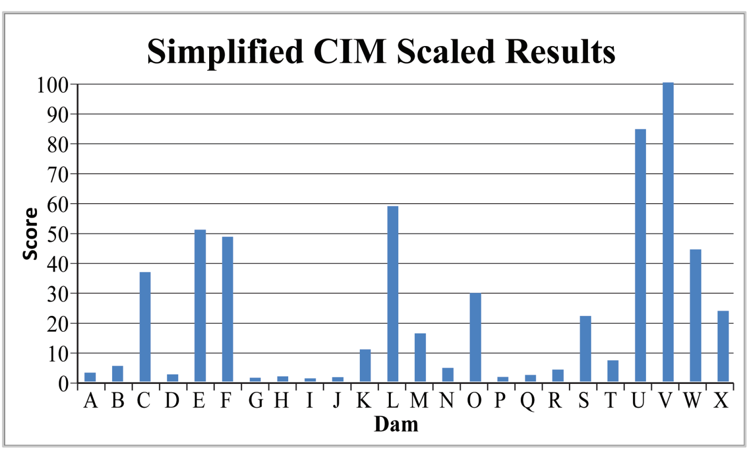

Figure 5.
SCIM's results scaled between 1 and 100.

4.3 Javanese Dam Safety Methodology

The majority of dams inspected scored as satisfactory and only 2 dams scored as unsatisfactory (Figure 6). The poor conditions of dams E and F warranted this ranking. Dams E and F are flood control structures that are not in use year round. The risk of failure would only be present during the winter and spring seasons. Dams B, D, and X are all within the 75 to 55 range and need improvement. A summary of the dam safety results is in Appendix H.

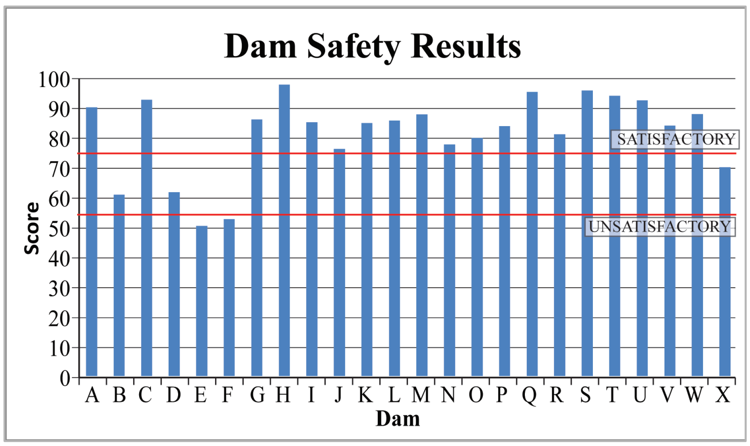

Figure 6.
Javanese dam safety priority rank.

4.4 WRVAT Assessment

WRVAT results rate Dams O, S, U, V, and C as the dams most vulnerable to fail (Figure 7). All of these dams are high and significant hazard dams with large consequence factors. A summary of WRVAT results is in Appendix I.

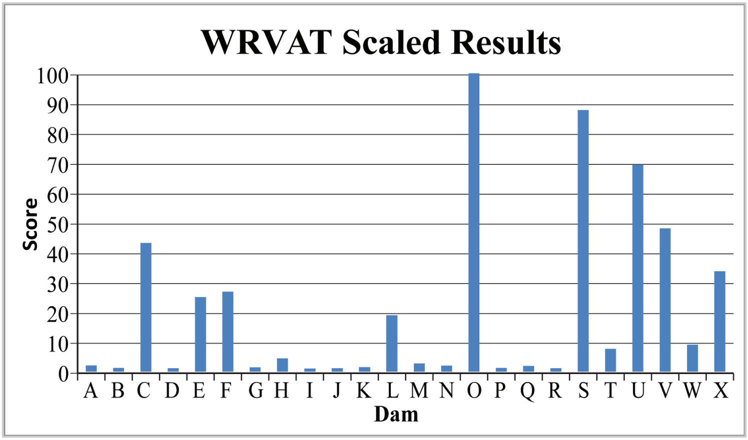

Figure 7.
WRVAT results scaled between 1 and 100.

4.5 Proposed Assessment Method

PAM rated Dams E, F, U, C and O as the dams most vulnerable to fail. These dams have high consequence factors. A summary of PAM results is in Appendix L.

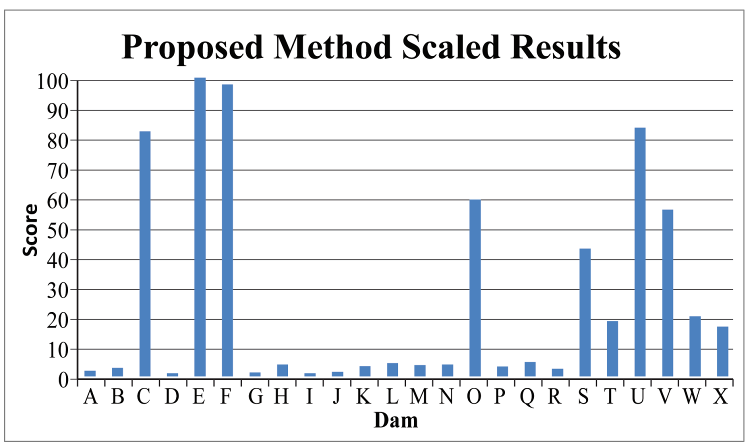

Figure 8.
PAM's results scaled between 1 and 100.

Chapter 5: Priority Rankings

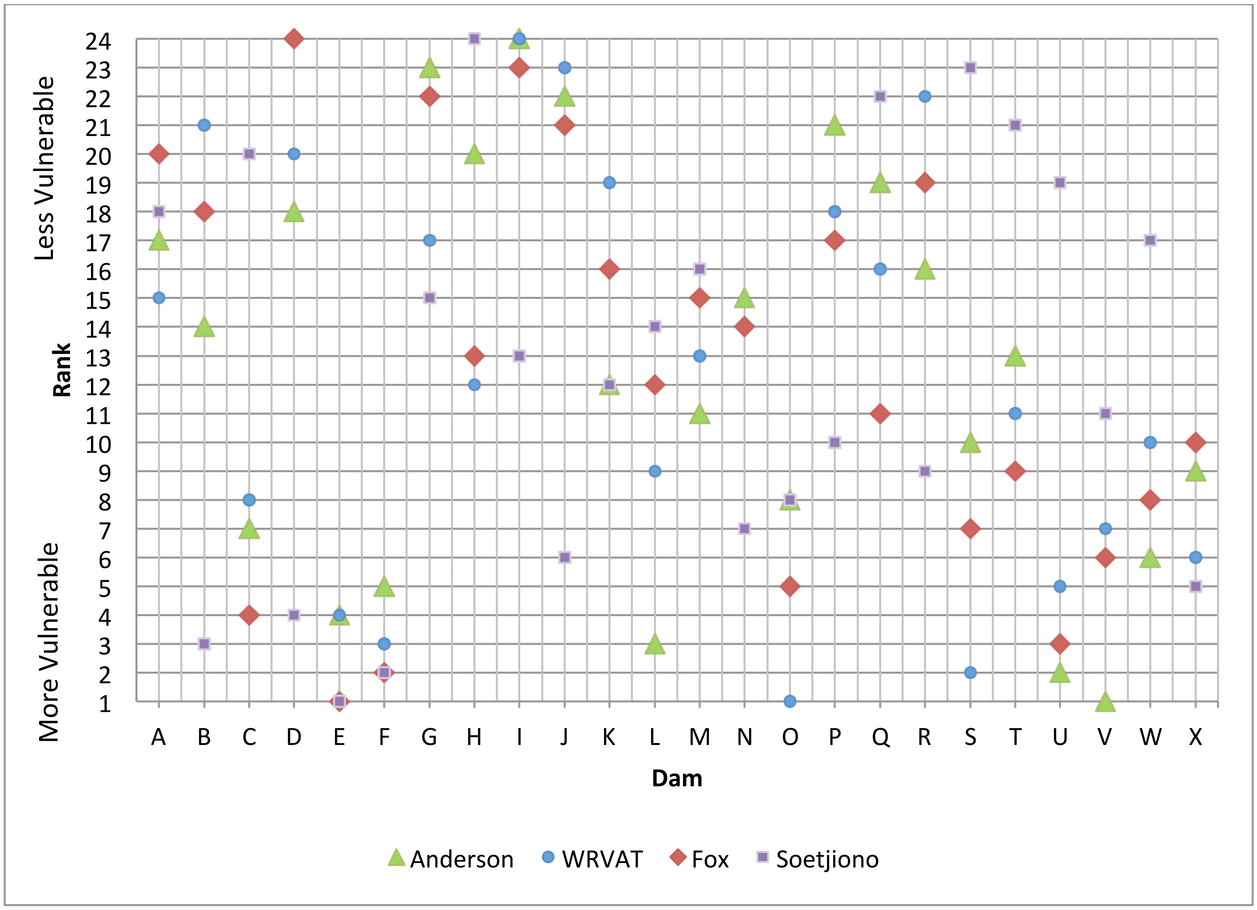

Figure 9.
Comparing the ranks of the four indexing methods' results.

The results of the four methods considered were ranked according to the dam's likelihood to fail (Figure 9). Comparing the dam ranks of each method allowed for discrepancies between the different methods. An initial analysis of the rankings reveals similarity between SCIM's, WRVAT's, and PAM's results while the Javanese method's results rarely agree.

The Javanese method does not consider the consequence of a dam failure as an important factor. Dams B, D, I and J are all examples of dams that were in poor condition but have modest consequences in the event of each dam failing. Dams C, T, U, and W were all high and significant hazard dams according to MDEQ, but rank as the least vulnerable to failure because the dams were well maintained.

