Analysis of Dam Failures and Development of a Dam Safety Evaluation Program

THESIS

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By

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Abstract

Dam safety is developing into an increasingly more critical issue in the U.S. as many of our nations dams are deficient and at risk of failure. A dam failure can be a disastrous event with catastrophic consequences to the downstream area and the surrounding environment. Innundation from many dam failures have the potential for immense damage to property, the economy, the environment, and possibly fatalities. Many U.S. dams were built in first half of the 20th century and suffer from the effects of aging, deterioration, and poor engineering standards.

The goals of this study are to increase situational awareness of dam owners and regulators, provide a user friendly dam safety evaluation tool, and improve the nation's overall dam safety. The methods to achieve these goals include three steps:

1) Review and compile relevant dam safety background information such as different dam materials, designs, common failure causes, and proper inspection techniques;

2) Analyze recent dam failure and incident data from the Significant Incident Reporting (SIR) database and provide recommendations for future incident reporting;

3) Create a Knowledge Based Expert System (KBES) computer program as a tool to evaluate the overall safety level of an individual existing dam.

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Chapter 1) General Introduction

1.1) Introduction: Current Dam Safety Issues

With approximately 84,000 dams in the United States, they are undoubtedly an integral part of our nation's infrastructure. These dams serve numerous purposes which include, but are not limited to: flood control, water and power to cities, irrigation for agriculture, fire protection and recreation. Avoiding catastrophic dam failures is imperative to protect and sustain these benefits. Some dams retain thousands of acre-feet of water, rise high above ground, and span great lengths. Dam failures can release uncontrollable water flows which can result in severe consequences to downstream areas. When a dam breach occurs, the flooding can cause enormous economic losses, residential and agricultural damages, and even more importantly, loss of life.

Dam infrastructure has become an increasingly larger crisis in the U.S. Many U.S. dams pose a serious threat to people and property because of factors that include: 1) deficiencies and deterioration from aging; 2) older dams constructed prior to improved modern construction standards; and 3) an increase in the number of high hazard level dams. A high hazard dam is briefly defined as dam whose failure would result in the probable loss of life along with large economic consequences downstream.

The American Society of Civil Engineers (ASCE) has publically recognized this crisis in its *2013 Report Card for America's Infrastructure.* In this report, dam infrastructure received a "D" as its comprehensive grade. Deterioration and outdated standards are both key influences. The average life expectancy for a dam is approximately 50 years, and the ASCE reports the average age of dams in the United States to be 52 years old. By 2020, it is projected that 70% of dams will be over 50 years old. These older structures were built under the best standards of the time, but with improvements in scientific and engineering standards, these dams are no longer expected to be safely operational. According to the ASCE 2013 report, there are an estimated 4,000 deficient dams, 2,000 of which are deficient high hazard dams.

The increasing number of high hazard dams is also a serious issue. Many dams erected in the past were built as low hazard dams due to the undeveloped rural land downstream. The U.S Census Bureau estimates that by 2050 the United States population will increase by about 130 million people. Population growth is spurring development into the unpopulated areas downstream of these dams. This can result in previously built low hazard dams to become high hazard, increasing the need for a stricter regulatory and design standard. According to the ASCE, the number of high-hazard dams has increased from 10,118 in 2002 to nearly 14,000 in 2012.

(ASCE: http://www.infrastructurereportcard.org/a/#p/dams/conditions-and-capacity)

There are several challenges in solving these critical issues which include: lack of funding for dam rehabilitation, lack of regulation and emergency preparedness, and a low level of public awareness. Driving all these issues and subsequent activities in the dam safety community is the increasing risk of dam failures.

Generally, the dam's owner is solely responsible for the safety and liability of the dam and for financing its upkeep. Many different entities own and operate dams, with most of them privately owned. This private ownership makes funding for safety inspections, maintenance, and rehabilitation a big challenge. Figure 1-1 was created using the information from a report from January 2009 by the Association of State Dam Safety Officials (ASDSO). Figure XX shows that about 68.8% of dams are privately owned, 19.8% are owned by local government, 5.1% by the state, and federal and public unities own about 5.7%.

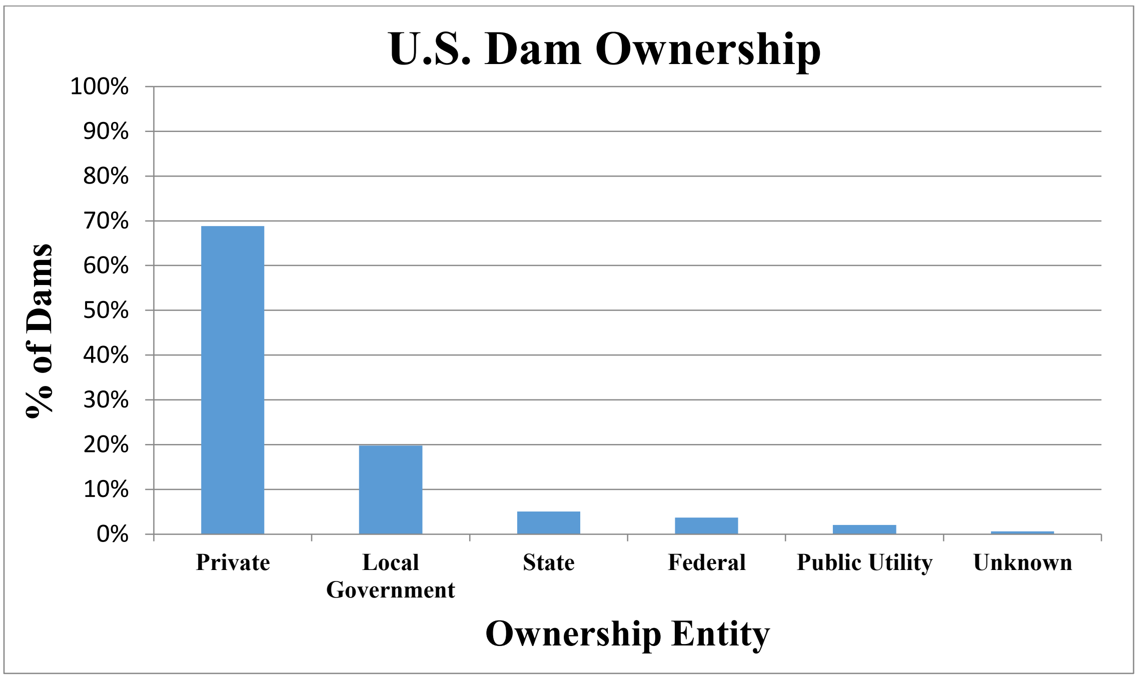


Figure 1-1: Dam Ownership Breakdown

(Data from ASDSO, Jan 2009: *The Cost of Rehabilitating Our Nation's Dam)*

Lack of funding for dam upgrades and repair is a serious issue, especially in the private sector. In many cases the dam owners cannot afford the cost of the dam's maintenance and rehabilitation which can sometimes cost into the millions. States are responsible for the oversight of approximately 77% of dams listed in the National Inventory of Dams (ASDSO - Journal of Dam Safety. Volume 11, Issue 3, 2013). Although many states offer loan programs, funding assistance through government or private sources is minimal at best. Reported by the ASDSO in December 2012, it was estimated that the total cost for non-federal dam rehabilitation was $53.69 billion, and for high hazard level dams was approximately $18.2 billion. (http://www.damsafety.org/news/?p=c0fdade4-ab98-4679 -be22-e3d7f14e124f#regulation)

The United States dam safety community is led primarily by the ASDSO. They provide a strong unified voice with effective programs and policies toward the furtherance of dam safety. Figure 1-2, created by the ASDSO, shows a map of historic dam failures with their respective time period and casualty rate. The large red dot in the gulf coast represents New Orleans during Hurricane Katrina. This map is not comprehensive and does not include any failures post 2010 or for numerous levee flooding's in the central states. There would also be much more activity if the map included Hurricane Irene which hit many dams in New York and New Jersey in 2011. It shows a large number of fatalities directly from dam failures in the last 25 years. The dam safety community hopes to reduce these numbers and fatalities as we move forward to a generation of infrastructure reform.

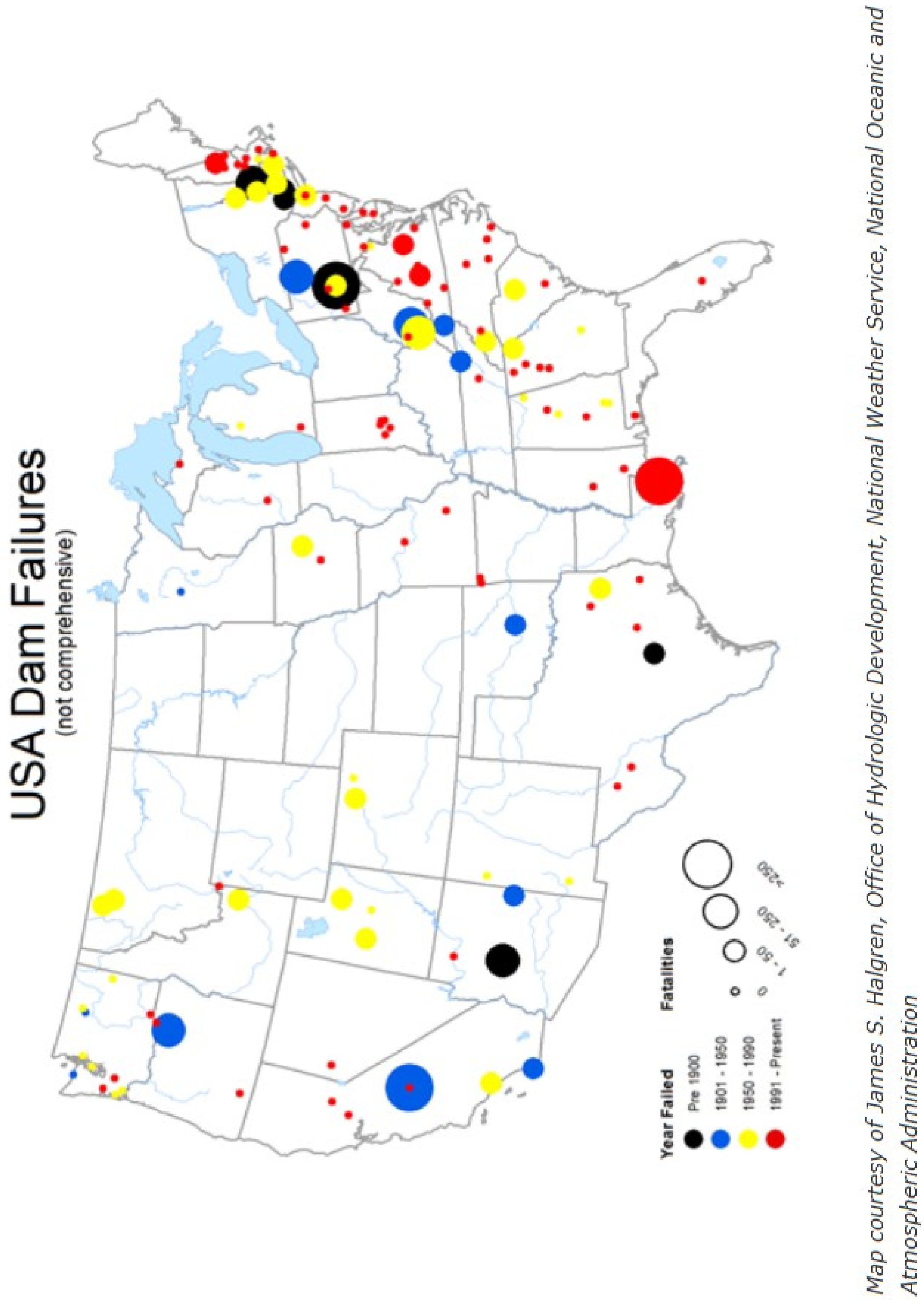


Figure 1-2: USA Dam Failures (ASDSO, 2010: http://www.damsafety.org/news/?p=412f29c8-3fd8-4529-b5c9-8d47364c1f3e)

The ASDSO, ASCE along with other organizations are leading the efforts to improve dam infrastructure, awareness, and safety. The focus of this study is to examine past dam failures and non-failure incidents using the Significant Incident Reporting (SIR) database. The ASDSO has been collaborating with the Department of Homeland Security Office of Infrastructure Protection for the past few years on the SIR database as a way to improve situational awareness. The ASDSO Dam Failure and Incidents Committee (DFIC) have undertaken a project to examine the incidents in the SIR. This study is designed to support the committee's task and provide analysis of correlations and trends in the incidents. The study will also incorporate a safety evaluation tool for use after a thorough inspection of the dam.

1.2) Goals and Objectives

The overall goal of this project was to strengthen the safety of dam infrastructure in the United State and decrease the number of avoidable dam failures in the United States. To accomplish this task this study will analyze recent dam failures and incidents and create a dam safety evaluation tool. In concert with the ASDSO's DFIC, this study analyzes the SIR database to find trends and correlations in recent dam failure and non-failure incidents. By disseminating these findings and making this tool available to federal dam safety regulators, dam owners and others, dam safety regulations may become more structured and allow a more systematic evaluation of dams so that their safety levels can be prioritized.

The methodology of this study will occur in this order: 1) review proper dam safety inspection techniques, and categorize different dam types and causes of failures; 2) examine past trends and correlations from the SIR database to gain insights and statistics; and 3) use these studies to create a post-inspection dam safety evaluation tool. This tool is a Knowledge Based Expert System (KBES) computer program used to estimate a dam's overall level of safety and risk. This tool is intended to be used after the dam has been inspected, so that expert determinations can be made about the potential enabling and triggering causes of failure. By combining these 3 steps in the assessment of dam safety it can be understood with greater certainty which dams require the most immediate attention, and it can help narrow the focus of resources required to address these critical dams.

1.3) Scope of Research and Study Design

The SIR database has been assembled by the combined efforts of the ASDSO and the DHS Office of Infrastructure Protection. All entries are from United States dams that have reported a dam incident. It is important to note that this study does not include all historic dam failure incidents but only the ones reported in the SIR.

The current SIR database includes 337 incident reports which include: 72 historical failure incidents prior to 2008, 99 failure incidents from 2008-present, and 166 "non-failure" incidents from 2008-present. "Non-failure" incidents are dam events that required attention and without intervention would likely have resulted in dam failure. These non-failure incidents were fixed or remediated before the failure of the dam;

however there is a great deal to learn from them. The SIR collects basic information on the dam with incident information including the dam type, incident cause, location, hazard level, date, brief description, if an Emergency Action Plan (EAP) was enacted, fatalities, damages, etc. Incidents collected in the SIR include both failure and non-failure incidents with about 50% of records being non-failure incidents since 2008.

The database examination in this study will look at main SIR variables including: dam type, incident cause, incident state, if the dam failed, hazard level, and if an EAP was enacted. It provides the analysis and statistics of these variables and how they correlate with one another. This study will also implement a tool which can be used to evaluate the overall safety level of an existing dam. This tool uses the statistics and findings of the SIR database along with a review of inspection techniques and categorizations of failure causes.

1.4) Significance and Potential Benefits

There is no known comprehensive dam failure database but the SIR is the beginning attempt at developing such a database. It is a relatively new endeavor taken on by the ASDSO and the DHS Office of Infrastructure Protection. Analysis of the current SIR reports along with the implementation of a dam safety evaluation tool can play a significant role in increasing national dam safety and awareness.

The findings in this study will be presented by a group in the DFIC at an ASDO conference in September 2014. Benefits include raising public awareness of the SIR database and increasing situation awareness of dam owners and regulation entities through the study's results. Public awareness of dam safety will bring the important task of rehabilitating our deteriorating dams into the limelight, making funding and regulation a more manageable task. State and federal dam safety regulators as well as private dam owners will have the means to improve their situational awareness and evaluation techniques.

The tool created in this study can be used to improve the overall safety level of existing dams. After a dam is inspected, this tool can be used in combination with the determinations made by an inspection team to provide an overall safety rating.

With the current state of dam infrastructure it is clear that continued efforts in dam safety will benefit the entire nation. Dam failures are not only a risk of public safety but can cost the economy millions of dollars in damages and losses. This makes dam safety research extremely significant and beneficial to cities, agriculture, wildlife, and the economy.

1.5) Challenges and Limitations

The main limitations with this study deal with the scope of the SIR database. The SIR is not comprehensive and only includes 72 reports prior to 2008. With the relatively small sample size of SIR reports, the results and statistics from its analysis are more susceptible to bias from being dominated by recent disasters. Some examples of bias may include the overwhelming majority of embankment dams reported, the high number of extreme weather incidents as a result of Hurricane Irene in 2011, and larger frequencies of incidents in NY and NJ as a result. The SIR database is in its early stages of development and will increase its analytical power with time as more reports are added. There is no known comprehensive dam failure database accessible, but the ASDSO is implementing a valuable reporting method with the SIR.

The KBES computer program uses the statistical data from the SIR to justify its evaluations. Because the program does not directly update with the input of added reports, it will need to be adjusted as the SIR database becomes larger. With the progression to a more complete and larger database, the KBES will become more accurate and be able to actively stand behind its evaluations: the larger the database the better the program. While the KBES tool has many objective components in its analysis, it also has a strong subjective component. Evaluations and assessments are rated by using fuzzy logic, and the expertise and experience of the inspector are important for meaningful results.

1.6) Conclusion

The U.S. prides itself on the strength and power of its infrastructure. Dams unquestionably are an integral part of this system serving numerous purposes. It is important to inspect, maintain, rehabilitate, and evaluate dams across the country in order to avoid catastrophic dam failures. Dam failures can cause massive damage to property, the economy, and agriculture, but can also result in fatalities. The risk of dam failures is drastically increasing as these aging structures deteriorate and become deficient. Many older dams were built without proper design capacities, concrete mixes, and engineering standards. Increases in population and development downstream of dams has increased the number of High Hazard dams, and thus increased the need for better design standards. It must be a joint effort to overcome the many challenges and find feasible solutions to the dam crisis in the U.S. Increasing public awareness and emergency preparedness, as well as providing funding and proper regulation are the biggest issues facing the dam safety community.

The goals of this study are to increase situational awareness of dam owners and regulators, provide a user friendly dam safety evaluation tool, and improve the nation's overall dam safety. The method to achieve these goals include three basic steps: 1) review and compile relevant dam safety information such as different dam materials, designs, common failure causes, and proper inspection techniques; 2) analyze the SIR database and provide recommendations for future incident reporting; and 3) create a KBES to be used as a tool to evaluate the overall safety level of an individual dam.

The SIR database is a relatively recent endeavor and can provide significant benefits to the future of dam safety. Examining the SIR database provides analysis of recent dam failures and incidents while uncovering its flaws so that recommendations can be made. This is extremely important to the future of dam safety and avoiding potentially disastrous failures.