The availability of current data is essential to assess index a dam inventory accurately. WRVAT is an assessment tool that relies on a current database for information about the dam's intrinsic and extrinsic vulnerabilities. MDEQ records lacked the information required to determine the extrinsic vulnerabilities for most of the dams visited. Information collected during fieldwork was used to classify the animal activity and owner neglect at a dam. Results of WRVAT ranks were remarkably consistent with those of SCIM and PAM, both of which consider the physical condition of the dam. Minor inconsistencies in the WRVAT method can be attributed to the method used to determine consequence, in particular the population grid. A population grid distributes the population evenly throughout the area. Current population data was not available at the time of this study. Dams D, L, O, S, and X have vulnerability areas located near a populated area.

SCIM weighted the extrinsic variables (age and seismic hazard) and the design adequacy factors (spillway capacity and slope stability) as the most important variables. Dams L and V are both young dams with suspect design located in moderate seismic hazard areas.

Consequence was the most important variable in PAM's method. If the consequence of a failure was determined to be zero, the dam was deemed to be least important (Dam D). Consequence was based on the most recent population data.

More detailed comparisons are required to accurately distinguish the four methods. Spearman's rank correlation coefficients were calculated for each indexing method to determine the similarity between each rank (Table 13). Spearman's coefficient is a nonparametric correlation method that expresses the similarity of ranking sets. The coefficient varies between +1.0 (perfect correlation) and -1.0 (inverse relationship) (Davis, 2002).

	WRVAT	WRVAT w/ Field C	SCIM	JAVANESE	PAM
WRVAT	1	0.869	0.785	-0.110	0.898
WRVAT w/ Field C		1	0.753	-0.046	0.963
SCIM			1	0.083	0.823
JAVANESE				1	-0.094
PAM					1

Table 13.
Spearman's coefficients calculated between each method.

There is a substantial relationship between the ranks of SCIM, WRVAT, and PAM, but the Javanese method ranks do not correspond with the other methods. Javanese method provides an indexing method that prioritizes based on the dam's physical conditions and how the conditions affect the overall performance of the structure. Although both SCIM and PAM consider the physical condition of the dam, the condition factor and risk of failure associated with those conditions are not as important. The Javanese dam safety indexing method will be excluded from further analysis.

Chapter 6: Analysis and Discussion

6.1 Overview

Correlations between the results of the three remaining methods were conducted to measure the relationship between each (Table 26). It is expected that PAM will correlate well with both SCIM and WRVAT because PAM contains parts of other methods. PAM incorporates WRVAT's intrinsic vulnerability and SCIM's total risk index with an extrinsic vulnerability and a field defined consequence factor. PAM and WRVAT are consequence driven assessments.

SCIM, WRVAT, and PAM present useful methods that consider different factors to index a dam inventory. Indexing results are plotted against each other and similar components of each method will be compared in order to verify initial observations, identify groups of dams with similar characteristics, and to provide an explanation of the differences between the SCIM, WRVAT, and PAM methods (Table 14).

	WRVAT	PAM	SCIM
WRVAT	1	0.855	0.561
PAM		1	0.640
SCIM			1

Table 14.
Correlation Coefficients between the three indexing method results.

6.2 Dam Groupings

The total index values were scaled between 0 and 1 and plotted to identify dams with similar attributes that cluster together (Figure 10). A summary of results is located in Appendix L.

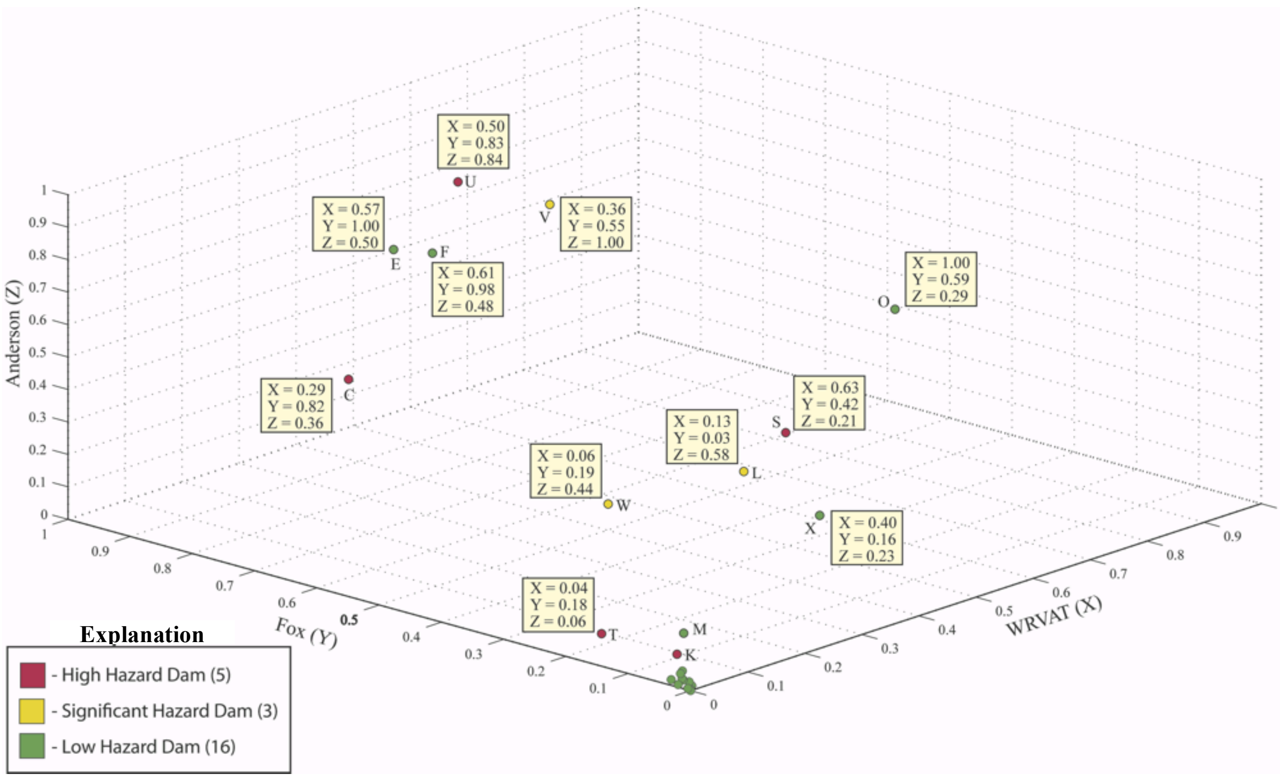

Figure 10.
The three methods plotted with figures with indexing values. Dams are colored according to MDEQ hazard classification.

The study inventory can be divided into different groups according to similar attributes. Five groups are identified in Figure 11. The Good Group consists of 13 dams that vary in size, owner type, physical condition, location, and purpose, but are either at low risk of a failure or have little consequence in an event of failure. Dam H has the largest embankment and reservoir capacity in the group, but was in the best overall condition of the entire study inventory. Dam K is also included in this group despite its high hazard classification; it is well maintained and only poses a threat to the residents directly below the embankment. Dam M is a small dam that is located within a major city. There are no major distinctions within the Good Group; therefore the group will be excluded from the remainder of this discussion.

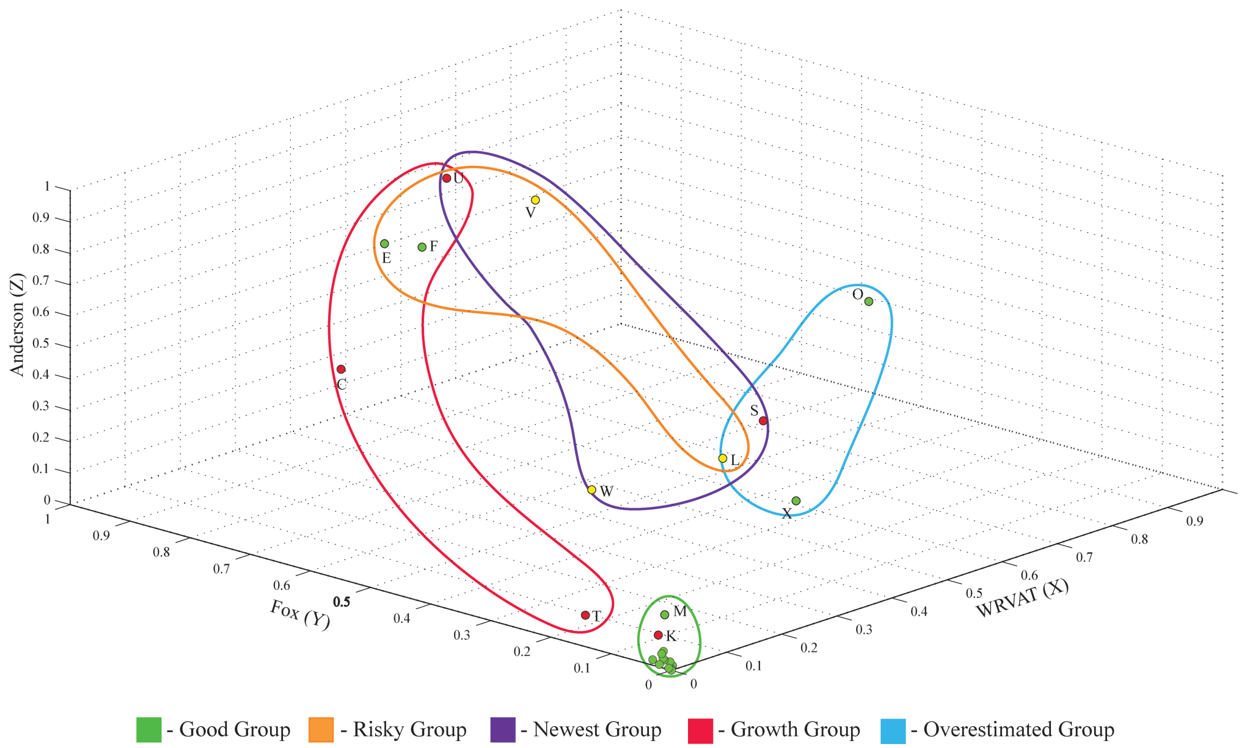

Figure 11.
Dams grouped according to similarities.

The Risky Group (E, F, V, L, and U) consists of the dams that possess the greatest risk associated with a failure as result of the poor conditions of the dams as observed during fieldwork and downstream consequence (Figure 12). The condition of a dam is highly variable. Conditions observed during fieldwork and the current conditions presently at the dam can differ. Dams E and F were in the worst physical condition.

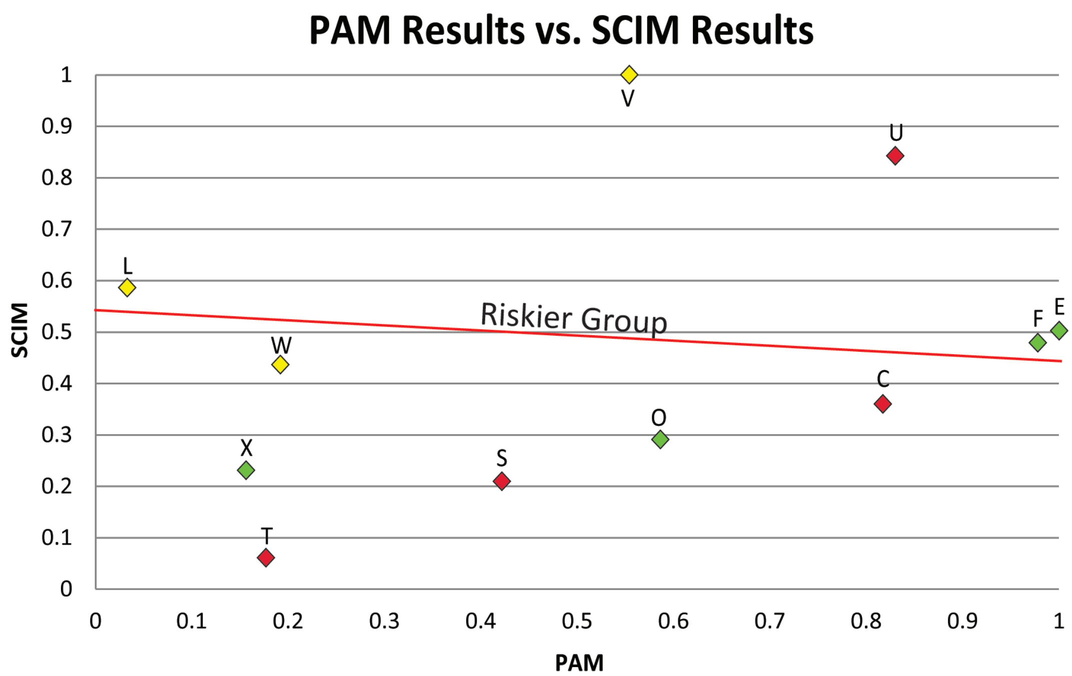

Figure 12.
Denotes the lower boundary of the Riskier Group

Since the initial fieldwork, conditions at both dams have improved moderately over a three-month time period, but the improvements were not included in this analysis. Coincidentally, WRVAT results for both of these dams in their initially observed conditions are similar to results calculated using SCIM.

The Newest Group consists of five younger dams with a combination of large storage capacity and suspected inadequate spillway capacity and slope stability design (Figure 13). All dams in this group are classified as high or significant hazard. Major erosion and seepage problems were repaired on dams U, V, and W (MDEQ, 2011).

Growth Group (5 dams) is characterized by the increased consequence resulting from a significant amount of downstream development since 2000. This group demonstrates the importance of an updated inventory of dams. New development was determined by studying historical satellite imagery. 2000 census data, used by WRVAT to account for the population within the consequence area, provides a rough approximation of total population of an area by distributing the population between census tracts.

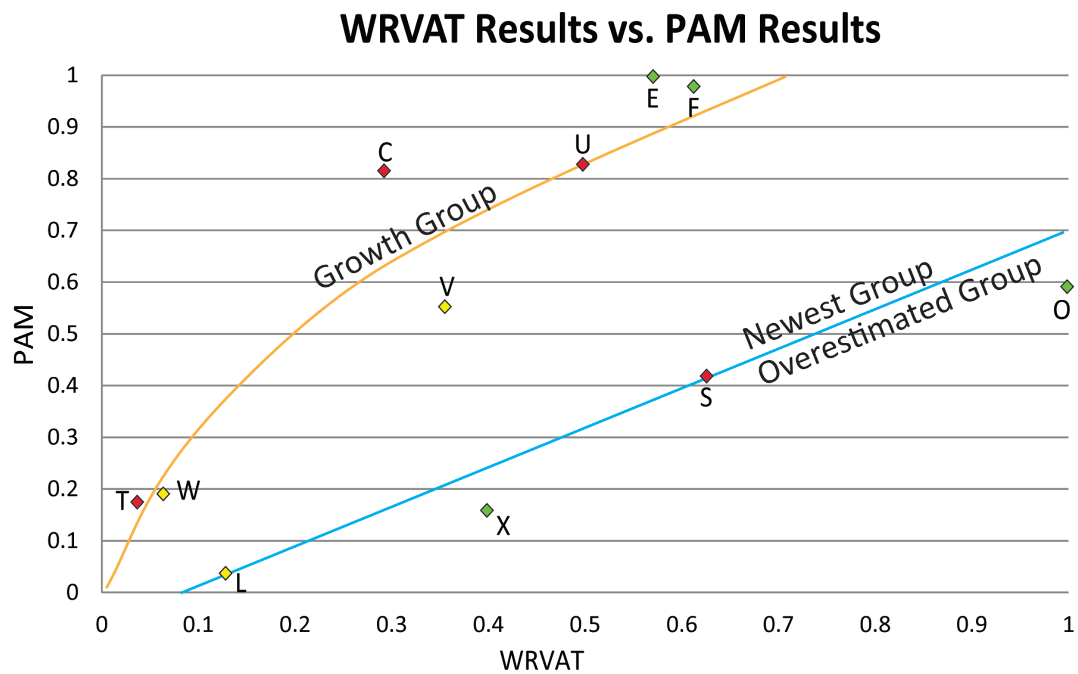

Figure 13.
Denotes the boundaries between the Growth, Newest and Overestimated Consequence Groups.

Dams C, T, and U are all large high hazard dams that are located in rural areas with newer downstream development unaccounted for in the WRVAT analysis. Dams E and F are near a city center, thus new development is better represented within the census tract grid.

WRVAT can also exaggerate the consequences of a dam failure. The Overestimated Group consist of Dams L, O, S, and X that have their consequences overestimated by WRVAT. Different users' interpretations of VADUS output could alter the WRVAT consequence factors calculated (Figure 14). The same termination criterion was used for all VADUS calculations. The initial VADUS calculation was applied to 3,005 dams, which did not allow for a detailed review of each output area. The difference can be attributed to user interpretation, inaccurate dam locations, or varying DEMs used during data preparation. The difference between the two interpreted areas would have minimal effect on PAM's results because the additional area has little farmland and few inhabitants. Dams L and X are near higher populated cities but their assessment areas do not include many inhabitants. Dam S would affect a highly populated area, but much like Dam O and Dam X, the assessment area is over extended. Anomalies within the available DEMs can contribute to erroneous output. Offsetting these complications is tedious work and very time consuming. VADUS is programmed to terminate once the depth of water in a cross section is less than one foot. If the terrain is featureless and flat, VADUS output will dissipate in all directions until the one-foot stopping criterion is met.

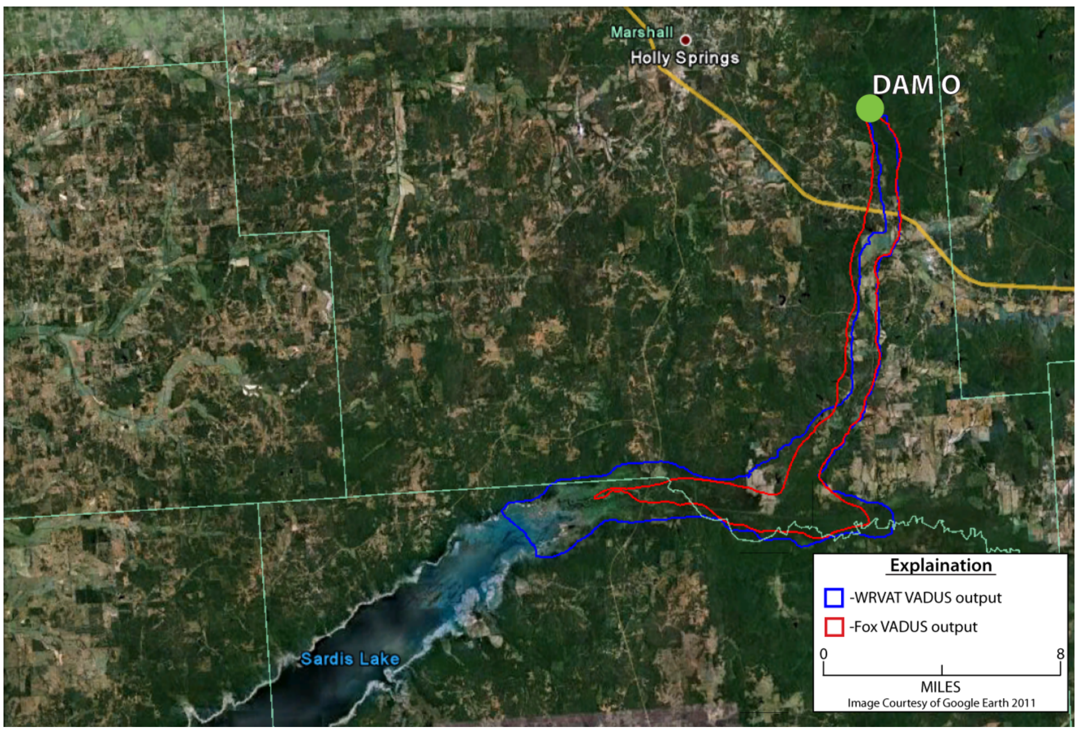

Figure 14.
Difference in user interpreted VADUS output for Dam O.