Chapter 2) Background: Dam Types, Failure Causes, and Inspection Techniques

2.1) Introduction

Taking the first steps to solve the dam safety issues presented in Chapter 1 requires an understanding of different dam types, failure modes, and inspection techniques. There are many causes of failures and incidents, each depending on the dam's material, design, surrounding environment, construction methods, etc. This chapter will examine the different types of dams, examine the primary failure modes, and explain what to look for when performing a safety inspection.

This study focuses on the two most common groupings of dams: concrete and embankment. These groups include many designs and are commonly susceptible to different causes of failure. There are enabling causes that are deficiencies in the dam structure and triggering causes that are outside factors that can adversely affect the safety of a dam. The level to which a certain failure cause affects the overall safety of a dam varies in different dams and is dependent on many factors. Based on all the failure modes and dam deficiencies of both embankment and concrete dams, the causes are grouped into eight major categories (4 enabling causes and 4 triggering causes). These will be the criteria by which the Significant Incident Database is analyzed and how the post-inspection safety evaluation tool is used.

A dam's hazard level is also explained in this chapter. Hazard levels are important when dealing with design standards and prioritizing safety measures. It is based on the consequences of a dam failure in the downstream area. Stricter design criteria are given to dams based upon the amount of damage the dam could potentially produce. Dams in densely populated areas, where the consequences due to inundation would be severe are treated more delicately than in undeveloped regions. When evaluating overall safety, it is crucial to understand the different causes of dam failures, materials, designs, and hazard levels.

2.2) Dam Types and Designs

The two major categories of dam types upon which this study will focus include embankment dams, and concrete dams. These two types make up the vast majority of dams in the U.S. and dominate the SIR database. The design and construction materials of the dam play a crucial role in how it counteracts the major hydraulic forces or resists erosion and seepage pressures. Concrete and Embankment dams are completely different in their structural design and susceptibility to certain deficiencies. To understand the causes and prevention methods of dam failures and incidents, it is important to first understand their design and material composition.

2.2.1) Embankment Dams

Embankment dams are constructed primarily of natural materials from the earth, mainly soil and rock. They are very common and have many advantages over concrete dams in regard to site topography and cost. They can be built on either rock or soil foundations making them suitable at many sites where concrete dams cannot be built. The fact that embankment dams are built from excavated materials at or near the dam site means that the construction is more affordable than involving the production of concrete.

A distinct disadvantage to embankment dams is their probability of failure if overtopped, which is the most common cause of dam failures (described in Section 2.3.1). Due to their makeup of earth materials and level of permeability embankment dams are more prone to certain failure modes than concrete dams, and therefore, this leads to a large number of different factors to consider when inspecting embankment dams. The nature of earth and rock fill materials creates issues with seepage, erosion, overtopping, etc. Animals can also burrow through embankment structures, and vegetation growth can cause stability and piping issues. There are two major categories of embankment dams: earth-fill and rock-fill.

2.2.1.1) Earth-Fill Embankment Dams

According to the Bureau of Reclamation, "Inspection of Embankment Dams", an earth-fill dam is defined as "A dam containing more than 50 percent, by volume, earth-fill materials (fill composed of soil and rock material's that are predominantly gravel sizes or smaller)" (Veesaert, Page 2). The three main types of earth-fill dams are hydraulic-fill dams, homogeneous rolled-fill dams, and zone rolled-filled dams.

Hydraulic-fill dams are typically an older form of earth-fill dam. During construction, water is used for transporting the fill material through pipes into its final position. After discharge, the coarser material is deposited, and the fine material is carried into the central portion of the fill. This creates a zoned embankment with a relatively impermeable core. Many problems can arise from this type of construction. The fill is saturated when placed causing high pore pressure in the core, which can lead to instability of the embankment. Also, the water slowly drains from the core and can cause significant settlement over a long period of time. This method was common and economical before the advent of large earth moving equipment.

The other earth-fill embankment dams are rolled-fill types that are divided into 2 types: homogeneous rolled-fill dams and zoned rolled-fill dams. Both of these are constructed using materials from excavations and borrow pits, which are delivered on-site and spread in layers. Using power-operated rollers; each layer is compacted and bonded with the previous one. Homogeneous rolled-fill dams are constructed using one single kind of material throughout. This material must act as an impervious water barrier and have a relatively flat slope for stability. Modifications can be made where small amounts of pervious materials are placed to control seepage and allow the slope to be steeper.

The zoned rolled-fill dam is the most common type of rolled earth-fill dam. It consists of an impervious central core which is bordered by more pervious zones called shells. The shell material is stronger but coarser than the core, providing protection and support. Upstream, the pervious shell provides stability against fluctuating water levels and the downstream shell may act as a drain controlling seepage lines. “A zoned embankment is said to have a thin core if the horizontal width of the impervious zone at any elevation is either less than 10 feet (3 meters) or less than the height of embankment above that elevation in the dam” (Veesaert, Page 3).

2.2.1.2) Rock-Fill Embankment Dams

According to the Bureau of Reclamation, "Inspection of Embankment Dams", a rock-fill dam is defined as: "A dam containing more than 50 percent rock-fill materials (predominantly cobble sizes or larger)" (Veesaert, Page 2). Rock-fill dams consist of two structural components - an impervious core and a pervious rock-fill zone supporting outside for support. The two main types of rock-fill dams are diaphragm rock-fill dams and central core rock-fill dams.

Diaphragm rock-fill dams have a thin diaphragm created from impermeable material, while the embankment is constructed of rock that is cobble size or larger. The diaphragm can act as a blanket on the face of the upstream side of the dam, or can be a thin layer located in the vertical core. It consists of earth, concrete, asphalt or other impervious material. Diaphragm rock-fill dams have many advantages including a greater stability against downstream sliding. Reservoirs can also be lowered periodically to check the condition of an upstream diaphragm, making it easier to conduct maintenance and repairs if needed. Diaphragms located on the upstream side can also be constructed after any settling of already installed rock-fill sections. This settling could otherwise potentially rupture the diaphragm and decrease its integrity. One disadvantage of these outer diaphragms is that they are exposed and can be subject to weathering and damages.

Central core rock-fill dams are similar in configuration to zoned earth-fill dams. These dams have the advantage of using stronger, coarser rock-fill material rather than fine grained soils. This allows steeper external slopes and less material to be used making it a more economical design. The central earthen core is placed in a similar fashion to rolled earth-fill dams, and the outer shells are compacted with large vibratory rollers creating minimal settling. Properly designed central core rock-fill dams have a higher resistance to deformation during extreme events like earthquakes. However, before the advent of this vibratory roller equipment, settling was a much larger issue. Without this machinery, shells were simply dumped into place causing relatively large levels of settling over time. Dams constructed before the advent of this equipment may show a difference in settling between its fundamental zones, the rock-fill shell and the impervious core. The implication of this is that older central core rock-fill dams may not have been constructed with the engineering standards of today; and thereby altering the frequency, timing and techniques of inspection for these dams.

2.2.2) Concrete Dams

There are three main types of dams constructed from concrete: gravity dams, arch dams, and buttress dams. They are more expensive to build and are generally stronger and more durable than embankment dams. Basic factors that go into the concrete dam construction deal with the geological material of the abutments, the rock on which the foundation sits. These rock forms along with the concrete used to build the dam must be designed to provide adequate strength and stability.

2.2.2.1) Concrete Gravity Dams

Concrete gravity dams are generally the most massive of the different dam designs. They use their own weight to resist the water force from the reservoir and thus require enormous amounts of concrete. Gravity dams are designed to have every one of their sections stable on its own, independent of the other sections. The advantages of a concrete gravity dam are their rather simple design and durability. They need large amounts of material and construction time to build and therefore are relatively expensive. Since gravity dams use their own weight to hold back water, it is crucial that they are built on a solid foundation of bedrock. With the presence of any foundation defects, the stability of the entire structure is compromised.

2.2.2.2) Concrete Arch Dams

Concrete arch dams are built using less concrete and are therefore less expensive than gravity dams. Arch dams transfer a large portion of their loading forces to the foundation and abutments. This makes the material strength and stability of the foundation and abutment the most important factor when constructing. Arch dams are designed of a solid concrete curved in an arch upstream typically away from the reservoir. When the hydrostatic pressure of the water presses against this arch, it compresses and strengthens the wall pushing it into the foundation and abutments. For any proposed concrete arch dam, high strength foundations are needed to properly use the rock masses forming at the bottom and sides of the valley in which they are built. Concrete arch dams are common for narrow gorges or canyons where the abutment walls would be stable and steep for support.

2.2.2.3) Concrete Buttress Dams

Concrete buttress dams are constructed with an impermeable upstream wall which is reinforced in intervals of a series of buttress supports on the downstream side. Buttress dams are typically made from reinforced concrete making them heavy and pushing them into the ground. When water pressure increases, it pushes horizontally against the dam, and the rigid buttress supports resist these forces keeping the dam upright. Buttress dams became popular during the early 1900's and are a common choice for wide valleys where solid rock is rare.

2.3) Causes of Dam Failures and Incidents

There are many different ways in which a dam can fail. These failures are normally caused by a deficiency in the dam, an outside triggering event or a combination of the two. This section examines the different causes of dam failures in both embankment and concrete dams and then combines them into eight main failure cause groupings – 4 enabling causes, and 4 triggering causes.

2.3.1) Embankment Dam Failure Causes

Embankment dams, consisting primarily of earth and rock-fill materials are complex structures to assess because of problems such as water penetration, erosion issues and soil material strength, all of which need to be evaluated constantly. The primary causes of embankment dam failure include: 1) overtopping; 2) seepage and piping; 3) instability issues; and 4) lack of maintenance.

Overtopping occurs when the water level surpasses the height of the dam crest, causing it to spill over the dam. This can be detrimental especially to embankment dams. After water begins to overtop the dam, erosion of the dam crest occurs and removes massive amounts of material. This material makes up the weight that holds the dam in place against the hydraulic forces acting to level the dam. These forces and subsequent events normally lead to the complete failure and washing away of the embankment dam. Most dams overtop due to high water levels and heavy rain. Their spillway capacity may not be sufficient relative to the inflow of water that occurs. If the spillway is only designed to handle a low percentage of that area's Probable Maximum Flood (PMF) it is likely that an extreme weather event could cause the dam to overtop. Spillway design standards differ from state to state and depend on the hazard level of the dam. Large settlements of the foundation can cause loss of freeboard and could also result in overtopping.

Seepage and piping are also major causes of embankment dam failures. Seepage causes erosion and saturation in the embankment or foundation material and causes it to lose strength. This can cause sliding and slope stability concerns. Piping is when the seepage of water through the foundation or embankment begins to cause internal erosion. Erosion generally begins in the downstream portion of the dam, and works backwards toward the upstream end. The water forms channels through or under the dam's embankment or foundation which follow the path of maximum permeability. Depending on the level and location, seepage and piping are sometimes hard to catch, and in some cases may not become an issue until many years after construction. Piping paths through to the embankment core is a serious cause of failure, especially if it is below the average reservoir level. Piping can be avoided by lengthening the flow path of water seepage. This is done by the use of cutoff walls, internal drainage systems, impervious cores, and impermeable blankets that extend along the bottom of the upstream reservoir. Many inspection techniques can be used to indicate if seepage is an issue with an existing dam. (These methods are discussed in more detail in Section 2.5.1).

Structural and slope instability also can cause embankment dam failure. Instability of a dam is a serious problem and can cause sliding and movement of the embankment or foundation. Sliding can occur in embankment dams from slopes that are too steep, high pore pressures due to inadequate drainage, and loss of shear strength due to liquefaction of loose granular materials. Dams constructed on clay-shale foundations are also at risk of sliding, likely causing the embankment to fail. Seepage, different forms of erosion, and poor maintenance can also cause problems with stability. (Refer to Section 2.5.1 for inspection techniques to examine instability issues).

Embankment dams also fail due to maintenance concerns. These issues include inadequate slope protection, surface runoff erosion, inappropriate vegetative growth, and animal burrowing. These problems can cause instability, further the effects of seepage into the structure, and compromise the structural integrity of the dam. The protective layer of the embankment must be able to adequately prevent erosion from waves, wind and surface runoff. Vegetative growth lessens the strength of the soil material, and provides a habitat for burrowing animals. These animals, mostly rodents create large paths that increase seepage levels into the structure. (Inspection techniques for maintenance concerns are further discussed in Section 2.5.1).

2.3.2) Concrete Dam Failure Causes

Concrete dams have larger impermeable portion which is much more resistant to seepage than embankment dams. Dams made of concrete instead of earth and rock-fill material fail mainly due to instability or a strength defect either in the concrete, abutments, or foundation of the dam. Seepage can also play a roll through cracks in concrete, and beneath the dam creating hydraulic pressures and uplift forces. The main causes of concrete dam failures include: 1) foundation or abutment weakness; 2) poor concrete strength or deterioration; 3) Instability and 4) overtopping and erosion. The foundation and abutments strength are almost equally important as the concrete material used to construct the dam. Many concrete dams, specifically arch dams, transfer their load to the surrounding foundation and rock, making the geology and strength of these materials essential.

Any weakness or deficiency in the foundation or abutments can be detrimental to a concrete dam. All rock forms in contact with the dam must be able to handle heavy loads and maintain its strength without excessive displacement. When there are unwanted movements in the foundation of abutments it can overstress the concrete dam. Over time, seepage can also play a role in weakening the foundation or abutments. Water passing through the foundation material underneath the dam creates damaging uplift forces and if large enough can create sliding. To reduce uplift pressures on the foundation, curtain walls can be constructed into the ground to block or lengthen the line of seepage. Seepage erosion of rock joints, as well as movement and sliding along faults and bedding planes can also contribute to failure. Strength of the foundation and the abutments must be properly evaluated before constructing a concrete dam.

The concrete itself also plays a vital role in the safety of the dam. Structurally weak concrete due to low initial strength or subsequent concrete degradation is a huge concern. This inadequate or degraded concrete can lead to the inability of the dam to sustain large loads and result in failure. During construction, it is important the concrete meets design standards and be properly maintained over time. Older dams that were built in the early 1900's and before are more prone to certain chemical, weathering, and physical reactions. Concrete construction mix and design techniques used today were unknown at the time when many older dams were built.

Instability of a concrete dam can also be created from changes in design loading conditions that could occur from improper operation or unauthorized modifications to the spillway. Both of these factors can result in higher than intended reservoir levels and increase the loading conditions. Cracking and concrete deterioration can also create paths for seepage into the structure or abutments. Similar to embankment dams, seepage can also become an issue creating hydraulic uplift pressures or erosion.

Overtopping of a concrete dam can also cause failure. Similar to embankment dams, overtopping mainly occurs from inadequate spillway design combined with high heavy flooding. Typically, criteria for spillway capacities of concrete dams are decided at the state level, and depend of the hazard level and PMF of the area. When a concrete dam is overtopped, the supporting foundation or abutments incur erosion which could lead to overturning or sliding of the structure. The erosion factor is less in concrete than embankment dams during overtopping, and in many cases it may not cause complete failure if correctly acted upon timely. (Further descriptions of concrete dam deficiencies causing these failure modes, and inspection techniques are located in Section 2.5.2.)

2.4) Categorizing Enabling and Triggering Causes

As stated in the previous two sections, there are many different causes of dam failures. Based on knowledge of the most common types of failures, and analysis of the SIR database, eight primary groups of causes were established - (4 enabling and 4 triggering causes). The remainder of this study will deal almost exclusively with these groupings. This grouping of failure causes allows a more orderly task of analyzing the SIR data and creating the safety evaluation tool. The tables and descriptions in the following sections list the groups of enabling and triggering causes and detail how they can work to magnify the individual causes of failure.

2.4.1) Enabling Causes

Most dam failure and incidents are enabled by deficiencies or inadequacies inherent in the dam structure itself. Failure can occur as a result of one single enabling element or by some combination. Table 2-1 shows the potential enabling causes to be evaluated in an existing dam.

Table 2-1: Enabling Incident Causes

Symbol	Enabling Cause
E1	Overtopping
E2	Seepage and Piping
E3	Inadequate Spillway Design
E4	Slope or Structural Instability

(E1) *Overtopping* – is one of the most common causes of failure in both embankment and concrete dams. In the majority of cases, it is caused by an inadequate spillway design combined with high water levels from heavy rainfall or extreme weather (T1). Commonly, the three causative factors E1, E4 and T1 will combine to cause significant incidents or failures.

(E2) Seepage and Piping – is when water pushes its way through part of the dam structure. It can be found in the foundation, abutments, or dam wall itself. It has a larger impact on embankment dams, but also creates instability and uplift forces in concrete dams. Seepage and piping flows can be intensified during a number of triggering events making it common for a combination of E2 with any triggering cause (T_i) to cause failure.

(E3) Inadequate Spillway Design – can be a result of poor engineering practices. Spillways of low hazard dams are designed with a lower capacity causing overtopping (E1) to commonly occur during heavy rainfall or extreme weather events (T1).

(E4) Slope or Structural Instability – can be the cause of many different deficiencies in the dam's components. Steep slopes, uplift forces from seepage, low material strength, deterioration, and maintenance issues can all play a role in causing instability. Instability (E4) commonly causes the dam to fail in some combination with (E2), (T1), (T2) or (T4).

2.4.2) Triggering Causes

Table 2-2 shows the four main groups of triggering events that can lead to dam failure. These are impacts due to external factors and can cause deficiencies or aggravate a pre-existing deficiency in the dam. Dam failures can be caused by a single triggering event but are more commonly a result of a combination with one or more enabling causes.

Table 2-2: Triggering Incident Causes

Symbol	Triggering Cause
T1	Extreme Weather
T2	Deterioration or Poor Condition
T3	Equipment or Human Error
T4	Animal Activity or Excessive Vegetation

(T1) Extreme Weather – includes but is not limited to abnormally heavy rainfall, hurricanes, and earthquakes. Extreme weather events can happen suddenly, compromise structural integrity, raise the reservoir water to problematic levels, and increase seepage and piping. Most failures occur during extreme weather (T1) because it acts as a catalyst increasing the effects of all other enabling and triggering causes.

(T2) Deterioration or Poor Condition – is normally caused by aging of a dam or a lack of proper maintenance. Deterioration of a dam's material can cause cracking, instability, and create paths for internal erosion. Deterioration or poor condition (T2)

failures are commonly a result of some combination with seepage and piping (E2) and instability (E4).

(T3) Equipment Malfunction or Human Error – typically results in unpredictable forces that can cause failure to a dam all by itself. Malfunction and human error can result in the opening and closing of hydraulic gates, not implementing a timely EAP, and other detrimental actions. It can act alone or increase other deficiencies that are present.

(T4) Animal Activity or Excessive Vegetation – can lead to high levels of seepage and piping, and structural instability. It is almost exclusively found in embankment dams. If animal burrows or vegetation (T4) reach an unsafe level, it can cause dam failure in combination with (E2) and (E4).