6.3 Comparing Similar Factors

The consequence factors of WRVAT, PAM, and SCIM were correlated between each other (Table 15). WRVAT uses a computer-generated value that considers roads, universities, prisons, hospitals, and census data. The PAM involves time consuming fieldwork and deskwork. Houses, businesses, emergency responders, roads, and farmland were recorded for each dam. The population within the area was based on the size of houses observed. SCIM's method uses a generalized ranking table that considers population, industry, natural resources, and farmland. Scoring was based on fieldwork. Farmland included in SCIM and PAM and detail involved in WRVAT and PAM can account for the major differences between the consequence factors.

	WRVAT	PAM	SCIM
WRVAT	1	0.731	0.580
PAM		1	0.827
SCIM			1

Table 15.
Correlation coefficients between each method's consequence factors.

The consequence factor is the most influential term in WRVAT and PAM calculations. Therefore, it is important to accurately represent the consequences of a dam failure. WRVAT was recalculated using the fieldwork consequences (Figure 15). The new WRVAT results were very similar to those of PAM with minor differences between Dams H, K, L, M, N, P, and R. The differences can be attributed to the different extrinsic vulnerabilities and the total risk index based on the physical conditions of a dam.

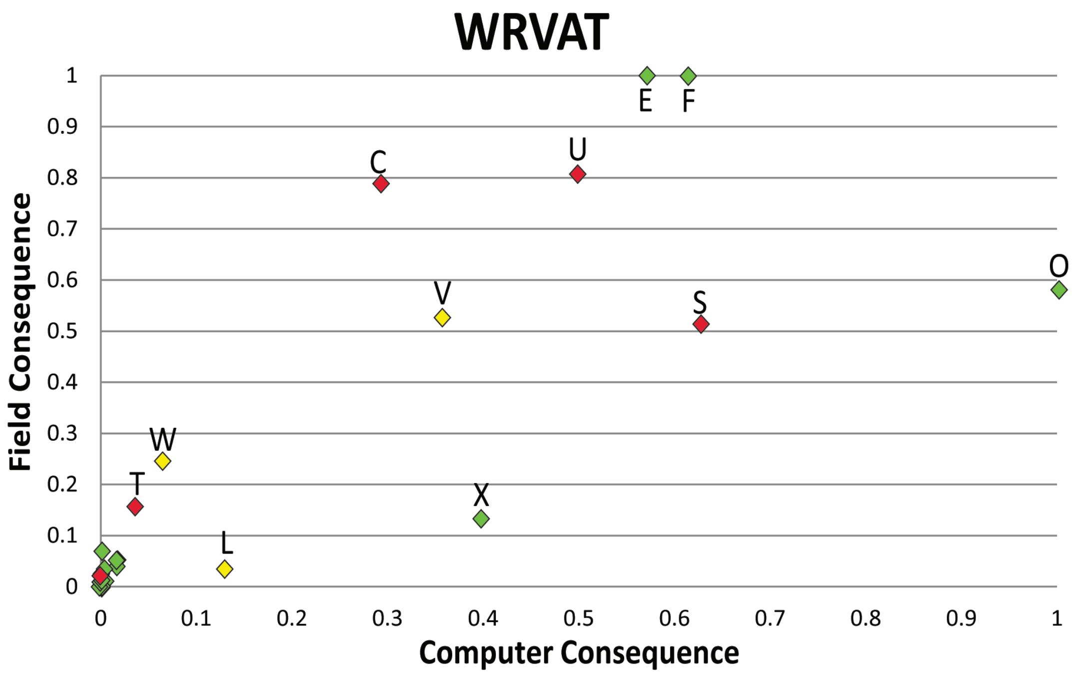

Figure 15.
Comparing WRVAT results calculated with different consequence factors.

SCIM considers extrinsic factors as the time dependent factors that affect a dam. The age and seismic hazard are the only two variables considered in SCIM's extrinsic calculation. WRVAT includes both variables in the intrinsic vulnerability. Extrinsic vulnerability is the damage done by an external threat. Intentional, unintentional, and animal activities are scored based on reported incidents to determine WRVAT's extrinsic vulnerability. The PAM method expands WRVAT to include a basic security variable by scoring the accessibility at each dam. Correlations between SCIM's extrinsic factor and the other two methods' extrinsic vulnerabilities resulted in no relationship. There is a strong relationship between WRVAT and PAM ($r = 0.83$). Removing IR_{TOT} from the PAM method and comparing the results to the new WRVAT results indicates that dams with higher consequence factors are more likely to be targeted by individuals with malicious intent, but heightened security at these dams can detour successful negative actions (Figure 16).

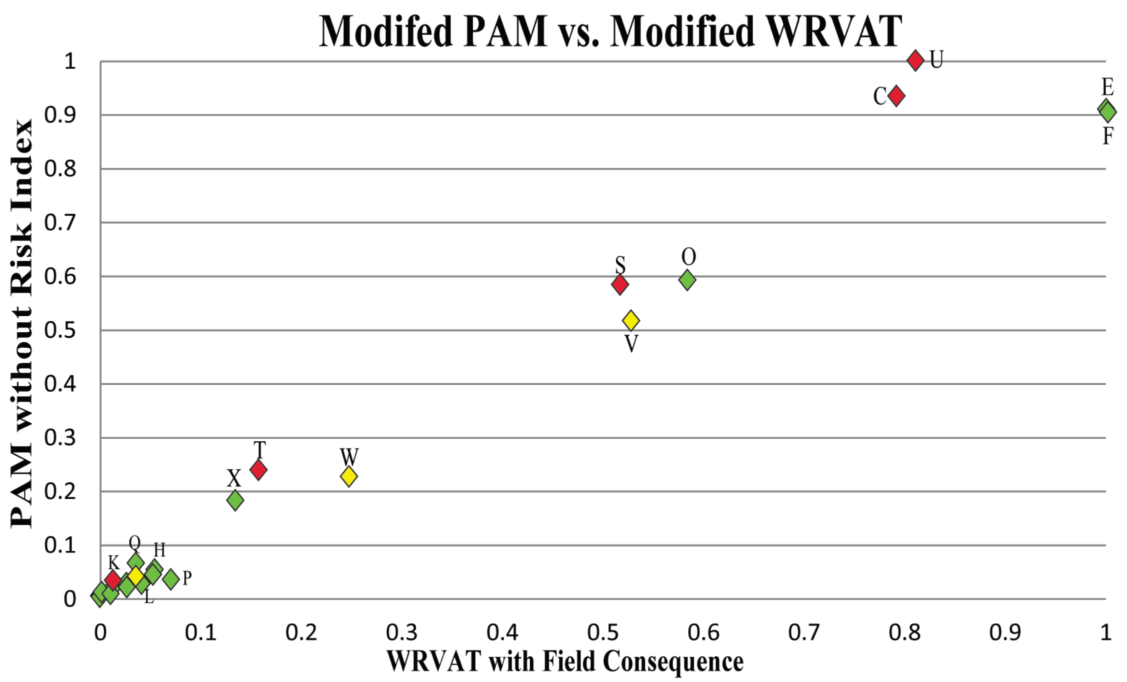

Figure 16.
Comparing WRVAT and PAM with different extrinsic vulnerabilities only.

6.4 Sensitivity Analysis of PAM

A thorough sensitivity analysis was applied to PAM and its components to determine which factors had the greatest impact on the results. All components were scaled between 0 and 1 before calculating vulnerability, but components were not scaled for the individual sensitivity analysis. Consequence is the most influential term when determining vulnerability using this method (Figure 17). Consequence is multiplied by the sum on the intrinsic, extrinsic, and risk factors (in order of importance). User defined multiplicative factors are applied to these three components to distinguish between them. A sensitivity analysis was conducted on each component individually except for total risk (IR_{TOT}). Changing the terms that comprise the risk component showed minimal effect on the overall risk total. All terms hold relatively equal importance.

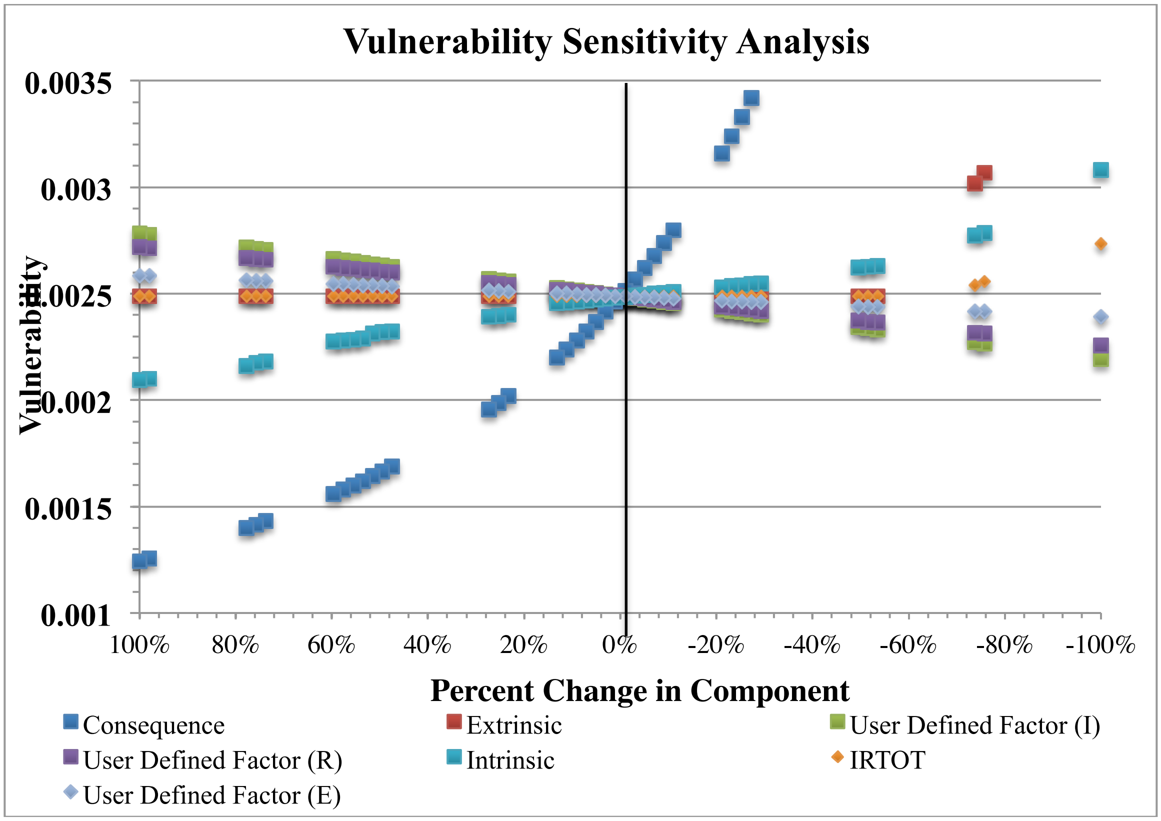

Figure 17.
Sensitivity analysis of PAM vulnerability components.

Land use and transportation are the most influential consequence components (Figure 18). Both of these components are dependent on the amount of farmland and/or transportation type within the vulnerable area. Total land use and transportation values are not restricted to a maximum limit like inhabitance and residential structures. The user-defined factors are applied to all four-consequence components. Inhabitance, which is weighted heaviest for this study, was the least significant consequence component. More accurate population or occupancy data, increasing the weight, and increasing the ranking scale would increase the importance of this component and warrants serious consideration.

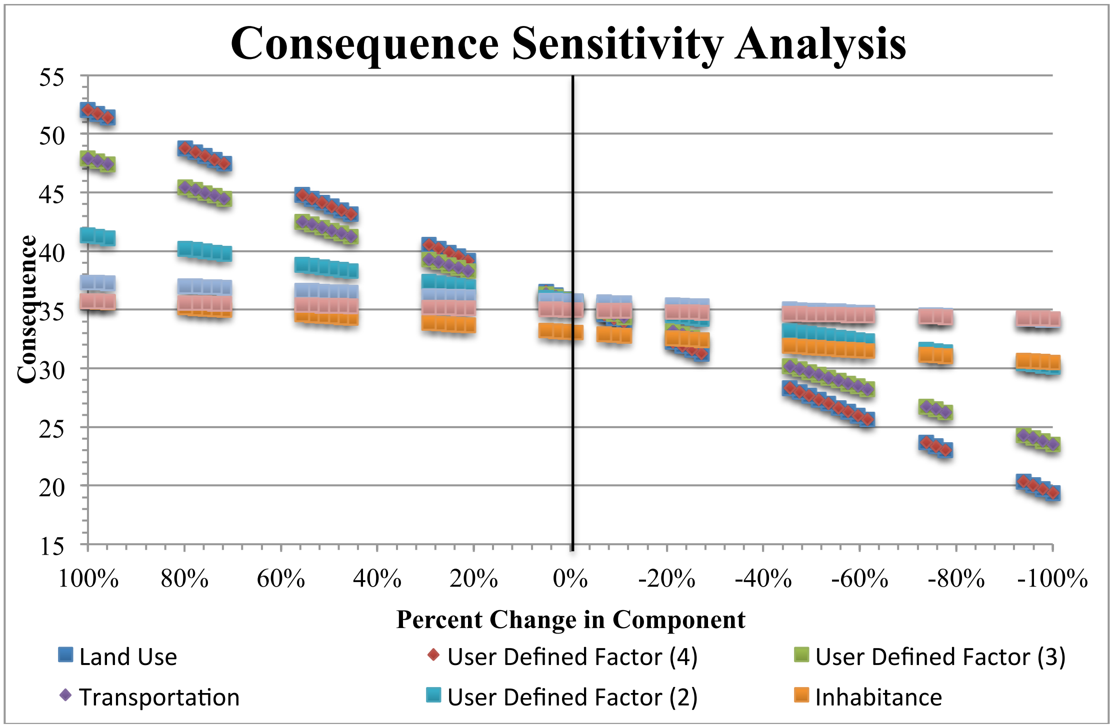

Figure 18.
Sensitivity analysis on the consequence components.

Spillway capacity, seismic hazard, slope stability, and age are the most important intrinsic components (Figure 19). Age, dam height, foundation type, and dam type, respectively, are of lesser importance. These four components are averaged against each other, whereas design components and time dependent components are averaged amongst themselves. Owner neglect is overwhelmingly the most important extrinsic component (Figure 20). Accessibility of the dam structure and likelihood of an attack make up the threat ratio. The overall sensitivity of PAM is best described as a consequence driven assessment method.

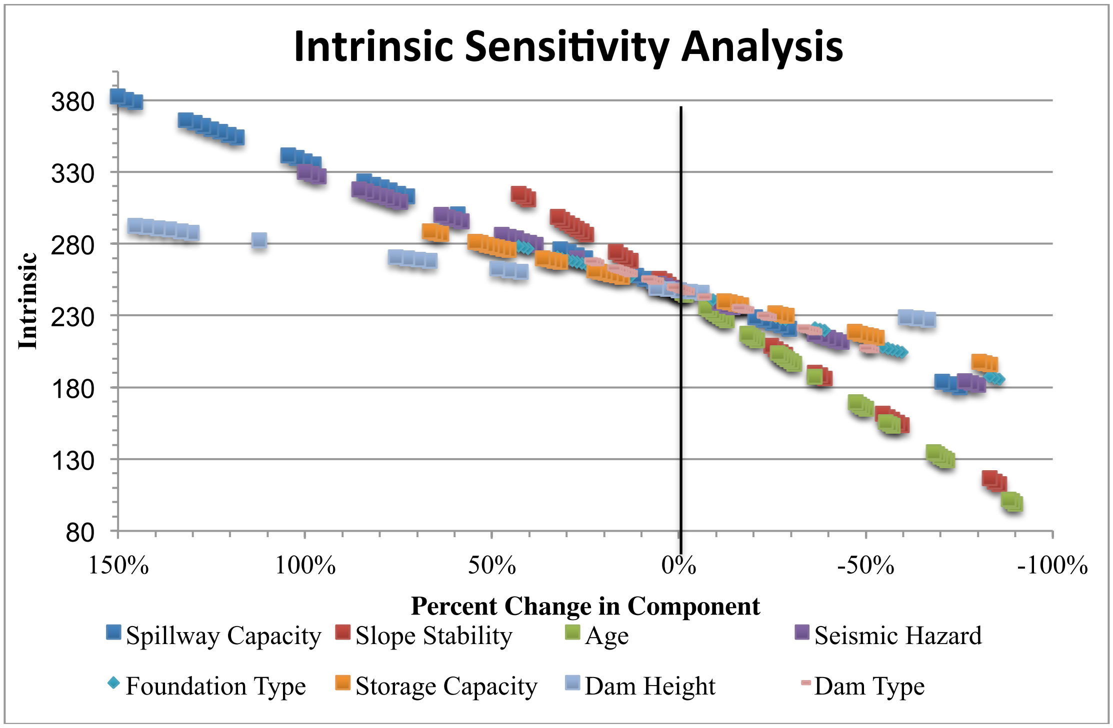

Figure 19.
Sensitivity analysis on the intrinsic components.

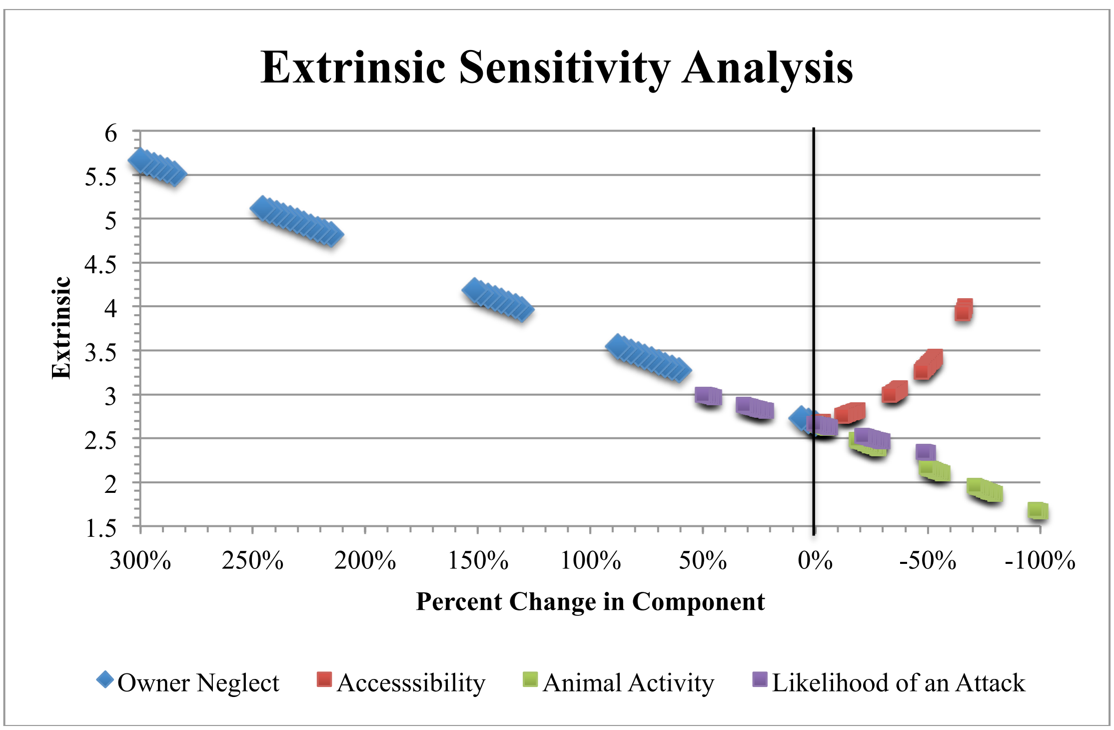

Figure 20.
Sensitivity analysis on the extrinsic components.