2.5) Inspection Techniques

Prior to the "Corps of Engineers (COE) Phase 1 Inspections", dam inspections had little formality or frequency. They mostly dealt with large dams or dams with serious deficiencies. The COE developed the first formal inspection process and basic tools for evaluation and inspection procedures. The goal of most current dam inspections is to measure the dam's performance compared to the original design. They are carried out at several levels from daily visual inspections to formal inspections requiring engineers with experience and high skill levels. This study investigates the more formal inspections that require expert knowledge and judgment.

The primary purpose of a formal inspection is to locate any deficiencies or problems that could affect the safety of a dam. Before a meaningful safety examination can be performed, a review of the dam design, geology, construction, structural behavior, maintenance and operation is needed. A meticulous visual examination of all exposed dam components is essential to determine any deficiencies and unwarranted behaviors. The entire surface area of the dam, its embankments, foundations, abutments, materials, hydraulic equipment, and piping should be examined carefully.

It is important to stress that the mere presence of a deficiency does not automatically mean the dam is at risk. Also, the magnitude of a deficiency does not always portray the magnitude of risk. Failures can occur suddenly after only subtle symptoms, and conversely, many dams suffer from an alarming appearance but are at very low risk of failure. The nature of the deficiency, its cause, the possible effects, and how the dam may be endangered are a matter of judgment and experience. The expertise of the inspection is vital to a successful dam safety evaluation.

2.5.1) Embankment Dam Inspection

Embankment dams can be subjected to many different types of deficiencies that can be detrimental to their safety. The purpose of inspection is to identify which deficiencies are present, determine their level of danger, and implement proper actions to fix them. A close up visual examination spanning the entire surface area of the dam is needed, and several passes with different viewing angles are recommended. This sometimes reveals a deficiency that may otherwise go unnoticed. The most important areas to cover include the embankment slopes, crest, abutments, and groins (where the embankment contacts the abutments).

2.5.1.1) Detectable Deficiencies

The main groupings of deficiencies that should be examined during inspection of embankment dams include: 1) seepage; 2) cracking; 3) instability; and 4) maintenance concerns.

Seepage becomes a problem when embankment or foundation material begins to move with the flow of water or when internal pressures build up from the hydraulic forces within the dam or foundation. Seepage can be mitigated by the use of internal drains which intercept and redirect the flow, and dams without internal drains are more likely to have seepage problems. Damage from seepage results in stability problems and seepage erosion, and saturation in the embankment or foundation can cause the earth materials to lose strength. Seepage erosion can occur when high hydraulic gradients are present; and this high gradient seepage, which normally occurs along conduits, abutments and foundation contacts, or through cracks, causes internal erosion. Seepage frequently appears as an exterior wet area or like a flowing spring; but also sand boils, noticeable changes in vegetation, and changes in drainage flow are also indications of seepage (Veesaert, *Inspection of Embankment Dams*. Pages 5-9). During inspection it is necessary to thoroughly examine the groins, outlet works, spillway conduits, and drainage pipes. Groin areas are less densely compacted and therefore less watertight and prone to seepage.

If seepage is observed, a proper investigation should follow to determine its extent and potential danger and the action that should be taken. The seepage flow rate and the determination if that rate is changing with time or reservoir level are key element in the assessment. The turbidity of the seepage water can indicate the level of suspended particles and internal erosion. The reservoir level should be noted when looking at seepage flows and compared to inspections during past and future reservoir elevations. An increase in seepage flow rate for a similar reservoir elevation is cause for concern.

Cracking is another possible deficiency in embankment dams. Cracks can be located in the crest or slopes of the dam. Inspectors must look for forms of longitudinal and transverse cracks (Veesaert, Pages 11-13). Longitudinal cracking is in the direction along the length of the dam. These cracks allow water to enter the embankment decreasing the strength of the adjacent material. Transverse cracking is perpendicular to the length of the dam. This type of crack can be very dangerous if it is located below the reservoir level, providing a path for water into the dam's core. When either longitudinal or transverse cracks are observed, their dimensions are to be recorded, they should be closely monitored for changes, and their cause should be determined.

Instability can be a very dangerous deficiency for embankment dams and carries with it the potential for sliding. A steep embankment coupled with rapid changes in water levels can cause unstable slides to occur. The compacted earth material in embankment slopes can also loose strength due to seepage or surface runoff. Most cases of sliding are shallow and are not much threat to safety, but deep slides can be a major risk and need to be dealt with immediately. Instability can also present as depressions or low spots in the embankment. This is caused from settlement of the dam foundation or varying forms of erosion. Settlement can pose a risk of overtopping as it may lessen the freeboard to an unsafe level. Sinkholes can also form from depression instability, and they should be investigated immediately to determine their threat to the dam (Veesaert, Pages 13-16).

The last detectable deficiencies are related to maintenance, including poor slope protection, surface runoff erosion, vegetative growth, and animal burrows. Slopes are typically protected by riprap or vegetative cover to prevent erosion from waves, runoff, and wind. The inspection must make sure the slope is adequately protected and report any embankment damage. Surface runoff erosion is a common maintenance issue and can turn into a serious problem if unchecked. Damage is created from deep erosion gullies which can form on the slopes, groins, or central embankments. They shorten the path of seepage, and if severe enough can cause breaching of the dam crest. If surface runoff erosion is detected, repairs should be made and measures taken to prevent a more serious problem.

Vegetative growth must also be examined on the dam site. Excessive growth can prevent access to the dam and surrounding areas making it difficult for inspection and maintenance. Vegetation needs to be controlled by periodic mowing and other means. If vegetative growth is apparent, inspectors must look for deep-rooted areas, ensure no vegetation is on the protective riprap, and check for seepage nearby (Veesaert, Pages 17-18). Vegetation also provides a habitat for rodents and burrowing animals. Animal burrows can significantly weaken the embankment dam and form large seepage pathways. If burrows are detected, their size, location, and any seepage nearby must be investigated. If they pose a threat to the dam, the burrowing animals should be removed or eradicated and the damage repaired.

2.5.2) Concrete Dam Inspection

There have been many advances in concrete technology during the evolution of dam construction. Several current construction standards for designing strong, durable concrete were unknown during the development of older dam structures. A large number of these aging dams still exist today and are responsible for retaining huge volumes of water. It is crucial that these structures be inspected regularly and proper maintenance measures are taken when needed. Concrete dams should be visually examined to find any deficiencies or unsafe trends that occur.

2.5.2.1) Areas of Inspection

Every exposed surface of a concrete dam should be thoroughly examined during a safety inspection. The main groupings of these areas include: 1) abutments and foundation; 2) upstream and downstream faces; 3) galleries; and 4) the dam crest. Each area is structurally important to the dam's overall safety and can give information pertaining to different types of deficiencies.

The abutments and foundation in concrete dams are sometimes difficult to examine. While inspecting these areas it is important to determine if any foundation displacements or seepage is occurring. Displacements should be measured in both horizontal and vertical directions. If displacements and movements are found, there are two important criteria to consider. First, it needs to be determined if the displacements are continuous along the structure or if there are offsets. Second, an examination should be performed to evaluate if the displacements stabilize with time and remain the same at constant reservoir levels. Increases in displacement rates at constant water levels are a significant concern. If seepage is present, a further investigation of possible piping in the abutments and foundation materials is needed (Veesaert, *Inspection of Concrete and Masonry Dams*. Pages 1-2).

The upstream and downstream faces of the dam need to be inspected to check for signs of distress or movement. Any areas of seepage on the downstream face should be investigated further to determine the source and path of the water. Observing the dam faces can help indicate if deficiencies such as chemical, weathering, or physical attack are present. These deficiencies can often be recognized and dealt with before they compromise the safety of the dam.

Galleries in a concrete dam, including drains and instrumentation can indicate leakage that is present. It can also give a view from within the structure to determine if any cracking or movement has occurred. Galleries contain instrumentation that is pertinent to the dam's safety. Instrumentation devices can include uplift pressure gauges and foundation movement gauges that should be checked for serviceability. These gauge readings should also be recorded and compared with past readings to check for any changes or unsafe trends.

The dam crest is relatively easy to examine during inspection and can expose many potential safety problems. Movements in the horizontal and vertical directions, weathering effects, and chemical or physical attacks can be found through inspection of the dam crest. Displacements and offsets that are the result of foundation movement and settlement can be detected. Cracking or deterioration found in the surface could be a potential indicator of chemical or physical attacks in the concrete or weathering effects.

2.5.2.2) Detectable Deficiencies

There were several potential deficiencies that can adversely affect a concrete dam. The main are of concern deal with the concrete itself and its structural strength, durability, and resistance to chemical and freeze-thaw damage. Low concrete strength and durability can cause the dam to be unable to withstand imposed loads. All concrete surfaces of exposed areas should be inspected and tested for strength and durability (Veesaert, Pages 2-3).

Damage to concrete can also be the result of poor mix design or construction practices. Examples of this include chemical reactions from sulfate, alkali-aggregate reactions, and the freeze-thaw cycle. Concrete areas of the dam with surface spalling could be the result of sulfate attack. This occurs when low sulfate-resistant cement concrete is exposed to sulfate in soil of ground water. This issue would commonly be found it dams built prior to 1930, when mix designs did not recognize sulfate attack. Alkali-aggregate reactions (AAR) are also an issue with older dams. This can cause severe cracking, loss of strength and distortion of the concrete. AAR damage is mostly seen near the surface and is evident by the appearance of white precipitate. Dams built prior to 1940 are more susceptible to this type of reaction because proper cement and aggregate combinations were not yet employed. Freeze–thaw damage can cause pattern cracking and increasing deterioration of the surface. Concrete mix designs prior to 1942 did not account for freeze-thaw action, making dams from this era another concern.

2.6) Hazard Level Classification

As a measurement of failure consequences, dams have a hazard-level assigned to them. The hazard-level of the dam does not deal with its risk of failure or the condition of the dam; but rather by the potential amount of downstream damage *should* it fail. When considering dam safety regulations the ability to accurately estimate the downstream consequences of a dam failure is essential. The hazard level and associated regulations are directly linked to the dam's location, size, and demographics of the downstream area.

The hazard classification system is currently characterized by three distinct levels: high-hazard, significant-hazard, and low-hazard. According the ASCE, these hazard levels are defined as follows:

"High-hazard dam - A dam in which failure or incorrect operation is expected to result in loss of life and may also cause significant economic losses, including damages to downstream property or critical infrastructure, environmental damage, or disruption of lifeline facilities."

"Significant-hazard dam - A dam in which failure or incorrect operation is not expected to cause loss of life, but results in significant economic losses, including damages to downstream property or critical infrastructure, environmental damage, or disruption of lifeline facilities."

"Low-hazard dam – A dam located in a rural or agricultural area where failure would only cause the loss of the dam itself but may cause minor damage to nonresidential and normally unoccupied buildings, or rural or agricultural land."

(ASCE 2013 Report Card for America's Infrastructure, Pages 1-2)

The hazard level given to each dam is crucial when determining its safety priority. High-hazard dams, in which loss of life is at stake, are without question the most important dams when considering maintenance and design standards. Specifications for building and designing dams in areas that would make them high-hazard are much stricter than undeveloped low-hazard areas. These requirements, especially spillway capacity, vary from state to state but are universally less strict for lower hazard dams. For example, in Ohio, the spillway design capacity regulations require the dam's spillway to adequately handle a certain percentage of that area's PMF. For high hazard Ohio dams, the spillway capacity must be 100% PMF, for significant hazard – 50% PMF, and for low hazard – 25% PMF.

The changing of a dam's hazard-level and the aging of dam infrastructure have presented many challenges for dam safety regulations. Due to America's increasing population and development into rural areas, many dams formerly considered to be low or significant-hazard have now changed to a high-hazard level. The design standards associated with these dams must be re-evaluated to ensure safety to the downstream area. The age of dams also contributes to the rise of outdated engineering standards in design and construction. With the development of new scientific, technological, and engineering practices, many dams need to be renovated and even re-built in some cases.

2.7) Emergency Action Plan

The purpose of a dam's EAP is to protect lives and reduce damages downstream in the event of a disaster. It is a formal document that identifies possible emergency conditions at a dam and specifies what actions should be followed to minimize consequences. According to the *Federal Guidelines for Dam Safety: Emergency Action Planning for Dams,* which was last updated in 2013:

“The EAP includes:

- Actions the dam owner will take to moderate or alleviate a problem at the dam
- Actions the dam owner will take, and in coordination with emergency management authorities, to respond to incidents or emergencies related to the dam
- Procedures dam owners will follow to issue early warning and notification messages to responsible downstream emergency management authorities
- Inundation maps to help dam owners and emergency management authorities identify critical infrastructure and population-at-risk sites that may require protective measures, warning, and evacuation planning
- Delineation of the responsibilities of all those involved in managing an incident or emergency and how the responsibilities should be coordinated”

(*Federal Guidelines for Dam Safety: Emergency Action Planning for Dams*, Pages 1-3)

In the event of a dam failure, especially in high hazard dam locations, it is crucial that all requirements of the dams EAP are carried out in a timely manner. When a dam is in the progression of failure, there is not much time to coordinate safety precautions and make the ‘at-risk’ downstream areas aware of the situation. Quick and decisive action must be taken, and having an EAP makes the dam owner clear of his responsibilities.

According to the ASDSO, the national percentage of high hazard dams with an EAP has increased from 35% to 69% for the period of 1999 to 2012 (ASDSO – Journal of Dam Safety. Volume 11, Issue 3. 2013). It is a goal to develop EAP's for every high-hazard dam by 2017.

2.8) Conclusion

In order to understand a dam's safety level, a solid background and awareness of historic events is needed. All dams are different and react to their environment in different ways. When investigating and inspecting an existing dam for deficiencies it is important to recognize many factors including: 1) its history; 2) its material and design; 3) the surrounding geology; 4) its potential failure causes; 5) the development downstream; and 6) what deficiencies to look for.

A meaningful dam inspection requires experience, expertise, and careful judgment on the part of the inspector. This judgment is crucial due to variability of each dam and the uncertainty of different failure conditions. The information compiled in this chapter is imperative to properly assess an existing dam. The combination of the background information in this chapter, the analysis of the SIR database in Chapter 3, and the incorporation of a KBES dam safety evaluation tool in Chapter 4 provide an approach to dam safety solutions and evaluations.

Chapter 3) SIR Analysis and Results

3.1) Introduction to the SIR Database

This chapter includes the analysis of the inputs stored in the SIR database. The purpose of this analysis is to find trends and correlation in the data to improve situational awareness of dam owners and regulators. The SIR analysis and statistics also provide the framework for the overall dam safety evaluation tool. The sections in this chapter will examine the distributions and frequencies of failure and non-failure incidents in the SIR based on certain variables in the database. These variables include: 1) dam type, 2) incident cause, 3) state, and 4) hazard level. The incident causes used are the enabling and triggering groupings located in Chapter 2.

3.1.1) SIR Scope

For the past few years, the ASDSO and DHS Office of Infrastructure Protection have collaborated on the SIR database. This information is available in a web-based interface as a module of the Dams Sector Analysis Tool (DSAT). Currently, the SIR entries used for this study have 337 total reports including: 72 historical failure incidents prior to 2008, 99 failure incidents from 2008-present, and 166 "non-failure" incidents from 2008-present. A non-failure incident is one in which there is a dam behavior that requires remediation, and it is corrected before failure occurs. These non-failure incidents would likely have caused failure if not handled in a proper and timely manner.

These reports contain information about each incident that includes: The dam type, incident cause, state (location), hazard level, whether the EAP was enacted, incident date, failure/non-failure, a brief description, etc. As time passes, the SIR will update and receive additional information on new dam failures and incidents that occur across the country. This will increase the sample size and therefore improve the value of statistical analysis, allowing the dam safety tool to create more accurate evaluations.

3.1.2) SIR Limitations

The SIR database and the analysis derived from it have several limitations. First, the database is not complete. It is not comprehensive prior to 2008, and even since 2008 it has been challenging to compile information on all occurring incidents. The data received for each incident greatly depends on the diligence of each party responsible for reporting the incident, causing some failures or incidents to go unreported. Another limitation occurs within the actual reporting of an incident. When the responsible party reports an incident, certain data fields may be omitted, and there is no oversight to assure a complete submission. This makes it difficult for the statistical analysis to create a complete picture, especially in these early years of SIR where the database is relatively small. This small database size also enables bias to occur in some statistics. For example, extreme weather events dominate the incident causes mainly due to Hurricane Irene in 2011. Another form of bias created by Hurricane Irene may be the high number of incidents occurring in New York and New Jersey. As time continues the database will continue to increase in size, minimizing bias and creating a larger sample size for a stronger statistical analysis.

Another limitation in the SIR has to do with the reporting of extreme weather events. This is the most dominate cause of all incidents in the database and better clarification is required as to the true definition of an extreme weather event. Finally, the incident reporting does not contain a data field which outlines whether or not a high water flow event exceeded the design standards for that particular dam.

3.2) SIR Database Analysis

This section of the study shows the analysis of the current SIR database and its 337 incident reports. It shows the number of frequencies according to certain criteria of the report. The goal is to find statistics, trends, and correlations that can be learned from and improve the overall situational awareness of the dam safety community. The analysis is mostly in the form of charts and bar graphs indicating the frequency of certain events matched against various criteria.

The main criteria this examination will focus on includes: 1) dam types; 2) incident causes; 3) incident state (location); 4) hazard level; and 5) if an EAP was enacted. The results look at either the distribution of total incidents or break them into failure and non-failure categories. In some cases, it is revealing to match two or more criteria up against one another. For all graphs and figures, the corresponding numeric values are also included in a chart or charts.

3.2.1) Incidents by Dam Type

The failure and non-failure incidents are broken down into the category of dam type. Chapter 2 reviewed the different types of embankment and concrete dam designs, which dominate the incident reports. In the SIR database there are many possible inputs for dam types; however, this study lists them as embankment, concrete, timber crib, masonry, or other as they are they are the most common types. Figure 3-1 graphically shows the number of both failure and non-failure incidents in each dam type category.

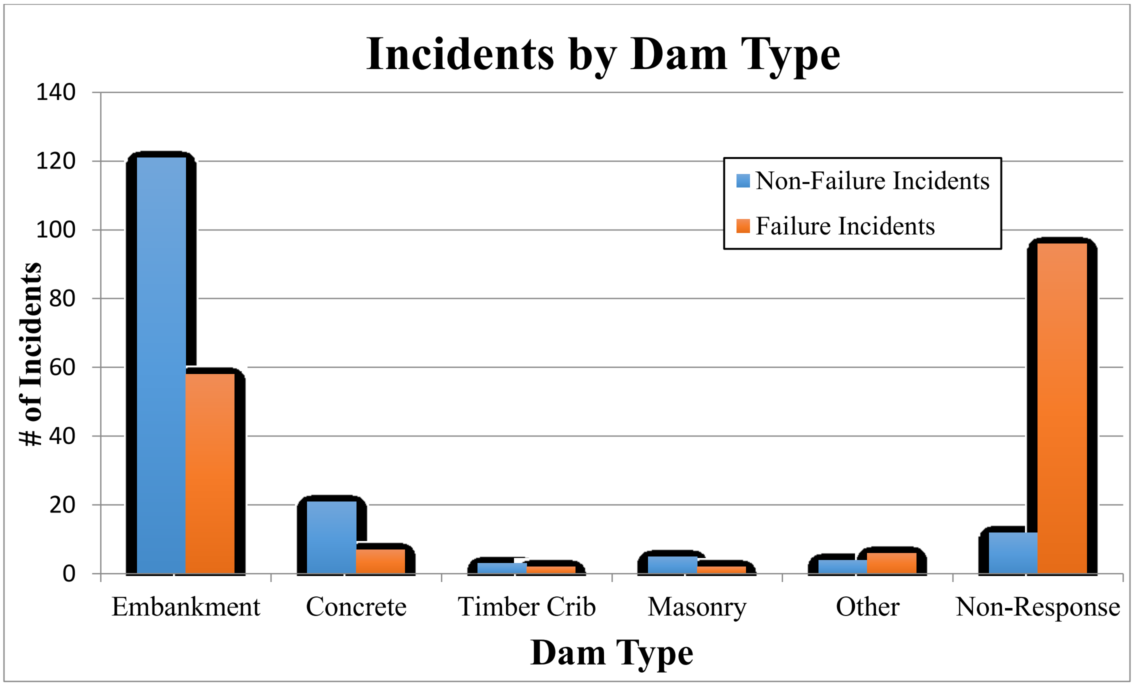


Figure 3-1: Failure and Non-Failure Incidents - by Dam Type

The vast majority of incidents reported are associated with embankment dams. The most obvious reason for this is that they make up a large portion of the total of all United States dams; however, it also may indicate that embankment dams are more prone to varying failure causes and susceptible to more deficiencies. Concrete dams are a distant second likely due to their greater structural strength. They are less prone to seepage, piping and erosion than embankment dams. Chapter 2 discusses embankment and concrete dam deficiencies and failure modes in more detail. Timber crib and masonry dams have a very low number of incidents primarily because they are less common dam types. For this reason, the area of focus for dam types will mainly be on embankment and concrete.

It is also important to note that a large number of reports did not include the dam type (108 non-responses). These 'dam type' reporting omissions are the responsibility of the individuals completing the incident reports. The 108 of 337 total reports that failed to respond to 'dam type' shows a lack of diligence in the reporting methodology. As more incidents are added to the database measures must be taken to improve compliance with dam incident reporting. It may also be possible to make an attempt to retrieve missing data.

3.2.2) Incidents by Cause

This section looks at the distribution of failure and non-failure incidents by their cause. The incident causes that can be entered into the SIR are numerous and varied, but analysis of the database has shown that all of these causes can be grouped and then divided into eight critical failure and non-failure incident causes, (4 enabling causes and 4 triggering causes). These enabling and triggering causes were described in detail in Chapter 2.

For the purpose of this study some SIR causes are grouped together and fall under one of these eight categories. For example, both seepage and piping are separate causes in the SIR database, but in this analysis they are grouped together as 'Seepage and Piping' (E2). Instability (E4) is a group including slope stability, structural stability, and settlement. The SIR has earthquakes and extreme weather events as two different causes, but in this analysis they both classified as extreme weather (T1). Deterioration and Poor

Condition (T2) also includes cracking incidents which would otherwise be separate. Equipment malfunction and human error (T3) are grouped under the same category, as well as animal activity and excessive vegetation (T4) because they relate to one another.

Figure 3-2 shows the number of incidents associated with each of the four enabling and four triggering causes. It can be seen that most incidents are associated with extreme weather or overtopping, but most of these are non-failure incidents which do not result in dam failure. Extreme weather is the leading cause of dam incidents and almost exclusively is accompanied by heavy rain storms and high water levels which the dam must resist. These factors exacerbate other deficiencies which may already be present in the dam. Extreme weather is also associated with overtopping of the dam, which is discussed in a later section.

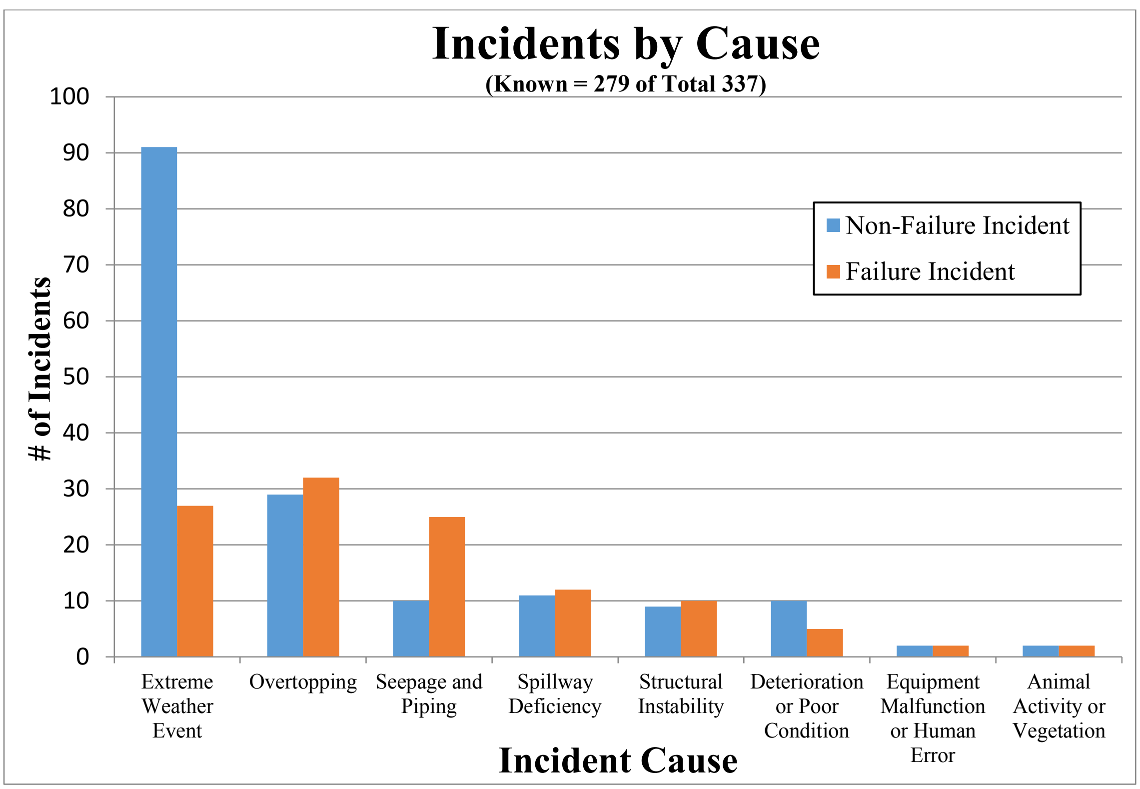


Figure 3-2: Failure and Non-Failure Incidents – by Cause

Seepage and piping, spillways, structural stability, and deterioration are also of concern, but not to the extent of extreme weather and overtopping incidents. Equipment and human error, and animal activity and vegetation are more uncommon.

Table 3-1 shows both the numbers and percentages associated with Figure 3-2. The table also includes the percentages of each enabling and triggering cause located in the last column. Instances in which reports did not include the incident cause (58 of 337 total) are not included in these statistics.

Failure and Non-Failure Incidents by Cause (Known = 279 of Total 337)				
Incident Cause	Incident Type		TOTALS	
Enabling Causes	**Non-Failure**	**Failure**	**Total #**	**Total %**
E1) Overtopping	29	32	61	21.9%
E2) Seepage and Piping	10	25	35	12.5%
E3) Spillway Deficiency	11	12	23	8.2%
E4) Instability	9	10	19	6.8%
ENABLING TOTAL	59	79	138	49.5%
Triggering Cause	**Non-Failure**	**Failure**	**Total #**	**Total %**
T1) Extreme Weather Event	91	27	118	42.3%
T2) Deterioration or Poor Condition	10	5	15	5.4%
T3) Equipment or Human Error	2	2	4	1.4%
T4) Animal Activity or Vegetation	2	2	4	1.4%
TRIGGERING TOTALS	105	36	141	50.5%
OVERALL TOTALS	**164**	**115**	**279**	**100.0%**

Table 3-1: Incident Cause Distribution – Failure and Non-Failure Incidents

3.2.3) Incident Cause vs. Dam Type

After examining incidents by dam types and incidents by cause, this section now looks at how they relate to each other. Figure 3-3 shows the incident cause vs. the different dam types. While the number of incidents for each cause is the same, the distribution of each dam type is now clear.

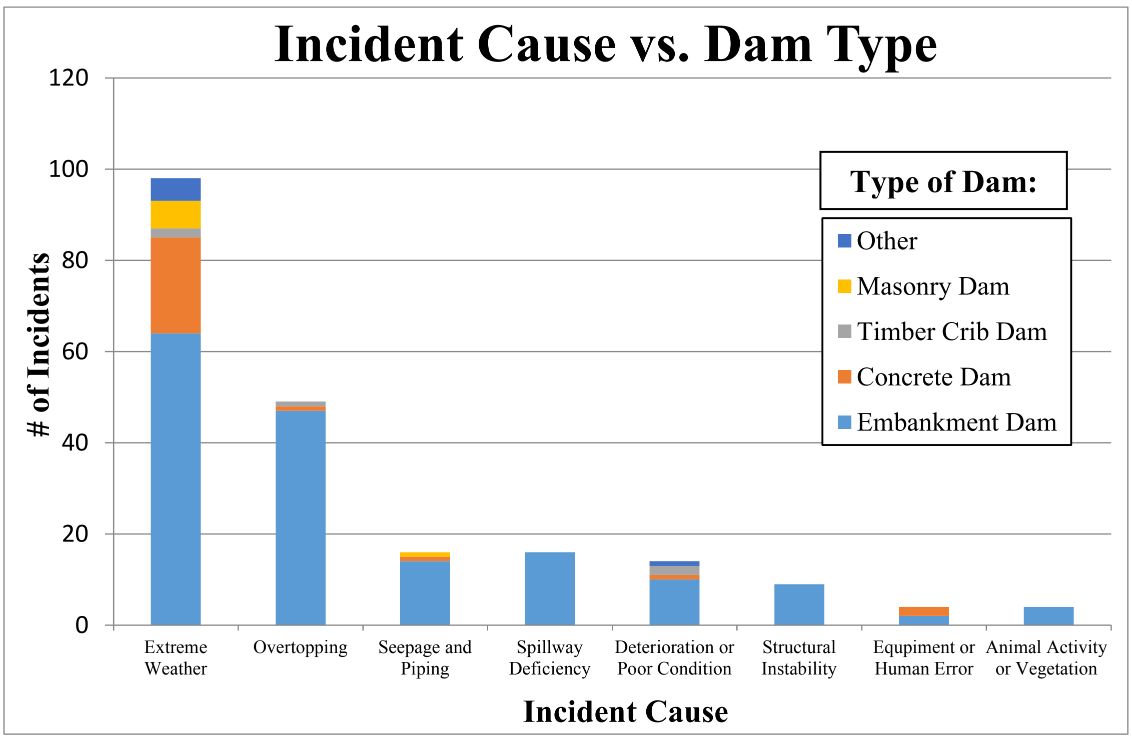


Figure 3-3: Incident Cause vs. Dam Type

Embankment dams have incidents occurring from a wide range of causes, which could prove their vast failure mode susceptibility. The majority of them, as expected, are from extreme weather and overtopping. Conversely, concrete dam incidents have almost exclusively occurred due to extreme weather events.

Table 3-2 shows the numerical values represented in Figure 3-3. Figure 3-4 and Figure 3-5 show the distribution of embankment dams and concrete dams respectively. Due to the large majority of extreme weather incidents, Section 3.2.5 investigates these reports and shows how they breakdown by their descriptions.

Incident Cause vs. Dam Type										
Dam Type	**Enabling Causes**				**Triggering Causes**					
	E1	**E2**	**E3**	**E4**	**T1**	**T2**	**T3**	**T4**	**Unknown**	**TOTALS**
Embankment	47	14	16	9	64	10	2	4	13	**179**
Concrete	1	1	0	0	21	1	2	0	2	**28**
Timber Crib	1	0	0	0	2	2	0	0	0	**5**
Masonry	0	1	0	0	6	0	0	0	0	**7**
Other	0	0	0	0	5	1	0	0	4	**10**
Non-Response	12	19	7	10	20	1	0	0	39	**108**
TOTALS	**61**	**35**	**23**	**19**	**118**	**15**	**4**	**4**	**58**	**337**

Enabling Causes		**Triggering Causes**	
E1	Overtopping	T1	Extreme Weather
E2	Seepage and Piping	T2	Deterioration
E3	Spillway Deficiency	T3	Equipment or Human Error
E4	Instability	T4	Animal Activity or Vegetation

Table 3-2: Incident Cause vs. Dam Type

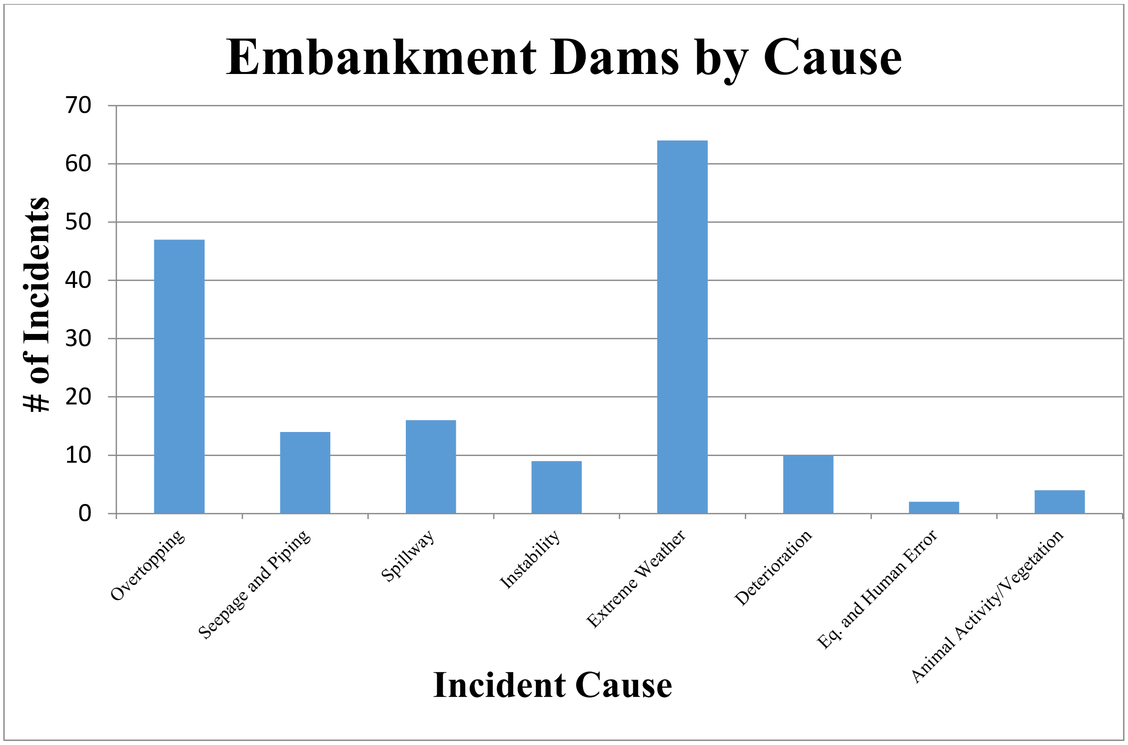


Figure 3-4: Embankment Dams – by Incident Cause

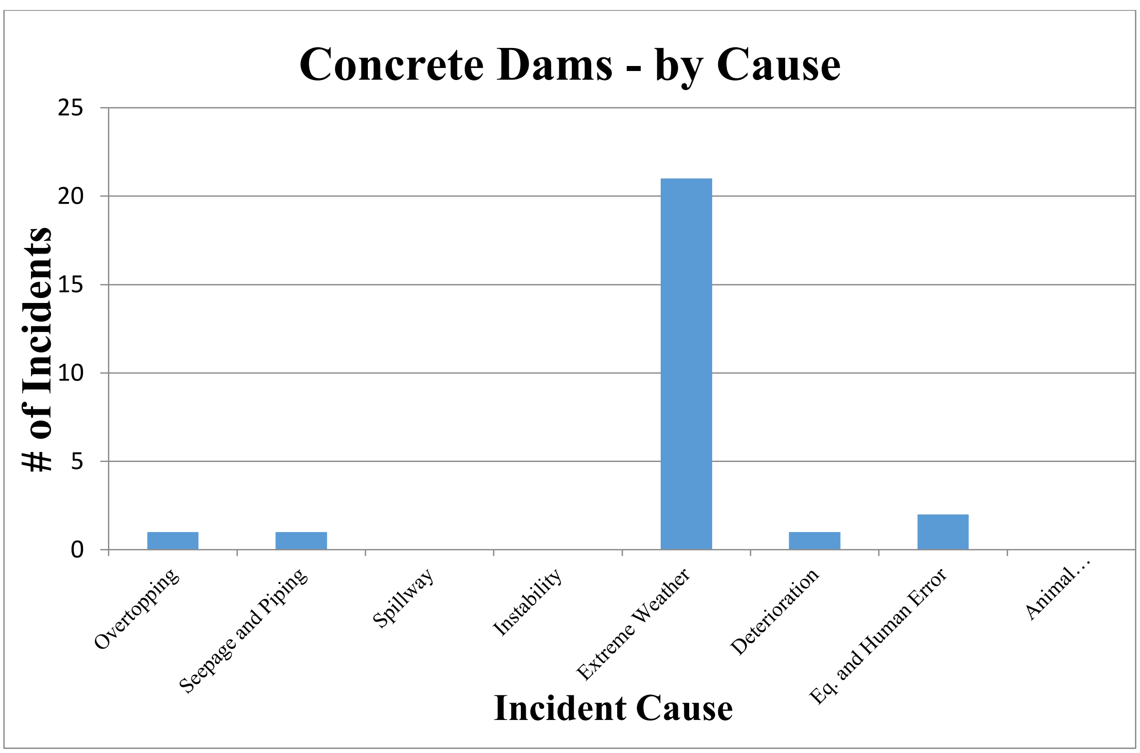


Figure 3-5: Concrete Dams – by Incident Cause

3.2.4) Distribution of Enabling and Triggering Causes

This section looks at the percentage of incidents caused by each of the eight enabling and triggering causes. These percentages are listed in Table 3-3, which is what sets the framework for much of the KBES dam safety evaluation tool in Chapter 4. The higher the percentage of incidents from a particular cause, the higher the risk for dam failure.