6.5 Adjusting Probability of Failure Mode Type to Mississippi

During fieldwork, the remains of two dams were encountered. The suspected failure mode was piping along the spillway, but there was no data available for either dam. The majority of reported dam failures in Mississippi are due to piping (MDEQ, 2011). The dam failure cases studied by USCOLD to develop the probability of failure modes ($P[M_i|F]$) in this analysis are not representative of the dams in Mississippi. The USCOLD study considered well-documented large concrete and earthen dams throughout North America. A lack of detailed information about dam failures prevented accurate Mississippi-specific failure mode probabilities to be applied during this analysis. Hypothetical probabilities were estimated based on field observations, known case studies, and personal communications with MDEQ (Table 16). There were no significant changes in the result rankings (Figure 21).

Failure Mode	Estimated Failure Mode Probability
Overtopping	0.20
Piping	0.60
Mass Movement	0.10
Surficial Erosion	0.10

Table 16.
Estimated Failure Mode Probabilities considering Mississippi dam Failures

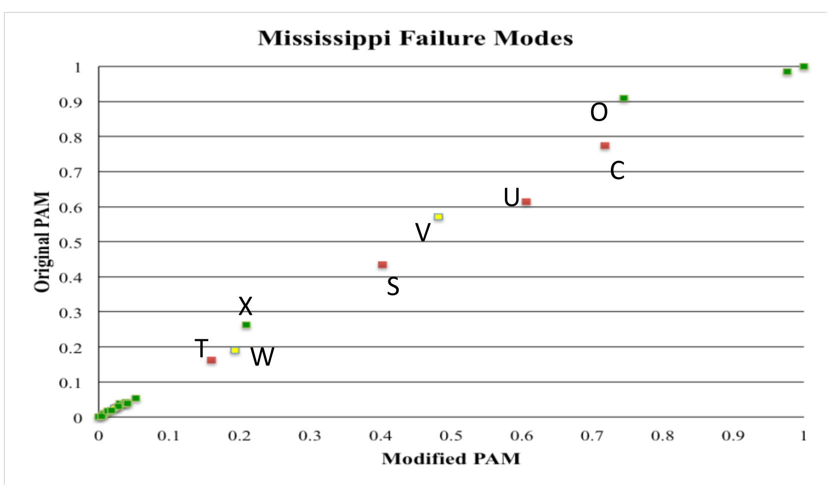

Table 21.
Calculated results of PAM using probabilities of failure modes specific to Mississippi plot against the original PAM results

Chapter 7: Conclusion

7.1 Advantages and Disadvantages

Indexing methods provide an effective means to systematically assess a dam inventory. Maintaining consistency during assessments is essential to all indexing methods. Each method reviewed in this study has advantages and disadvantages (Table 17). Some methods are better suited for different areas. The Javanese dam safety method is best restricted to smaller dams in unpopulated areas. The dams that rated in Good Group by the other methods were more distinguishable by the dam safety method. The physical condition of a dam is the primary factor for prioritizing dams in this method. SCIM, WRVAT and PAM are applicable to similar inventories. Distinctions between these three methods are in the detail required in the results. The user should select an indexing method based on the required information, resources available, and budget.

Indexing Method	Advantages	Disadvantages
WRVAT	• Cost Effective • "Quick" Assessment • Customizable • Expandable Consequence	• Condition Assessment • Relies on up to date data • Census Data • Security
SCIM	• Condition Assessment • Risk Component	• Generalized Consequence • Security • Threat
PAM	• Includes a Security factor • Thorough Consequence • Condition Assessment • Customizable	• Time Consuming • Impractical for a large inventory
Javanese	• Condition Dominant Assessment • Risk Component	• Consequence • Security • Threat

Table 17.
Advantages and Disadvantages of each indexing method included in this study.

7.2 Recommendations

An automated program that can quickly determine the risk of a dam failure would be beneficial in Mississippi. Connecticut and Massachusetts are in the process of implementing such programs to serve as an early warning system for state officials and the impacted communities (Baribault et al., 2010) (Gregory et al., 2010). The limitation in accurately prioritizing a dam inventory is the availability and management of data. Acquiring all of the data required to manage Mississippi's dam inventory would involve policy changes within the state governing and regulatory agencies.

Mississippi has 3715 inventoried dams. This number increases yearly as new dams are built, unregistered dams are found, and paperwork is filed. Data pertaining to high and significant hazard dams is the focus of current database improvements by MDEQ. Moving to a digital database would improve organization and accessibility while reducing the required physical space. Permits, inspection results, repairs, etc. could be submitted digitally and organized using database management software. Questionable data submissions would be easier to identify, letters to owners could be automatically generated, and compliance enforcement could be tracked using a digital database with management tools.

Low hazard dams are not required to be regularly inspected. It is the responsibility of a dam owner to properly maintain their dam. Mandating triennial assessments of all low hazard dams would ensure that a dam is well maintained. A generalized assessment guide could be implemented that numerically scores components of the dam. Results could be submitted through a “user friendly” web interface and added to the database. A conditions-based assessment could be completed to assess the dam inventory, but more data would be required to determine the consequences of a dam failure.

Calculating an inundation area for an entire dam inventory can be a time consuming task. VADUS offers a conservative assessment of the area that would be vulnerable to a dam failure. VADUS does not consider flood routing and is not suited for flat topography (Mississippi Delta region), but it does allow a user to calculate assessment areas for multiple dams. HEC-RAS is the breach modeling method preferred by MDEQ. USACE offers a GIS based tool that efficiently calculates an inundation area one dam at a time.

Census tract data is publicly available and is updated every ten years. Results are low resolution and in some areas do not represent the true population in that area (See Figure 14). Two alternatives to census tract data are parcel ownership data or using satellite imagery of the state. Parcel ownership data is used by county tax offices and is not available to the public. Not all counties use digitized systems although standardizing the entire state’s parcel data on a digital standard has been proposed. Ownership parcel data would not give information about the population or about the size or locations of houses within the impacted area, assuming that one house is located on each parcel. House locations and sizes can be determined using classified statewide hyperspectral imagery to extract residential housing data (Momm et al., 2010). Imagery can also be used to determine the amount of farmland within an impacted area. Population data would need to be assumed for both datasets.

A large initial investment would be required to implement a database management tool. If Mississippi adopted an inventory management tool that considered intrinsic vulnerability, extrinsic vulnerability, physical conditions, and consequence, the dams within the inventory could be prioritized to conditions or risk depending on the user's need. A tool of this magnitude would improve database organization, increase work efficiency, and ensure regulatory compliance. The required data would benefit the existing database regardless of a management tool. It is important to hold all dam owners accountable to maintain their structures.

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LIST OF APPENDICES

APPENDIX A

Dam Inventory for this Study

DAM	County	Hazard Potential	Year Completed	Owner Type	Purpose
A	PERRY	Low	1963	State	Recreational
B	FORREST	Low	1960	Private	Recreational
C	PONTOTOC	High	1974	State	Recreational
D	MONROE	Low	1965	Local	Other
E	LAFAYETTE	Low	1958	Local	Flood Control
F	LAFAYETTE	Low	1951	Local	Flood Control
G	GEORGE	Low	1993	Private	Recreational
H	FORREST	Low	1972	State	Recreational
I	FORREST	Low	1959	Private	Recreational
J	FORREST	Low	1965	State	Recreational
K	LAFAYETTE	High	1994	Private	Recreational
L	LAFAYETTE	Significant	1999	Private	Recreational
M	LEE	Low	1980	State	Recreational
N	LAFAYETTE	Low	1959	Private	Recreational
O	MARSHALL	Low	1966	Local	Flood Control
P	MARSHALL	Low	1935	State	Recreational
Q	LAFAYETTE	Low	1961	Local	Flood Control
R	COPIAH	Low	1961	Private	Recreational
S	LEE	High	1978	State	Flood Control
T	STONE	High	1965	State	Recreational
U	LAMAR	High	1985	Private	Recreational
V	LAFAYETTE	Significant	2002	Private	Recreational
W	LAFAYETTE	Significant	1999	Private	Recreational
X	LAFAYETTE	Low	1991	Private	Recreational

Table 1.
Inventory of dams selected for this study.

APPENDIX B

Fieldwork Checklist

Dam:________________

Date:_______________

Embankment

1. Is there major vegetation growth near the crest of the dam?

2. How much freeboard is there? (CF2)

3. Is there embankment protection on the upstream side? (CF5)

4. Is there surface drainage around the dam?

5. Are there any signs of major erosion? (CF5)

6. Are there any signs of animal activity on the embankments?

7. Are there any wet/ damp areas on the embankment? Not weather related (CF6)

8. Are there any signs of mass movement on the embankment? (CF8)

Foundation

1. Are there any signs of piping at the foundation? Pooling? (CF7)

2. Are there any signs of mass movement at the foundation? (CF9)

Spillway

1. Type of spillway?

2. Is the spillway intake obstructed? (CF1)

3. What is the condition of the low level outlet works? (CF3)

4. Is there an Emergency Spillway?

5. Are there any signs of erosion around the spillway? (CF4)

6. What is the flowrate out of the low level outlet?

7. What is the condition of the downstream drainage area?

Reservoir

1. Estimate the current level of the reservoir?

2. Is there a noticeable amount of floating debris in the reservoir?

Security

1. Is the dam easily accessible? Road access?

2. Are there any gates?

3. Locks?

4. Security presence?

5. Are there recreational areas near the dam?

Failure Mode

- Overtopping:

- Piping:

- Surficial Erosion:

- Mass Movement:

Consequence Mapping

1. Number of houses marked (Estimated Size (Large, Medium, Small))
2. Land use in the area
    a. Businesses:
    b. Emergency responders:
    c. Schools:
    d. Other:

APPENDIX C

Ideology During Fieldwork

Assessing the deficiencies in the condition of a dam, how those deficiencies affect the overall performance of that dam and contribute to the four failure modes considered were left to the judgment of the dam inspector. The checklist in Appendix B was completed during visits of all dams included in this study. Dam visits focused on four major components: (1) the embankment, (2) the spillway, (3) the downstream channel, and (4) the accessibility of the dam. Photographic evidence of dam conditions was taken of noted deficiencies. Although several dams were in poor condition, those conditions did not indicate looming failure of the associated dam. Questions that were kept in mind during visits:

- Does the deficiency increase the likelihood of a failure occurring?
- Will the deficiency severity increase quickly when subjected to normal conditions?
- Are there any indications that a repair was attempted?
- How does the deficiency affect the overall performance of the dam?