Enabling and Triggering Cause Percentages	
Enabling Failure Causes (49.5%)	**Failures and Incidents (%)**
E1) Overtopping	21.86
E2) Seepage and Piping	12.54
E3) Spillway Deficiency	8.24
E4) Structural Instability	7.52
Triggering Failure Causes (50.5%)	**Failures and Incidents (%)**
T1) Extreme Weather Event	42.28
T2) Deterioration or Poor Condition	4.66
T3) Eq. Malfunction or Human Error	1.43
T4) Animal Burrowing	1.43

Table 3-3: Enabling and Triggering Causes – Percentage Distribution

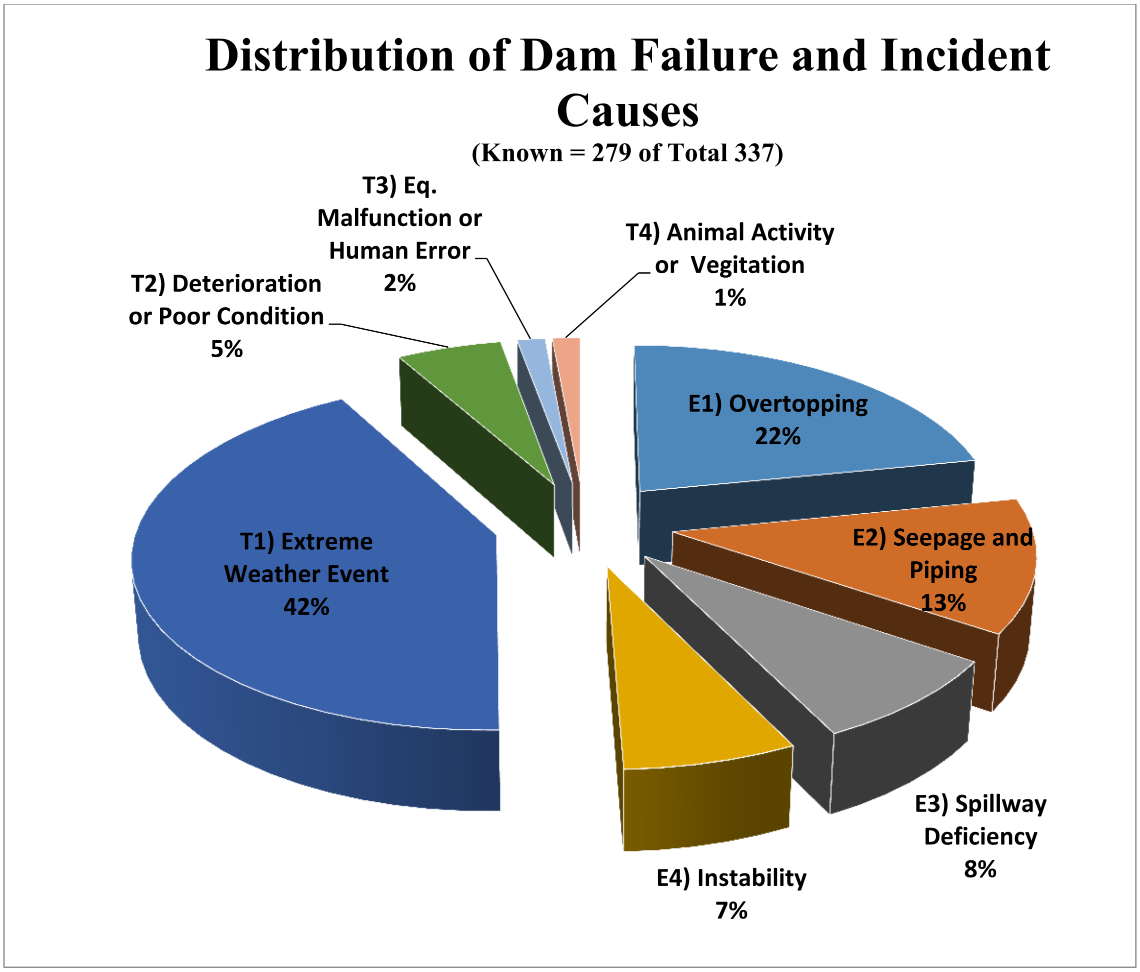


Figure 3-6: Distribution of Enabling and Triggering Causes - Pie Chart

Figure 3-6 is a pie chart showing the percentages listed in Table 3-3. Extreme weather events and overtopping account for approximately 63% of the incident causes found in the SIR. Animal/vegetation activity and equipment/human error only account for about 3%.

It can be seen that the deficiencies determined to cause a high probability of overtopping or high water levels due to extreme weather will bear the most failure and safety risk.

3.2.5) Extreme Weather Events

The previous sections showed that extreme weather events were the largest cause for incidents in the SIR. This portion of the study will isolate these reports and breakdown their description. In order to accomplish this, it was necessary to access and review each of the Extreme Weather event incident descriptions to determine how the dam failed. After reading the extreme weather descriptions the main categories they could fall into include: 1) hurricane; 2) overtopping; 3) heavy rainfall; 4) erosion; and 5) other. Figure 3-7 shows the total number of extreme weather incidents associated with each of these categories.

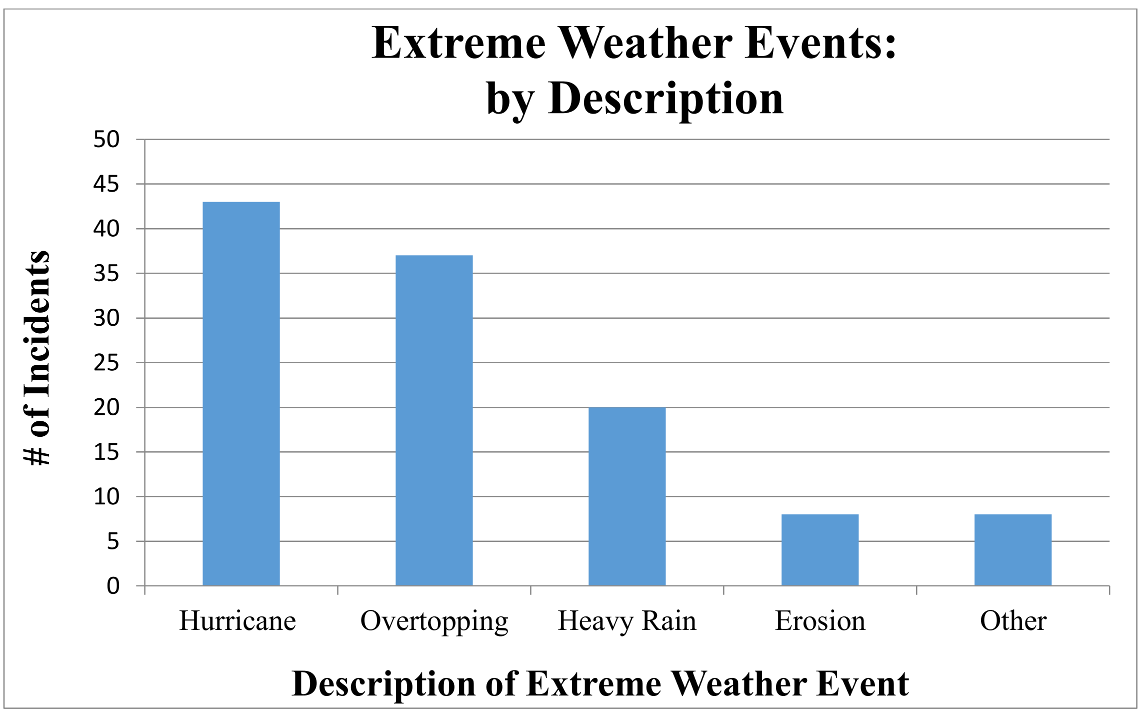


Figure 3-7: Extreme Weather Incidents – Breakdown by Description

Table 3-4 breaks down these totals from Figure 3-7 into failures and non-failures. This information highlights that most incidents occur due to high water flows. It can be concluded that this data supports the focus of the dam safety community on studying extreme flow events and focusing efforts on developing dam designs and technology that allows dams to safely handle large flows.

Extreme Weather Event: by Description			
Description	Incident Type		
	Non-Failure	Failure	TOTAL
Hurricane	41	2	43
Overtopping	25	12	37
Heavy Rainfall	13	7	20
Erosion	6	2	8
Other/Sinkhole	6	2	8
TOTAL	91	25	116

Table 3-4: Extreme Weather Incidents- Breakdown by Description

It is difficult to draw other conclusions from this data because the descriptions do not include whether the water in-flow has exceeded the state's design standard for that particular dam's hazard class. It could be recommended that future incident reports of extreme weather events include hurricanes, earthquakes, and extreme water flows that exceed the states design standards exclusively.

Also, it is important to note that earthquakes were not part of this analysis since they cannot be considered high flow events. They are however grouped with extreme weather events for the continued part of this study. The SIR reports 5 earthquake incidents (2 failures and 3 non-failures).

Table 3-5 breaks the extreme weather incidents down further by dam type. Figure 3-8 shows the graphical representation of these incident numbers listed in Table 3-5.

Extreme Weather Incidents: by Description			
Dam Type: Embankment			
Description	Incident Type		
	Non-Failure	Failure	TOTAL
Hurricane	21	1	22
Overtopping	16	7	23
Heavy Rain	8	3	11
Erosion	4	1	5
Other	3	0	3
TOTAL	52	12	64
Dam Type: Concrete			
Description	Incident Type		
	Non-Failure	Failure	TOTAL
Hurricane	8	0	8
Overtopping	5	1	6
Heavy Rain	4	0	4
Erosion	0	1	1
Other	2	0	2
TOTAL	19	2	21
Dam Type: Other or Unknown			
Description	Incident Type		
	Non-Failure	Failure	TOTAL
Hurricane	12	1	13
Overtopping	4	4	8
Heavy Rain	1	4	5
Erosion	2	0	2
Other	1	2	3
TOTAL	20	11	31

Table 3-5: Extreme Weather Events – Breakdown by Description vs. Dam Type

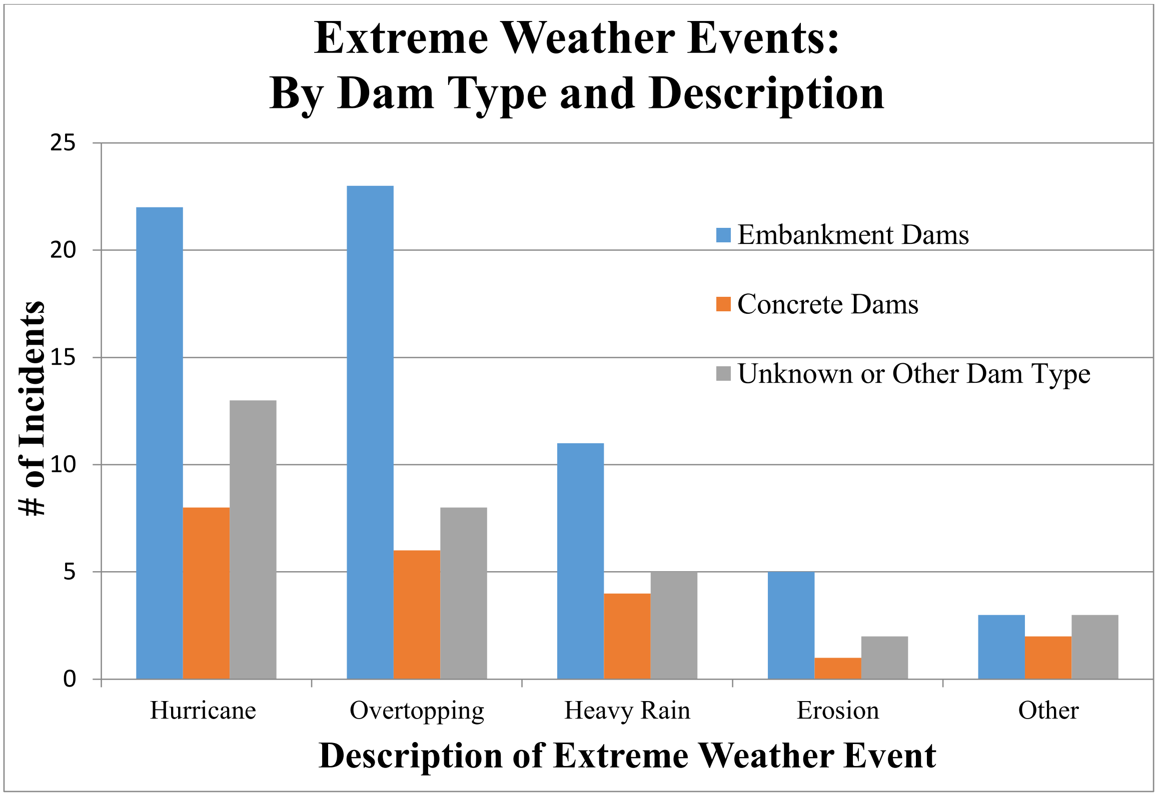


Figure 3-8: Extreme Weather Events – Breakdown by Description vs. Dam Type

This shows that all different dam types are susceptible to high flow events as they test any deficiency already inherent to the dam. Further conclusions are again difficult because the SIR does not request a description of the severity of the event. The severity could be classified by whether or not the inflow exceeded that particular dams design standard. (Design standards and spillway capacities are discussed in further detail in Section 2.6).

3.2.6) Incidents by State

This section examines the frequency of incidents in the SIR database according to their location by state. This portion of the analysis could be subjected to bias due to the disproportionally high number of incidents in New York (51) and New Jersey (38) is the result of Hurricane Irene in 2011. Other states with high incident counts include Texas, Ohio, North Carolina, Indiana, and Missouri. Design standards and capacities differ from state to state. These states with a high number of incidents could be the result of lower standards. They could also be the effect of that particular state having more flood disasters.

The next three pages show a chart, plot, and map relating to the number and percentage of incidents in each state. Table 3-6 lists each state that has recorded at least one incident in the SIR, and shows both the number of failure and non-failure incidents in that state. Figure 3-9 shows the graphical representation of Table 3-6. Figure 3-10 depicts a map of the United States that is color coded based on the percentage of SIR incidents that have occurred in that state.

This study does not compare the number of incidents in each state with that states design standards, hazard level, or the occurrences of flood disasters. These comparisons would provide useful analysis and could create awareness in states with lower standards experiencing many dam incidents.

Incidents by State			
State	Non-Failures	Failures	Total
AK	0	1	1
AZ	0	2	2
CA	4	7	11
CO	1	2	3
CT	0	2	2
DE	7	0	7
FL	0	1	1
GA	2	3	5
IA	2	2	4
ID	0	1	1
IL	0	1	1
IN	5	9	14
KY	2	1	3
MA	0	4	4
MD	1	9	10
MI	0	7	7
MN	0	2	2
MO	5	9	14
MS	4	6	10
MT	0	6	6
NC	6	10	16
NE	4	5	9
NH	7	0	7
NJ	24	14	38
NM	1	2	3
NV	1	0	1
NY	43	8	51
OH	10	5	15
OK	0	1	1
OR	0	2	2
PA	0	6	6
RI	0	2	2
SC	1	0	1
SD	0	1	1
TN	1	7	8
TX	24	6	30
UT	1	3	4
VA	4	4	8
VT	0	1	1
WA	0	7	7
WI	2	7	9
WV	0	5	5
TOTAL	162	171	333

Table 3-6: Failure and Non-Failure Incidents – by State

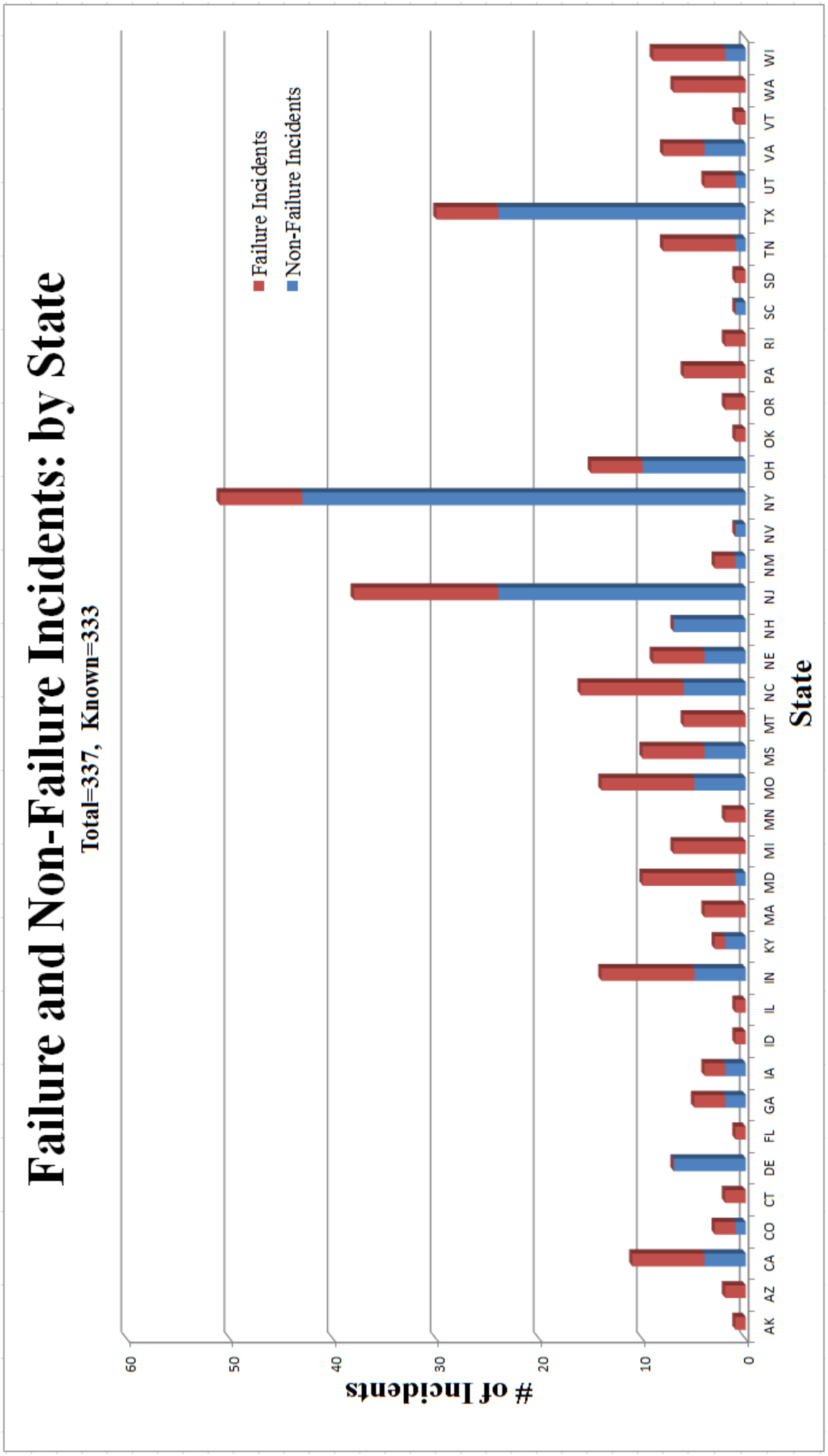


Figure 3-9: Failure and Non-Failure Incidents: by State

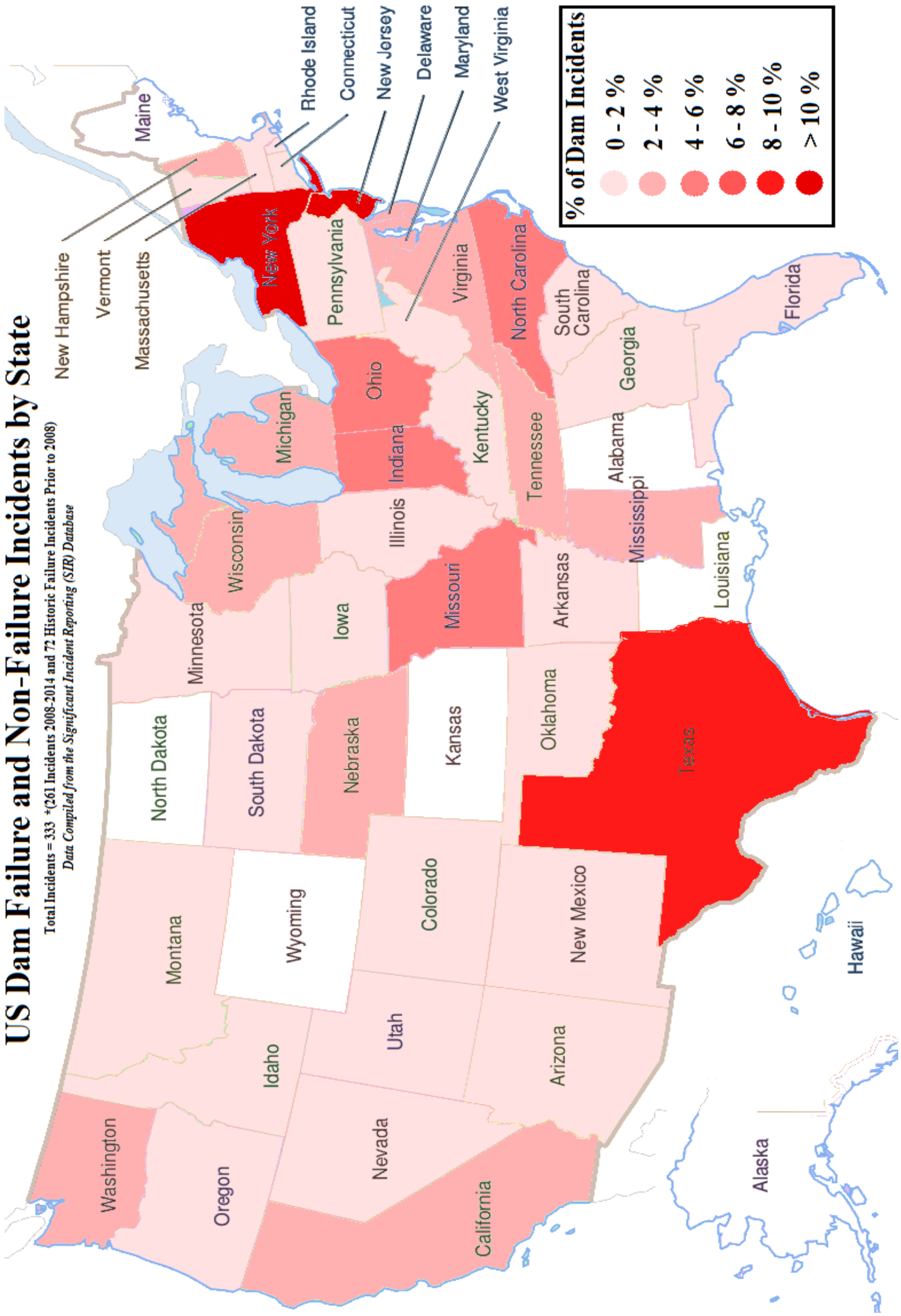


Figure 3-10: U.S. Dam Incidents in SIR by State (%)

3.2.7) Incidents by Hazard Level

Figure 3-11 show the frequencies of High, Significant and Low Hazard dams in the SIR database. They are broken down by the number of failure and non-failure incidents. High Hazard dams are better regulated, built to a higher standard than lower hazard dams, and have fewer failures due to spillway capacity issues. However, a large flood will challenge any dam in the area, encouraging non-failure incidents to occur. The number of non-failure incidents is relatively the same for all hazard levels, but due to the factors mentioned above, as the hazard level increases the number of actual failures is lower.

It is important to note the large number of failure reports in the SIR without including the Hazard Level (117 failure reports with non-response to this category). Since the dam's Hazard Level is extremely important in this analysis, better diligence on the part of the incident reporters is needed in the future.

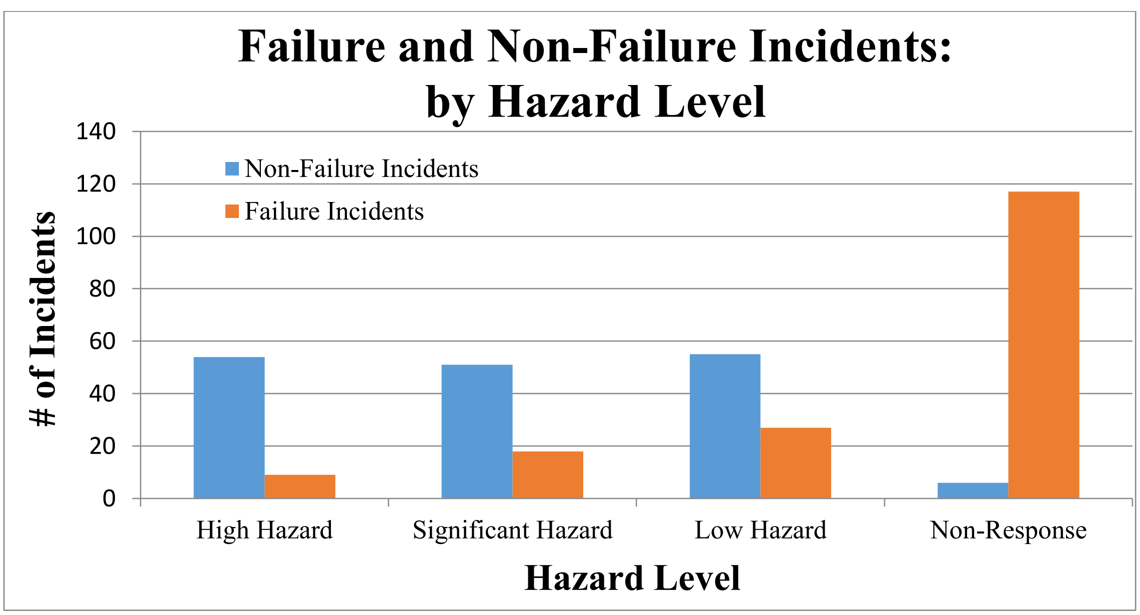


Figure 3-11: Failure and Non-Failure Incidents – by Hazard Level

3.2.8) Emergency Action Plan

Figure 3-12 illustrates the total number of reports in the SIR that had an Emergency Action Plan (EAP) enacted at the time of the incident. An overwhelming majority did not, which may indicate that the dam does not have an EAP or a failure to implement it on time.

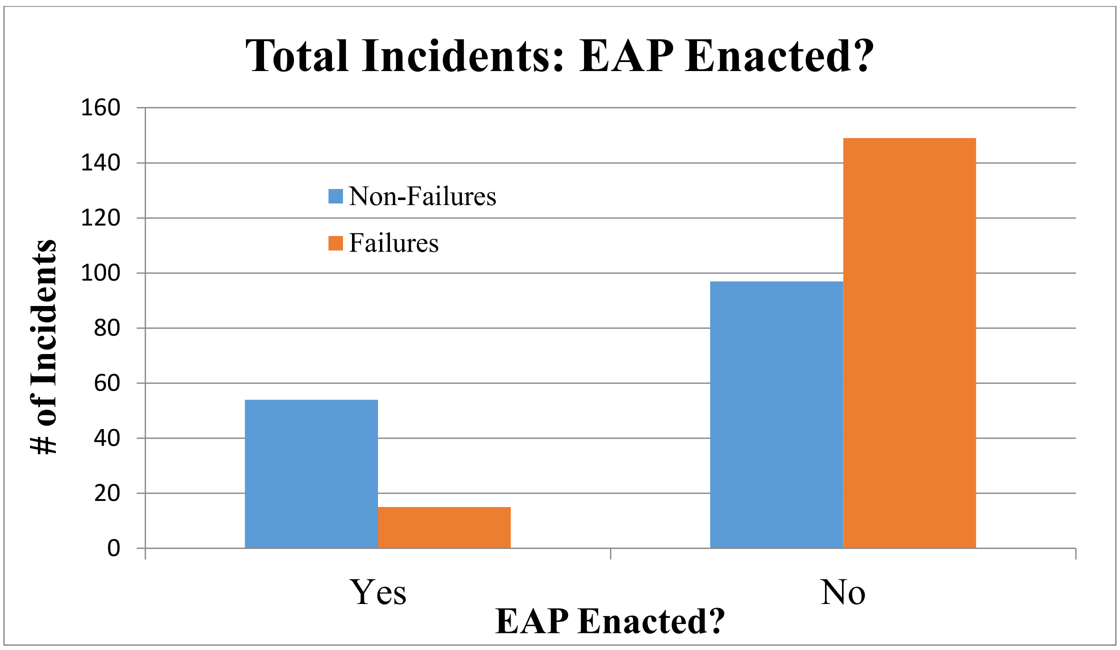


Figure 3-12: EAP Action of all Failure and Non-Failure Incidents

Figure 3-13 shows all the High Hazard dam reports in the SIR and whether or not an EAP was enacted at the time of the incident. It is extremely important for a High Hazard dam to have an EAP and enact it during a failure or non-failure incident. The downstream population and infrastructure are at risk when a High Hazard dam faces potential failure and need to be notified so decisive action can be taken. Unlike the trend for total reports, the majority of High Hazard dam incidents did have an EAP enacted.

While this is a step in the right direction, there should be a higher ratio of EAP implementations, especially in High Hazard dam failures.

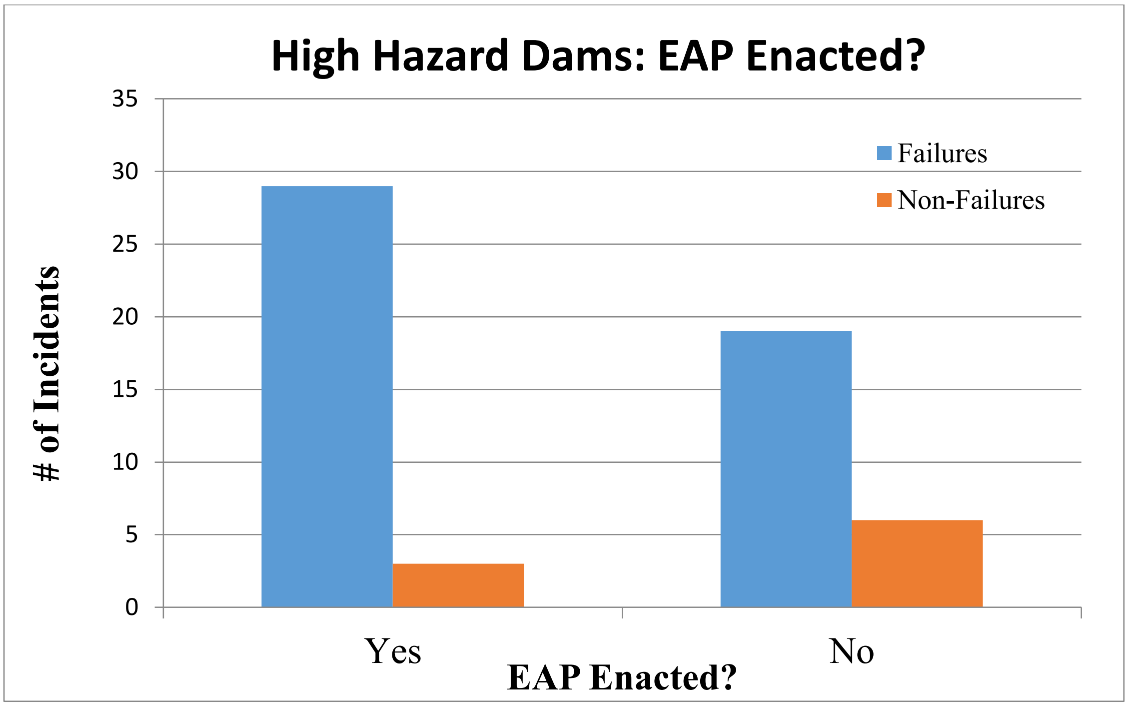


Figure 3-13: EAP Action for High Hazard Dam Incidents

3.3) Summary of Results

The SIR database currently contains 337 total reports including 265 from 2008 – April 2014 (99 Failures and 166 non-failure incidents) and 72 historic failure events prior to 2008. The Analysis of the SIR database in this study included statistical information on the variables: Dam type, incident cause, extreme weather events, the state, hazard level, and if an EAP was enacted. The following are the major points and findings from the SIR analysis:

- The majority of total SIR reports are from embankment dams (approx. 78% of known incidents). This is most likely due relatively large number of embankment dams in U.S. and that they are susceptible to more failure modes and deficiencies than concrete dams.
- The majorities of incidents have to do with extreme weather or overtopping. However, in most of these cases the incident did not result in dam failure.
- The data supports the focus of the dam safety community on studying extreme flow events, and focusing efforts on developing dam designs and technology that allows for safe handling of large flows.
- Extreme weather events are the leading cause of dam failures and incidents (42.3%). This indicates that most issues occur in high water events. The SIR data, however, does not specify whether the event exceeded the states design standard for the particular hazard class of dam in question.
- There are a high number of incidents reported in NY, NJ primarily due to Hurricane Irene. The number of incidents by state could be a function of which

states are most diligent in reporting, or which states had large floods since 2008. It would be informative to compare SIR numbers with the number of flood disasters in a state during that time.

- The number of non-failure incidents is relatively the same for all hazard levels, but because of the better regulation and design standards for high hazard dams-they have a lower number of failures.
- The majority of reports did not have an EAP enacted at the time of the incident. This could be due to the dam not having an EAP or that it was not activated in a timely manner. However, the majority of High Hazard dam incidents did have an EAP enacted. While this is a step in the right direction, there should be a higher ratio of EAP implementations, especially in High Hazard dam failures.

Recommendations for SIR reporting and thoughts for future analysis is included in Chapter 5.

Chapter 4) Dam Safety KBES Evaluation Tool

4.1) Introduction

The Dam Safety Evaluation Tool created in this study is in the form of a KBES. It incorporates the statistical analysis of the current SIR database and relies strongly on the judgment and experience of the inspecting party. The KBES uses fuzzy logic evaluations in order to account for the uncertainties and subjectivity in the inspection and evaluation process. This fuzzy logic concept to evaluate performances of structures is discussed in detail in Fabian C. Hadipriono's paper, *Assessment of Falsework Performance Using Fuzzy Set Concepts.* Many of the techniques and equations used in Hadipriono's paper are also used in this study to investigate dam safety.

The potential failure causes are assessed by the dam inspector in the form of a linguistic rating system. The fuzzy linguistic rating system is as follows:

1) Enabling Safety Level (ESL): [Very Good (VG) – Very Poor (VP)]
2) Triggering Frequency (TF): [Very High (VH) – Very Low (VL)]
3) Each of the enabling and triggering ratings correspond to an incident probability level (IP): [Very High (VH) – Very Low (VL)].

The KBES then creates three Membership Matrices with the following relations:

A) Enabling Matrix, RE: (ESL vs. IP)
B) Triggering Matrix, RT: (IP vs. TF)

C) Composition Matrix, RT o RE: (ESL vs. TF) - where “o” is a composition.

The final composition matrix (RT o RE) is used to create an Overall Dam Safety Evaluation Graph. The justification of these relationships is described in further sections and is weighted based on the statistical analysis of the SIR in Chapter 3.

4.2) Enabling and Triggering Failure Causes

Dam failures and incidents occur as a result of inherent deficiencies in the dam (enabling causes), outside factors or forces (triggering causes), or a combination of the two. Enabling causes are deficiencies intrinsic in the dam structure and could be a result of poor engineering design, materials, or geological deficiencies related to the dam. The enabling dam failure causes incorporated in the KBES include: E1) overtopping; E2) seepage and piping; E3) inadequate spillway design; and E4) instability. They are the main enabling causes of historic dam failures and were investigated in the SIR database of dam failures and incidents. These are shown and explained in greater detail in in Chapter 2.

The triggering dam failure causes are described as externally induced forces or factors creating adverse conditions. These causes can be in the form of T1) extreme weather; T2) deterioration or poor condition; T3) equipment malfunction or human error; and T4) animal burrowing and excessive vegetation. These events can cause failure by themselves or act as a driving force to intensify intrinsic dam deficiencies. These failure and incident causes are listed and explained in greater detail in Chapter 2.

4.2.1) Categorizing Incident Causes

Table 4-1 is used to classify how each of the enabling and triggering causes is weighted to determine how significant they are in predicting the occurrence of a dam failure or incident. Table 4-1 includes five categories, A – E, which correspond to the frequency of that incident cause in the SIR database. There are eight total enabling and triggering causes, and if each were equally represented they would each account for 12.5% of the database. Incident causes that account for 20% or more of the total SIR reports are placed in "Category A", and incidents accounting for 10-20% of the reports are placed in "Category B", etc.

Classes of Incident Causes by Percentage	
Category	**Incidents in SIR Database (%)**
A	> 20 %
B	10 - 20 %
C	4.6 - 9.9 %
D	2 - 4.5 %
E	0 – 1.9 %

Table 4-1: Classes of Incident Causes by Percentage

The failure causes are given different Fuzzy Relationships based on their Category (A-E). Table 4-2 shows the Fuzzy Relationship of each failure cause based on its linguistic rating input into the KBES.

Relationship Table by Class					
Incident Probability	Enabling Safety Level or Triggering Frequency				
	Very Poor (VP)	Poor (P)	Moderate (M)	Good (G)	Very Good (VG)
Very High (VH)	A, B	A			
High (H)	C	B	A		
Medium (M)	D	C	B	A	
Low (L)	E	D	C	B	A
Very Low (VL)		E	D, E	C, D, E	B, C, D, E

Table 4-2: Relationship Table by Class

4.2.2) Enabling and Triggering Relationship Tables

Table 4-3 includes all the failure causes (enabling and triggering) and their corresponding class level. Table 4-4 shows how the different safety levels (Very Poor – Very Good) of each enabling cause relates to the incident probability level (Very High – Very Low). Table 4-5 shows how the different frequency levels (Very High – Very Low) for each triggering cause relates to the incident probability level (Very High – Very Low). These are based on the SIR statistics and category level of each incident.