The embankment component included the upstream and downstream slopes, the crest, the downstream toe of the dam, and abutments. The embankment was inspected for evidence of mass movement, erosion, wet areas, slope protection against wave action, and animal activity (burrows and beaver activity). Common defects were erosional ruts and medium- size trees growing at or near the crest. A few dams exhibited major defects such as erosion~~s~~ of the upstream slope, sinkhole on crest, and longitudinal~~,~~ and transverse cracking.

The spillway includes the principle spillway, low-level outlet works, and emergency spillway if present. Spillway design was highly variable but all were checked for settlement, cracking, and blockages. The spillway discharge clarity was also observed to ensure internal erosion was not occurring. Spillway obstruction was the most common problem encountered.

The severity of blockage was determined by the amount of debris caught in the trashrack, the remaining flow compared to the reservoir level, and the remaining freeboard.

The downstream channel included the area immediately below the dam as well as the area further downstream that would be affected in the event of a failure. The area immediately below the dam should be channelized and protected from erosion. Unchannelized downstream areas were viewed as owner negligence because they increases the possibility of failure with the foundation caused by mass movement or piping. It was impossible to inspect the downstream toe and the foundation condition on dams visited with unchannelized drainage areas because of pooling water. The downstream channel should also be sufficiently protected against erosion as a result of turbid flow. Severe conditions were considered to be erosion undercutting the spillway outlet but were not encountered during this study.

Accessibility of a dam was determined by obstacles in place that prevented vehicular access, presence of officials or owners at the dam, and accessibility of spillway valves. The presence of recreational areas (campgrounds and fishing holes) was also considered. Dams with no preventative security measure are easily accessed and are considered to be more accessible to malicious acts whether they are intended to degrade the structure or not.

APPENDIX D

SCIM Dam Importance Summary

Intrinsic Factor

The intrinsic factor is the time independent variables and consists of height of embankment, type of dam, type of foundation, and storage capacity.

	Height of Dam (ft)	**Score**
I_1	< 9	1
	9-40.	3
	40-100.	6
	>100	10
	Type of Dam	**Score**
I_2	Rockfill (>= Cobble)	4
	Earthfill	10
	Type of Foundation	**Score**
I_3	Rock	1
	Moraine	5
	Alluvium	100
	Storage Capacity (acre-ft)	**Score**
I_4	< 50	1
	50-999.	3
	1000-50000.	6
	>50000	10

Design Factor

The design factors considered are spillway adequacy and slope stability. Spillway adequacy is the designed maximum flow a spillway can handle without overtopping the embankment. Known conditions are only selected if an official hydrologic and hydraulic analysis was in the MDEQ database for spillway adequacy. Slope stability is related to the likelihood that a slope is prone to instability.

	Spillway Conditions	**Score**
Spillway Adequacy (D_1)	**Known**	
	Capacity < 50% required	10
	Capacity > 50% required	5
	Capacity > required	1
	Suspected	
	Capacity < required	5
	Capacity > required	2
Slope Stability (D_2)	**Slope Conditions**	**Score**
	Known	
	FS < required	10
	FS > required	1
	Suspected	
	FS < required	7
	FS > required	2

Extrinsic Factor

Extrinsic factors are the time dependent variables of a dam and considered the age of the dam (E_1) and the Seismic hazard the dam could be subjected to (E_2).

	Age of the Dam	Score
E_1	0-9.	10
	10-29.	8
	30-59.	5
	60-99.	2
	>100	1
E_2	**Modified Mercalli Intensity**	**Score**
	V or lower	1
	VI	2
	VII	6
	VIII	8
	IX	10

Hazard Potential

Hazard potential was determined using field data and applying results to the table below (Anderson et al.,1999) to score each dam's hazard potential.

Area Affected	Score
Uninhabited and undeveloped area with few natural resources	1
Occasionally inhabited territory, Cultivated farmland	3
Rural Development (< 2000 people), small- and medium- size industries, some natural resources	5
Rural Development (> 2000 people), medium- to Large- size industries, major natural resources	8
Major City (>10000 people) Major industries	10

APPENDIX E

Physical Condition Ranking Tables

The observed physical conditions of the nine key components (Table 2) of a dam were scored using ranking tables proposed by Anderson et al., 2001. If there is an absence of any indicator described, a condition of 10 was assigned.

	Indicator	Scoring Range
Spillway Obstruction (CF1)	**Part of the spillway cross section if obstructed**	
	0-10% obstructed	7-10
	10-25% obstructed	4-7
	>25% obstructed	0-4

	Indicator	Scoring Range
Loss of Freeboard (CF2)	**Deviation from original crest elevation**	
	0-10% loss	7-10
	10-25% loss	4-7
	>25% loss	0-4
	Trees on or near crest	0-5

	Indicator	Scoring Range
Low- Level Outlet Condition (CF3)	**Obstructions in cross section of outlet pipes**	
	0-10% obstructed	7-10
	10-25% obstructed	4-7
	>25% obstructed	4-0
	Suspected but unverified obstruction	7-10

	Indicator	Scoring Range
Spillway Erosion (CF4)	**Observed erosion/deterioration of spillway channel**	
	None to Minor	7-10
	Some to Moderate	4-7
	Serious to Extensive	1-4
	Critical with sill lost	0

Embankment Surface Material (CF5)	Indicator	Scoring Range
	Loss of upstream slope protection	
	None to isolated and moderate loss or degradation	4-10
	Serious to extensive loss or degradation	1-4
	Critical loss or degradation (Bed material exposed)	0
	Loss of embankment surface material	
	Slight (0-1 ft.)	7-10
	Moderate (1-2 ft.)	5-7
	Extreme (>2ft.)	0-5

Piping in the Embankment (CF6)	Indicator	Scoring Range
	Turbid Flow	
	Evidence of a prior condition gone unrepaired	2-7
	Actively occurring	0-2
	Sinkholes or depressions on the surface of the dam	0-5
	Buildup of pore water pressure in embankment as inferred by uncontrolled seepage areas in the toe and abutment areas	
	Changes in surface vegetation	5-10
	Soft/wet areas on the surface	4-8
	Constant surface flow	2-7
	Increasing surface flow	0-4
	Stumps and root systems left in place on embankment or animal burrows present	0-5

	Indicator	Scoring Range
Piping in the Foundation (CF7)	**Turbid Flow**	
	Evidence of a prior condition gone unrepaired	2-7
	Actively occurring	0-2
	Sinkholes or depressions on the surface of the dam	0-5
	Buildup of pore water pressure in foundation as inferred by uncontrolled seepage areas in the toe and abutment areas	
	Changes in surface vegetation	5-10
	Soft/wet areas on the surface	4-8
	Constant surface flow	2-7
	Increasing surface flow	0-4

	Indicator	Scoring Range
Mass Movement of the Embankment (CF8)	**Buildup of pore water pressure in embankment as inferred by uncontrolled seepage areas**	
	Changes in surface vegetation	5-10
	Soft/wet areas on the surface	4-8
	Constant surface flow	2-7
	Increasing surface flow	0-4
	Surface evidence of impending mass movement such as cracking, shallow slides, and differential movement in the embankment or between the embankment and foundation	
	Minor and Localized	2-8
	Major and extensive	0-2

<table>
<tr><td rowspan="10">Mass Movement of the Embankment and Foundation
(CF8)</td><td>Indicator</td><td>Scoring Range</td></tr>
<tr><td colspan="2">Build up of pore water pressure in embankment and foundation as inferred by uncontrolled seepage areas</td></tr>
<tr><td>Changes in surface vegetation</td><td>5-10</td></tr>
<tr><td>Soft/wet areas on the surface</td><td>4-8</td></tr>
<tr><td>Constant surface flow</td><td>2-7</td></tr>
<tr><td>Increasing surface flow</td><td>0-4</td></tr>
<tr><td colspan="2">Surface evidence of impending mass movement such as cracking, shallow slides, and bulges</td></tr>
<tr><td>Minor and Localized</td><td>2-8</td></tr>
<tr><td>Major and extensive</td><td>0-2</td></tr>
</table>

APPENDIX F

Physical Conditions of the Dams and the Associated Risk

DAM	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
CF1	10	7	10	6	2	3	8	10	7	8	9	10	8	7	8	9	9	8	9	8	10	8	7	6
CF2	10	5	10	6	4	5	9	10	10	10	8	9	10	8	8	10	8	5	10	10	10	10	10	10
CF3	9	8	9	7	6	4	8	10	8	9	9	8	8	7	10	7	10	8	10	10	8	10	10	8
CF4	10	5	8	5	6	4	7	9	10	7	10	8	8	7	10	8	8	7	10	8	10	7	8	4
CF5	9	6	8	7	7	8	8	8	7	9	9	8	8	6	8	8	7	8	8	7	8	7	7	8
CF6	9	5	10	5	5	5	8	10	10	6	8	8	10	8	7	10	10	8	10	10	10	8	10	5
CF7	7	6	8	7	10	10	10	10	10	6	8	9	7	9	7	8	10	10	8	10	9	7	10	5
CF8	8	5	10	7	10	10	10	8	8	8	8	10	8	8	7	7	10	8	10	8	10	8	7	8
CF9	10	4	8	5	7	7	10	10	8	7	8	10	8	8	8	8	10	10	8	8	9	10	7	5
Risk corresponding to physical condition																								
IR1	0	2	0	4	85	74	1	0	3	3	7	0	13	5	20	1	3	4	6	6	0	34	42	16
IR2	0	8	0	6	9	8	1	0	0	0	7	10	0	7	3	0	2	3	0	0	0	0	0	0
IR3	2	7	19	2	12	18	2	0	0	0	1	38	7	2	0	6	0	7	0	0	63	0	0	5
IR4	0	3	8	2	2	3	0	0	0	1	0	4	2	1	0	1	2	2	0	2	0	13	7	4
IR5	1	2	3	1	7	4	1	2	1	0	2	8	4	4	5	0	1	1	8	5	6	6	5	3
IR6	2	13	0	4	35	35	2	0	0	4	11	29	0	6	23	0	0	6	0	0	0	27	0	30
IR7	9	4	12	4	0	0	0	0	0	2	5	6	10	1	10	1	0	0	8	0	10	27	0	13
IR8	2	3	0	1	0	0	0	2	0	0	2	0	3	1	5	1	0	1	0	3	0	7	9	3
IR9	0	3	6	2	5	5	0	0	0	1	2	0	3	1	3	1	0	0	6	3	5	0	9	7
IR_{TOT}	16	45	48	25	154	147	6	4	5	11	37	95	43	28	71	11	8	24	28	18	84	113	72	81