As the number of SIR reports increases through the years, so too will the accuracy of these statistics. The larger the SIR database, the better it will represent the incident cause probability distribution for dams in the real world.

Failure and Incident Cause – Class Levels	
Enabling Causes (49.5%)	**% of Incidents, (Class)**
E1) Overtopping	21.86, (Class A)
E2) Seepage and Piping	12.54, (Class B)
E3) Spillway Deficiency	8.24, (Class C)
E4) Structural Instability	7.52, (Class C)
Triggering Causes (50.5%)	**% of Incidents, (Class)**
T1) Extreme Weather Event	42.28, (Class A)
T2) Deterioration or Poor Condition	4.66, (Class C)
T3) Eq. Malfunction or Human Error	1.43, (Class E)
T4) Animal Burrowing	1.43, (Class E)

Table 4-3: Failure and Incident Cause - Class Levels

Fuzzy Relation Table: (ESL vs. IP)					
Incident Probability (IP)	Enabling Safety Level (ESL)				
	Very Poor (VP)	Poor (P)	Moderate (M)	Good (G)	Very Good (VG)
Very High (VH)	E1, E2	E1			
High (H)	E3, E4	E2	E1		
Medium (M)		E3, E4	E2	E1	
Low (L)			E3, E4	E2	E1
Very Low (VL)				E3, E4	E2, E3, E4

Table 4-4: Enabling Fuzzy Relation Table – ESL vs. IP

Fuzzy Relation Table: (TF vs. IP)					
Incident Probability (IP)	Triggering Frequency (TF)				
	Very High (VH)	High (H)	Moderate (M)	Low (L)	Very Low (VL)
Very High (VH)	T1	T1			
High (H)	T2		T1		
Medium (M)		T2		T1	
Low (L)	T3, T4		T2		T1
Very Low (VL)		T3, T4	T3, T4	T2, T3, T4	T2, T3, T4

Table 4-5: Triggering Relationship Table – TF vs. IP

For example using Table 4-5*,* if Extreme Weather, (T1), is given a frequency rating of Moderate (M) it would independently relate to a High (H) Incident Probability.

4.3) KBES Interface

4.3.1) Failure Cause Descriptions and Relationship Tables

The KBES has a series of interactive tabs for the user to navigate. Figures 4-1 and 4-2 provide background information on the potential enabling and triggering incident causes. When the user selects a specific enabling or triggering cause from the dropdown box, a description of that cause and a list of potential deficiencies that would relate to this cause during inspection are given. For example, Figure 4-1 shows the "Seepage and Piping" (E2) has been selected by the user. The program then gives the definition of Seepage and Piping, and lists various possible deficiencies that may be associated with E2.

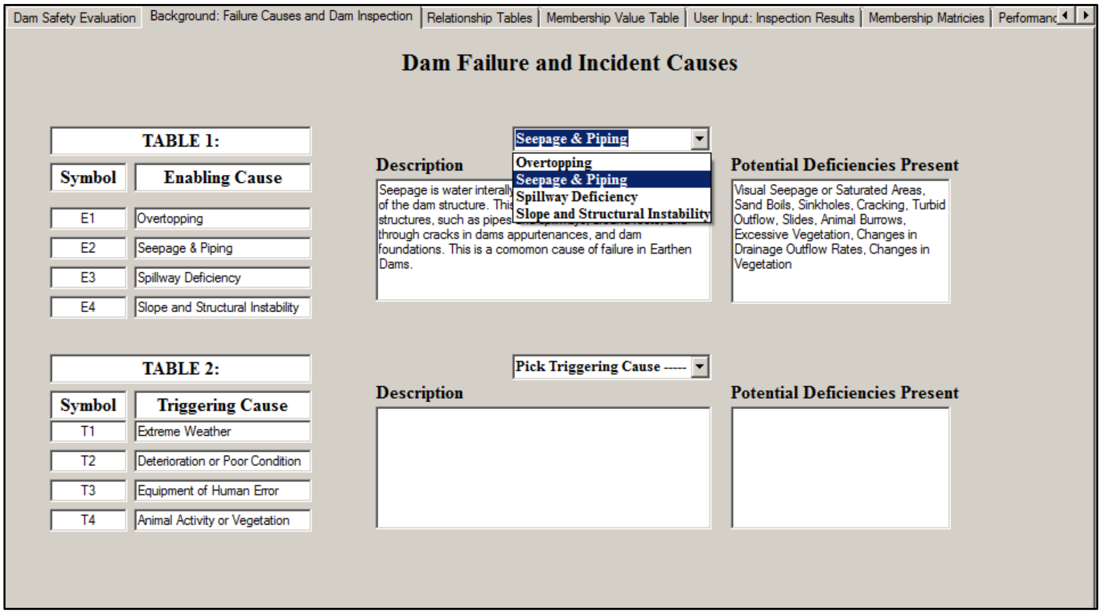


Figure 4-1: KBES Interface – Enabling Failure Causes and Potential Deficiencies

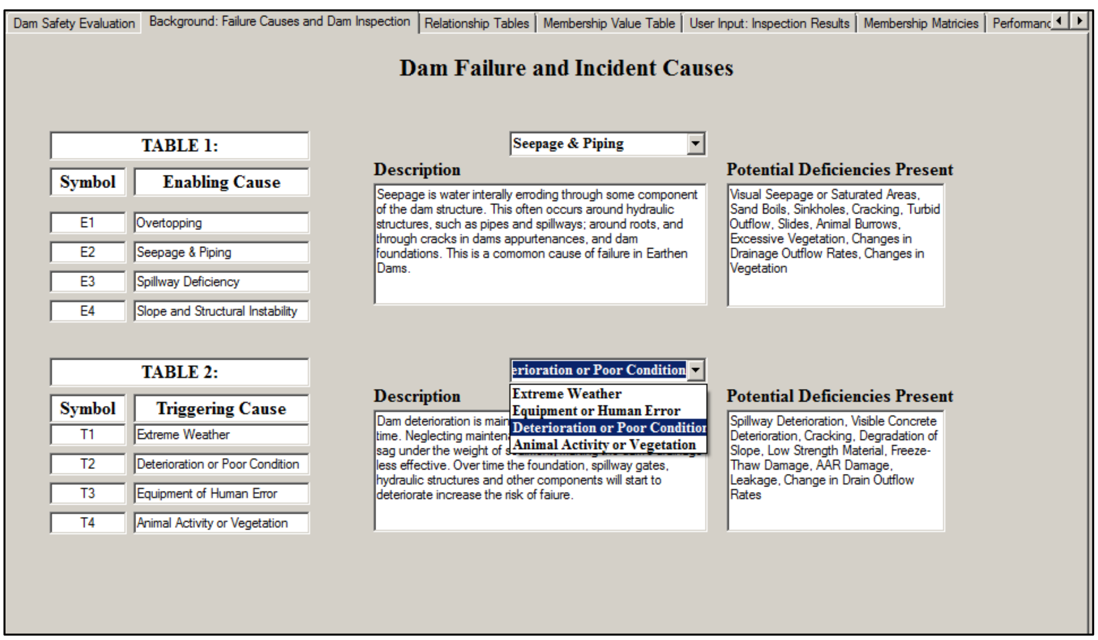


Figure 4-2: KBES Interface – Triggering Failure Causes and Potential Deficiencies

Figure 4-3 shows the Fuzzy Relationship Tables for each enabling and triggering failure cause.

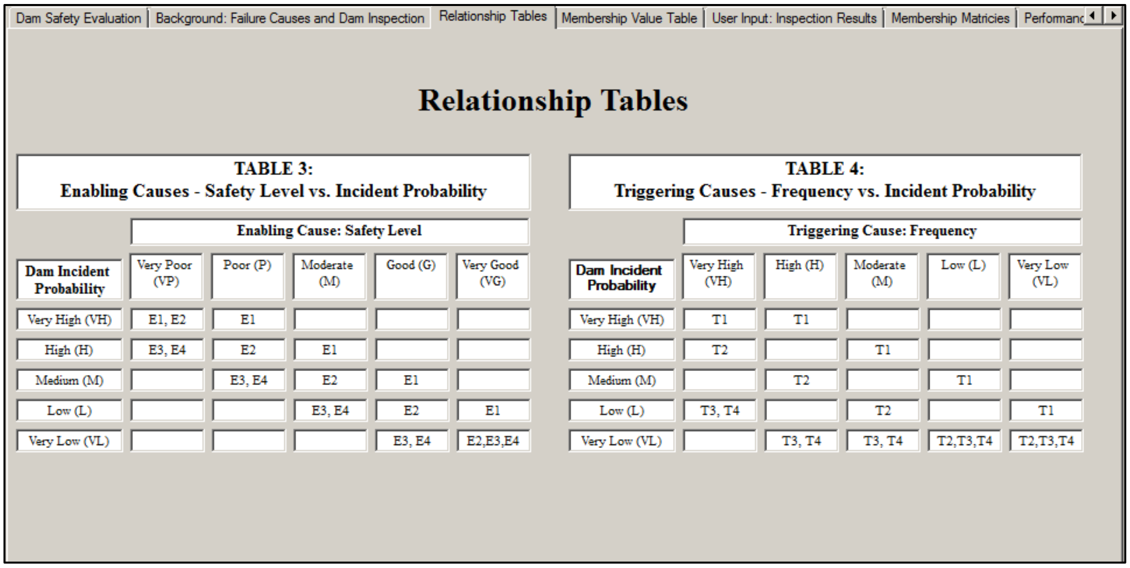


TABLE 3:
Enabling Causes - Safety Level vs. Incident Probability

Dam Incident Probability	Enabling Cause: Safety Level Very Poor (VP)	Poor (P)	Moderate (M)	Good (G)	Very Good (VG)
Very High (VH)	E1, E2	E1			
High (H)	E3, E4	E2	E1		
Medium (M)		E3, E4	E2	E1	
Low (L)			E3, E4	E2	E1
Very Low (VL)				E3, E4	E2,E3,E4

TABLE 4:
Triggering Causes - Frequency vs. Incident Probability

Dam Incident Probability	Triggering Cause: Frequency Very High (VH)	High (H)	Moderate (M)	Low (L)	Very Low (VL)
Very High (VH)	T1	T1			
High (H)	T2		T1		
Medium (M)		T2		T1	
Low (L)	T3, T4		T2		T1
Very Low (VL)		T3, T4	T3, T4	T2,T3,T4	T2,T3,T4

Figure 4-3: KBES Interface – Fuzzy Relationship Tables

4.3.2) Membership Values

Each Incident Probability (Very Low – Very High) corresponds to a range of numeric values from 0.0 to 1.0 with increments of 0.1. Figure 4-4 shows the Membership Value Table, which can be thought of as a level of certainty. Inside each numeric range is a corresponding level of certainty value (also a 0.0 – 1.0 scale). For example: a Very Low (VL) incident probability corresponds to the numerical range of x = (0.0, 0.1, and 0.2). Each of these three values is assigned a membership value, f(x). The membership value column is in the form [x1 |f(x1); x2 | f(x2); etc.] where "|" is a delimiter. This concept is discussed in great detail in the previously mentioned paper by Hadipriono. "Very Low" and "Low" probabilities share the same numeric range, but their membership value, f(x) is not the same for each x value. This is because a "Very Low" rating would have a greater level of certainty for x = 0.0 than a "Low" rating. The same is true for "Very High" and "High" probabilities.

Membership Function Table

<table>
<tr><th>Enabling Safety Level</th><th>Triggering Frequency</th><th>Dam Incident Probability</th><th>Numeric Range: (x)</th><th>Membership Vaules: f(x)</th></tr>
<tr><td>Very Poor (VP)</td><td>Very Low (VI)</td><td>Very Low (VL)</td><td>0.0 --- 0.2</td><td>[1.0 | 0.0; 0.9 | 0.1; 0.7 | 0.2]</td></tr>
<tr><td>Poor (P)</td><td>Low (L)</td><td>Low (L)</td><td>0.0 --- 0.2</td><td>[0.7 | 0.0; 0.9 | 0.1; 0.7 | 0.2]</td></tr>
<tr><td>Moderate (M)</td><td>Medium (M)</td><td>Medium (M)</td><td>0.3 --- 0.7</td><td>[0.4|0.3; 0.6|0.4; 0.8|0.5; 0.6|0.6; 0.4|0.7]</td></tr>
<tr><td>Good (G)</td><td>High (H)</td><td>High (H)</td><td>0.8 --- 1.0</td><td>[0.7 | 0.8; 0.9 | 0.9; 0.7 | 1.0]</td></tr>
<tr><td>Very Good (VG)</td><td>Very High (VH)</td><td>Very High (VH)</td><td>0.8 --- 1.0</td><td>[0.7 | 0.8; 0.9 | 0.9; 1.0 | 1.0]</td></tr>
</table>

Figure 4-4: KBES Interface – Membership Function Table, f(x)

4.3.3) User Input: Inspection and Assessment

Figure 4-5 shows the tab where user assessments and ratings are required for each enabling and triggering cause. It is important that these ratings are carried out after an expert inspection of the dam has been made.

Based on the judgment and experience of the inspecting party, a safety level is given for each enabling failure cause and a frequency is given for each triggering failure cause. Once the safety level and frequencies are chosen by the user, the corresponding incident probabilities will appear. Figure 4-5 is an example of a dam that has been very poorly rated in all enabling and triggering categories and will be used as an example of a very unsafe dam.

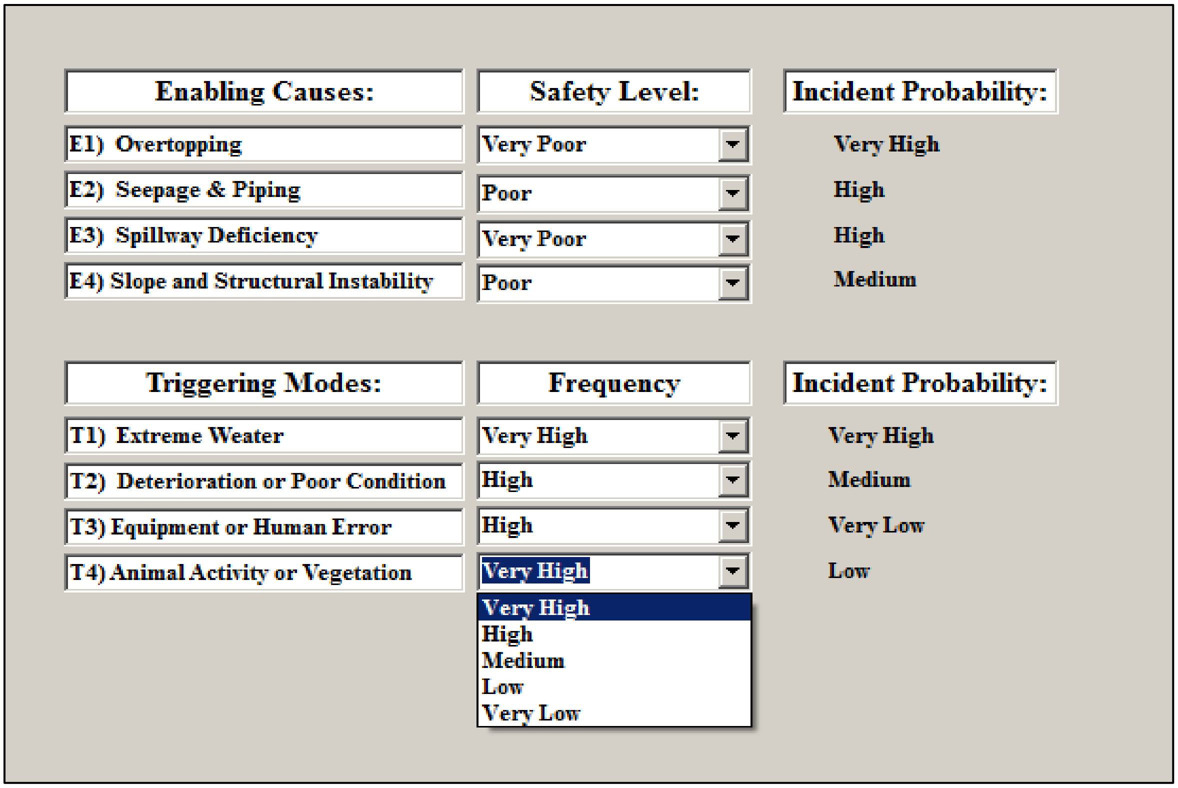


Figure 4-5: KBES Interface – User Input Tab

4.3.4) Membership Matrices

After each enabling and triggering failure cause is assessed and rated, three matrices are formulated. These matrices are created using the conjunctions and disjunctions of the different membership value sets discussed in the previous sections. To perform this type of evaluation of dams, many of the equations and methods from Hadipriono's paper are used and explained in this section.