APPENDIX G

SCIM Results Summary

DAM	I1	I2	I3	I4	E1	E2	D1	D2	V	H	I_{dam}	PR
A	3	8	0	3	5	1	8	7	78.8	2	157.5	0.019
B	3	8	0	3	5	1	4	7	57.8	2	115.5	0.042
C	6	8	0	6	5	3	5	10	150.0	6	900.0	0.358
D	1	8	0	3	5	3	5	7	72.0	1	72.0	0.014
E	3	8	0	3	5	5	2	7	78.8	5	393.8	0.502
F	3	8	0	3	5	5	2	7	78.8	5	393.8	0.479
G	3	8	0	1	8	1	2	7	60.8	1	60.8	0.002
H	3	8	0	6	5	1	4	7	70.1	3	210.4	0.006
I	3	8	0	1	5	1	2	7	40.5	1	40.5	0.000
J	3	8	0	3	5	1	4	7	57.8	1	57.8	0.004
K	3	8	0	1	8	5	4	7	107.3	3	321.8	0.098
L	3	8	7	6	10	5	4	7	247.5	3	742.5	0.582
M	3	8	0	3	8	3	2	7	86.6	5	433.1	0.152
N	3	8	0	3	5	5	2	7	78.8	2	157.5	0.035
O	6	8	0	6	5	6	2	7	123.8	4	495.0	0.288
P	1	8	0	3	2	6	5	7	72.0	1	72.0	0.005
Q	3	8	0	6	5	5	2	7	95.6	2	191.3	0.011
R	3	8	0	3	8	1	3	7	78.8	2	157.5	0.029
S	6	8	0	6	5	3	10	8	180.0	5	900.0	0.211
T	6	8	0	6	5	1	4	7	82.5	5	412.5	0.061
U	3	8	7	6	8	1	10	8	243.0	5	1215.0	0.842
V	6	8	0	3	10	4	10	8	267.8	4	1071.0	1.000
W	3	8	0	3	10	4	10	10	245.0	3	735.0	0.435
X	3	8	0	3	8	5	3	7	113.8	3	341.3	0.228

APPENDIX H

Javanese Dam Safety Results Summary

DAM	I_{dam}	IR_{TOT}	N
A	157.5	16.0	89.9
B	115.5	45.5	60.6
C	900.0	48.3	92.3
D	72.0	25.4	61.4
E	393.8	154.3	50.1
F	393.8	147.1	52.4
G	60.8	6.5	85.8
H	210.4	4.4	97.5
I	40.5	4.6	84.8
J	57.8	11.0	75.9
K	321.8	37.4	84.5
L	742.5	94.8	85.4
M	433.1	42.7	87.4
N	157.5	28.0	77.4
O	495.0	70.7	79.6
P	72.0	10.9	83.5
Q	191.3	7.9	95.0
R	157.5	23.7	80.8
S	900.0	28.5	95.5
T	412.5	18.2	93.7
U	1215.0	83.8	92.1
V	1071.0	112.8	83.7
W	735.0	71.7	87.6
X	341.3	81.0	69.8

APPENDIX I

WRVAT Extrinsic Vulnerability Summary

WRVAT's extrinsic vulnerability is the external threats associated with a dam. The intentional harm by humans (E_1), animal activity (E_2), and negligence of the dam owner (E_3) are based on reported problems. There were no reports filed in the database for the study inventory. Information collected during field work was used to satisfy the data requirements for extrinsic vulnerability

E1	**Harm by Humans**	**Score**
	Federally Owned	5
	State or Locally Owned	2
	Privately Owned	1
E2	**Animal Activity**	**Score**
	Multiple Reports	10
	1 Report	5
	No Reports	1
E3	**Owner Negligence**	**Score**
	Owner Negligence is rated by the severity of the problem reported. A score of 10 is given for non-compliance	10
		7
		4
		1

APPENDIX J

WRVAT Results Summary

DAM	I1	I2	I3	I4	A1	A2	D1	D2	E1	E2	E3	C	V
A	3	8	0	3	5	1	8	7	2	1	1	18.2	0.00638
B	3	8	0	3	5	1	4	7	1	1	7	3.2	0.00173
C	6	8	0	6	5	3	5	10	2	1	1	575.8	0.29323
D	1	8	0	3	5	3	5	7	2	5	10	2.2	0.00232
E	3	8	0	3	5	5	2	7	2	5	10	452.9	0.57072
F	3	8	0	3	5	5	2	7	2	5	10	487.0	0.61368
G	3	8	0	1	8	1	2	7	1	1	3	11.6	0.00271
H	3	8	0	6	5	1	4	7	2	1	1	81.4	0.01908
I	3	8	0	1	5	1	2	7	2	1	1	0.4	0.00000
J	3	8	0	3	5	1	4	7	2	1	7	1.7	0.00083
K	3	8	0	1	8	5	4	7	1	1	1	8.7	0.00241
L	3	8	7	6	10	5	4	7	1	1	1	121.5	0.13062
M	3	8	0	3	8	3	2	7	2	1	4	34.5	0.01796
N	3	8	0	3	5	5	2	7	1	5	7	19.0	0.01770
O	6	8	0	6	5	6	2	7	2	1	4	1577.5	1.00000
P	1	8	0	3	2	6	5	7	2	5	4	3.5	0.00257
Q	3	8	0	6	5	5	2	7	2	1	1	14.7	0.00510
R	3	8	0	3	8	1	3	7	1	5	4	1.6	0.00088
S	6	8	0	6	5	3	10	8	2	1	1	994.1	0.62710
T	6	8	0	6	5	1	4	7	2	1	1	158.1	0.03716
U	3	8	7	6	8	1	10	8	1	1	1	472.4	0.49843
V	6	8	0	3	10	4	10	8	1	1	2	395.3	0.35732
W	3	8	0	3	10	4	10	10	1	1	3	60.5	0.06570
X	3	8	0	3	8	5	3	7	1	1	7	495.2	0.39787

APPENDIX K

PAM Extrinsic and Consequence Summary

Scores assigned to variables for each dam for PAM's extrinsic vulnerability calculation.

DAM	C_R	A_D	E2	E3
A	2	3	1	1
B	2	3	1	2
C	4	3	1	1
D	2	1	2	2
E	3	1	2	2
F	3	1	2	2
G	1	2	2	1
H	2	3	1	1
I	1	3	1	1
J	1	1	1	2
K	2	1	1	1
L	2	2	1	1
M	2	2	1	1
N	1	1	2	2
O	2	2	2	1
P	1	3	2	1
Q	1	1	2	1
R	2	1	1	1
S	4	3	1	1
T	4	3	1	1
U	4	2	1	1
V	2	2	1	1
W	2	2	1	1
X	2	1	2	2

Scores assigned to variables for each dam for PAM's consequence factor calculation.

DAM	C1	C2	C3	C4	C
A	1	1	0.46	0.00	3.46
B	1	1	1.32	0.00	4.32
C	16	16	40.62	65.35	153.97
D	0	0	0.00	0.00	0.00
E	16	16	11.25	19.50	78.75
F	16	16	11.19	19.50	78.69
G	0	0	1.22	0.00	1.22
H	1	2	14.15	3.84	22.99
I	0	0	0.38	1.50	1.88
J	0	0	0.31	1.50	1.81
K	1	1	0.35	1.50	4.85
L	1	1	0.00	0.36	3.36
M	1	1	1.78	3.05	7.83
N	1	1	0.59	2.00	5.59
O	4	4	64.93	14.25	91.18
P	1	1	3.74	1.83	8.57
Q	0	0	4.69	5.47	10.16
R	1	1	0.81	0.00	3.81
S	8	8	24.82	32.30	81.12
T	16	16	15.14	3.53	66.67
U	16	16	22.77	5.27	76.04
V	2	4	21.14	26.76	57.90
W	1	1	10.27	9.23	22.50
X	1	1	7.25	6.40	16.65

APPENDIX L

SCIM, WRVAT, Pam Results

Results of SCIM, WRVAT, and PAM scaled between 0 and 1. The dam groupings are also listed. This is the information used to produce Figures 10 and 11.

DAM	SCIM	WRVAT	PAM	Group
A	0.019	0.006	0.008	Good
B	0.042	0.002	0.018	Good
C	0.358	0.293	0.818	Growth
D	0.014	0.002	0.000	Good
E	0.502	0.571	1.000	Riskier, Growth
F	0.479	0.614	0.977	Riskier, Growth
G	0.002	0.003	0.002	Good
H	0.006	0.019	0.029	Good
I	0.000	0.000	0.000	Good
J	0.004	0.001	0.005	Good
K	0.098	0.002	0.024	Good
L	0.582	0.131	0.034	Newest, Riskier, Overestimated
M	0.152	0.018	0.028	Good
N	0.035	0.018	0.029	Good
O	0.288	1.000	0.588	Overestimated
P	0.005	0.003	0.023	Good
Q	0.011	0.005	0.038	Good
R	0.029	0.001	0.015	Good
S	0.211	0.627	0.422	Newest, Overestimated
T	0.061	0.037	0.177	Growth
U	0.842	0.498	0.830	Newest, Growth, Riskier
V	1.000	0.357	0.554	Riskier, Newest
W	0.435	0.066	0.193	Newest
X	0.228	0.398	0.157	Overestimated

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