Figure 4-6 shows the Enabling Matrix, (RE), which is the Enabling Safety Level (ESL) vs. Incident Probability (IP) based on the user inputs shown in Figure 4-5. Since the linguistic variables ESL and IP of the enabling events (E) are in different universes of discourse, their fuzzy set membership values from Figure 4-4 are needed. The membership function of the relation RE2 (Seepage and Piping), for example, between fuzzy subsets Poor (P) and High (H) can be found through the use of equation [1]:

$$f_{RE2} = f_{H\,x\,P}(x_i, y_j) = \wedge\left[f_P(x_i), f_H(y_j)\right] \qquad [1]$$

Where Poor (P) is a subset of X and High (H) is a subset of Y; X and Y are universes associated with the ESL and IP respectively. The "∧" symbol denotes the conjunction which corresponds to the intersection "∩" in classic set theory. Equation [2] is used to find the disjunction of all enabling causes, RE. "V" is used as the symbol to represent disjunction in equation [2] (Hadipriono 1985: pp.52-53).

$$f_{Ri}(x_i, y_j) = V\left[f_{Ri}(x_i, y_{j)})\right] \qquad [2]$$

Membership Function Matricies

RE = IP x ESL

Enabling Saftey Level (ESL)

	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0.0	0	0	0	0	0	0	0	0	0	0	0
0.1	0	0	0	0	0	0	0	0	0	0	0
0.2	0	0	0	0	0	0	0	0	0	0	0
0.3	0.4	0.4	0.4	0	0	0	0	0	0	0	0
0.4	0.6	0.6	0.6	0	0	0	0	0	0	0	0
0.5	0.7	0.8	0.7	0	0	0	0	0	0	0	0
0.6	0.6	0.6	0.6	0	0	0	0	0	0	0	0
0.7	0.4	0.4	0.4	0	0	0	0	0	0	0	0
0.8	0.7	0.7	0.7	0	0	0	0	0	0	0	0
0.9	0.9	0.9	0.7	0	0	0	0	0	0	0	0
1.0	1	0.9	0.7	0	0	0	0	0	0	0	0

Incident Probability (IP)

Matrix 1: Enabling Safety Level vs. Incident Probability

Matrix 2: Incident Probability vs. Triggering Frequency

Matrix 3: Enabling Safety Level vs. Triggering Frequency

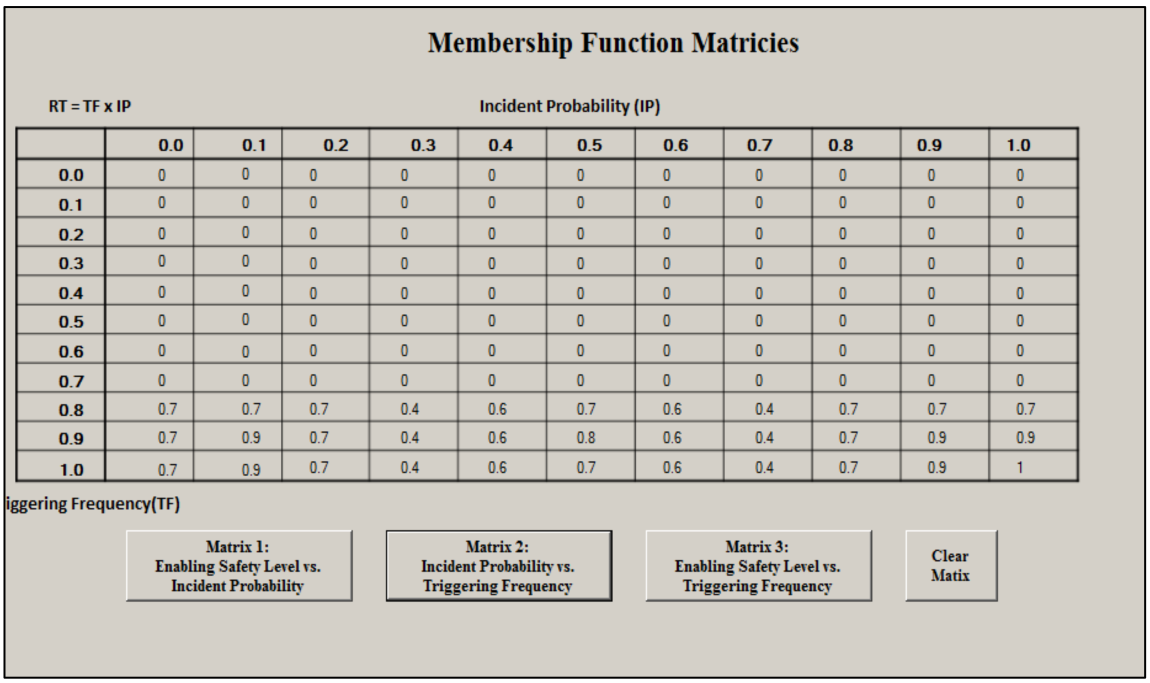
Clear Matix

Figure 4-6: Membership Matrix RE – Enabling Safety Level vs. Incident Probability

The same concept used for the Enabling Matrix RE is used to compute the Triggering Matrix, RT. The total relation of the Triggering Frequency (TF) and Incident

Probability (IP) is obtained by taking the disjunction of all relations RT*i* (for $i = 1,\ldots, 4$) (Hadipriono 1985: pp. 53). This makes IP a set in the space Y and the TF a set in the space Z.

Figure 4-7 shows Matrix RT based on the user input assessments of the triggering inputs shown in Figure 4-5.



	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0.0	0	0	0	0	0	0	0	0	0	0	0
0.1	0	0	0	0	0	0	0	0	0	0	0
0.2	0	0	0	0	0	0	0	0	0	0	0
0.3	0	0	0	0	0	0	0	0	0	0	0
0.4	0	0	0	0	0	0	0	0	0	0	0
0.5	0	0	0	0	0	0	0	0	0	0	0
0.6	0	0	0	0	0	0	0	0	0	0	0
0.7	0	0	0	0	0	0	0	0	0	0	0
0.8	0.7	0.7	0.7	0.4	0.6	0.7	0.6	0.4	0.7	0.7	0.7
0.9	0.7	0.9	0.7	0.4	0.6	0.8	0.6	0.4	0.7	0.9	0.9
1.0	0.7	0.9	0.7	0.4	0.6	0.7	0.6	0.4	0.7	0.9	1

Figure 4-7: Membership Matrix RT – IP vs. TF

Equations [1] and [2] show that Matrix RT is a set in the space (Z x Y) and Matrix RE is a set in the space (Y x X), and therefore are not in the same space. The integration between them can be performed through fuzzy composition in which both RT and RE are extended into a common space (X x Y x Z). The membership function of the composition, RT o RE is given by equation [3] (Hadipriono 1985).

$$f_{RT\ x\ RE}(x_i, z_k) = V\ [[f_{RT}(x_i, y_j, z_k)] \wedge [f_{RE}(x_i, y_j, z_k)]] \qquad [3]$$

By employing equation [3], the final Matrix (RT o RE) is produces showing the composition between Matrix RE and RT. Figure 4-8 shows Matrix RT o RE which is the ESL vs. IP.

Membership Function Matricies

RT o RE

Enabling Safety Level

	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0.0	0	0	0	0	0	0	0	0	0	0	0
0.1	0	0	0	0	0	0	0	0	0	0	0
0.2	0	0	0	0	0	0	0	0	0	0	0
0.3	0	0	0	0	0	0	0	0	0	0	0
0.4	0	0	0	0	0	0	0	0	0	0	0
0.5	0	0	0	0	0	0	0	0	0	0	0
0.6	0	0	0	0	0	0	0	0	0	0	0
0.7	0	0	0	0	0	0	0	0	0	0	0
0.8	0.7	0.7	0.7	0	0	0	0	0	0	0	0
0.9	0.9	0.9	0.7	0	0	0	0	0	0	0	0
1.0	1	0.9	0.7	0	0	0	0	0	0	0	0

Triggering Frequency

Matrix 1: Enabling Safety Level vs. Incident Probability

Matrix 2: Incident Probability vs. Triggering Frequency

Matrix 3: Enabling Safety Level vs. Triggering Frequency

Clear Matix

Figure 4-8: Membership Matrix (RT o RE) – ESL vs. TF

4.4) Overall Dam Safety Level Evaluation

In order to obtain the Overall Dam Saftey Level, the membership values in Matrix RT o RE are projected onto the Enabling Safety Level (ESL) space. This is done by implimenting equation [4]:

$$f_{Tx}(x_i) = V\ f_{RT\ x\ RE}\ (x_i, z_k) \qquad [4]$$

Tx is the projection of the membership values on the ESL space, X. The maximum value from each column of Matrix RT o RE is chosen as the final membership value of the overall dam safety level. Using the example inputs from a theoretically very unsafe dam, (Figure 4-5), the overall safety level projections from Matrix RT o RE (Figure 4-8) give:

Tx= [0.0 | 1.0; 0.1 | 0.9; 0.2 | 0.7] [5]

The rest of the ESL projections for X values of 0.3 – 1.0 have membership values of zero, indicing a zero probability for the given inputs. Equation [5] is graphically represented in Figure 4-9.

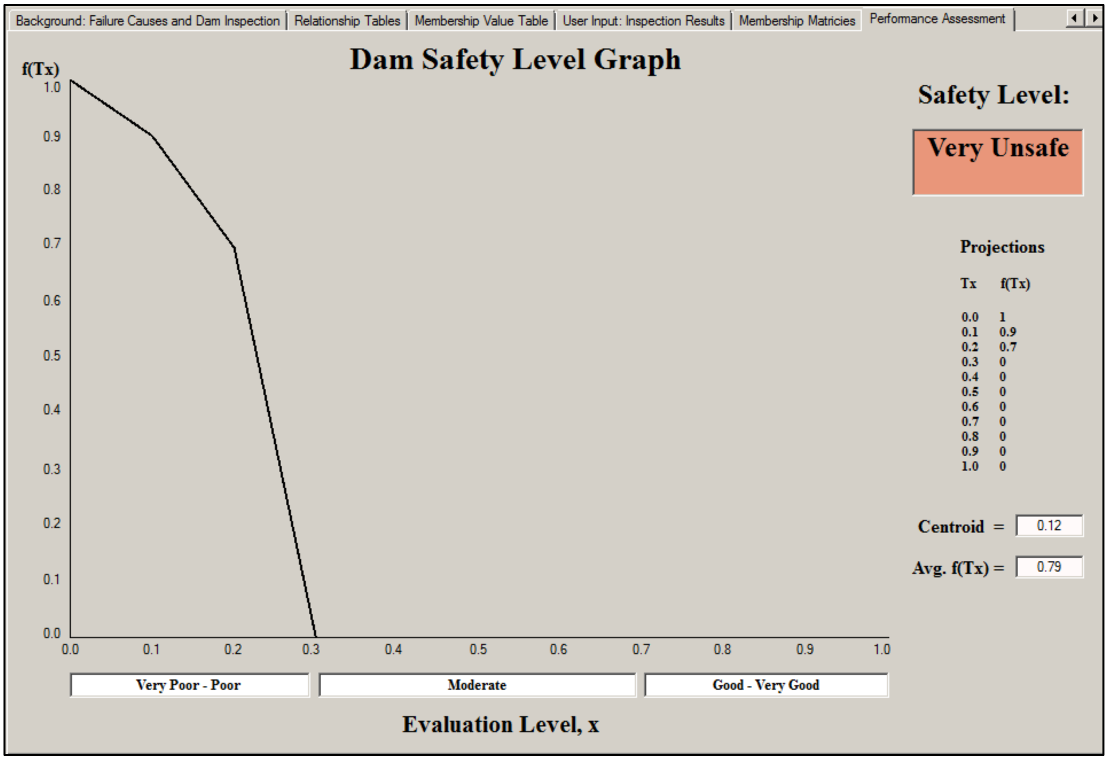


Figure 4-9: Dam Safety Level Graph Example – "Very Unsafe"

The y-axis of Figure 4-9 is the numberical projections, f(T*x*) from Matrix RT o RE which are shown on to the right of the graph. The dam's overall safety level in linguistic terms is shown in the top right hand corner, and is derived from the centroid of the graph. The x-component of the centroid is most important as the range in which it falls determines the overall safety level. These coorelations are listed in Table 4-6. There are many other combinations that will result in a 'similar' looking graph. An "Unsafe" evaluation is plotted in a similar fasion to a "Very Unsafe" evaluation, but the centroid and average level of certainty will differ.

Overall Safety Level from Centroid	
Overall Saftey Level	**Centroid *x* Value (Range)**
Very Safe	0.85 – 1.0
Safe	0.7 – 0.84
Moderate – Safe	0.56 – 0.69
Moderate	0.45 – 0.55
Moderate – Unsafe	0.31 – 0.44
Unsafe	0.16 – 0.30
Very Unsafe	0.0 – 0.15

Table 4-6 : Overall Safety Level from Centroid

4.4.1) Examples of Saftey Level Inputs and Evaluations

The example inputs in the previous section gave the final safety evaluation in Figure 4-9, depicting a “Very Unsafe” evaluation level. There are many possible inputs, assessments, and evaluations that can be made based on the judgement of the dam inspector. Figures 4-10 and 4-11 show the user inputs and corresponding safety level graph for a theoretical dam with a “Moderate to Unsafe” Safety Evaluation repectively.

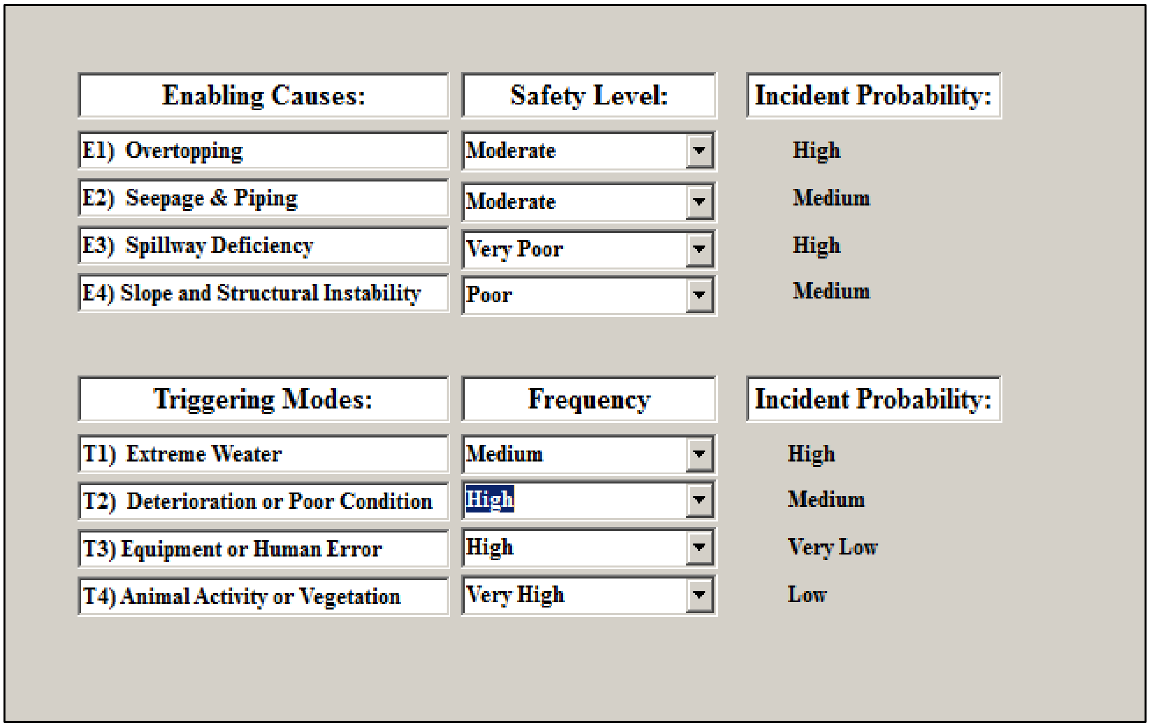


Figure 4-10: Sample Inputs for a “Moderate – Unsafe” Evaluation

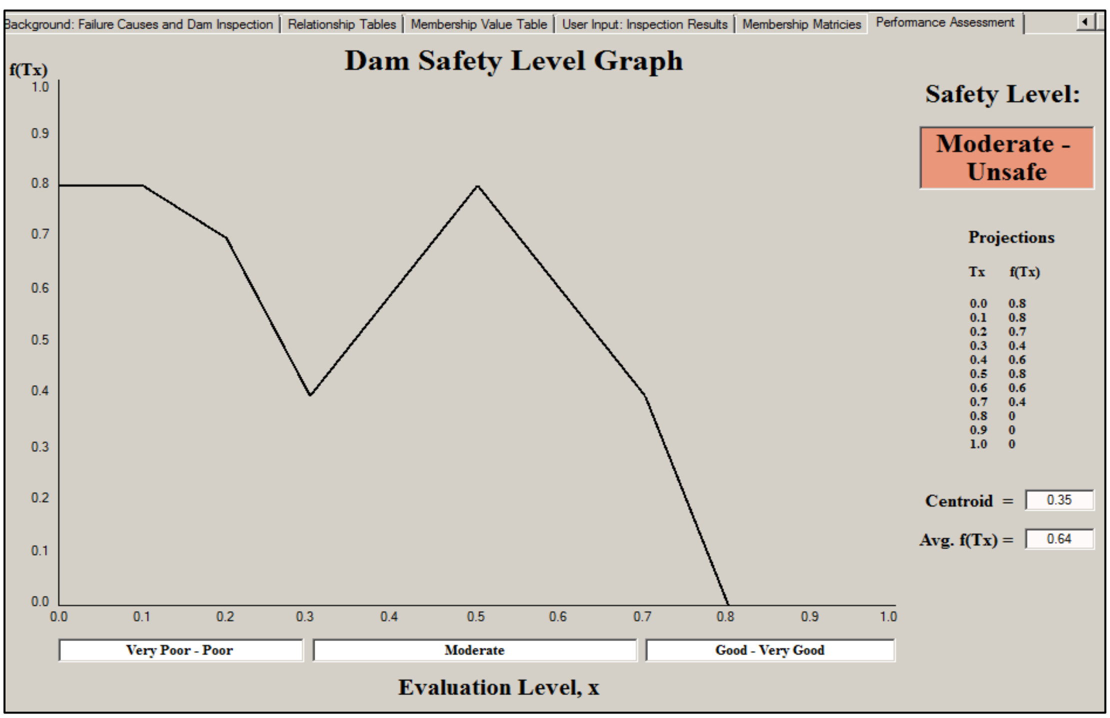


Figure 4-11: “Moderate – Unsafe” Saftey Level Evaluation

Figures 4-12 and 4-13 shows sample inputs and the safety level graph for a dam with a "Moderate" safety level respectivley. The x-centroid is located at 0.5 with an average level of certainty, f(Tx) of 0.56.

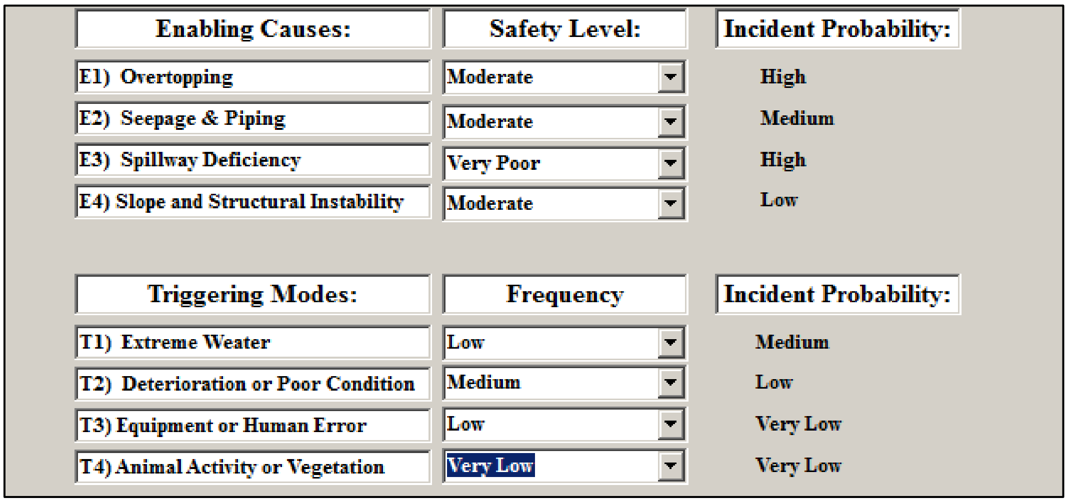


Figure 4-12: Sample Inputs for a "Moderate" Evaluation

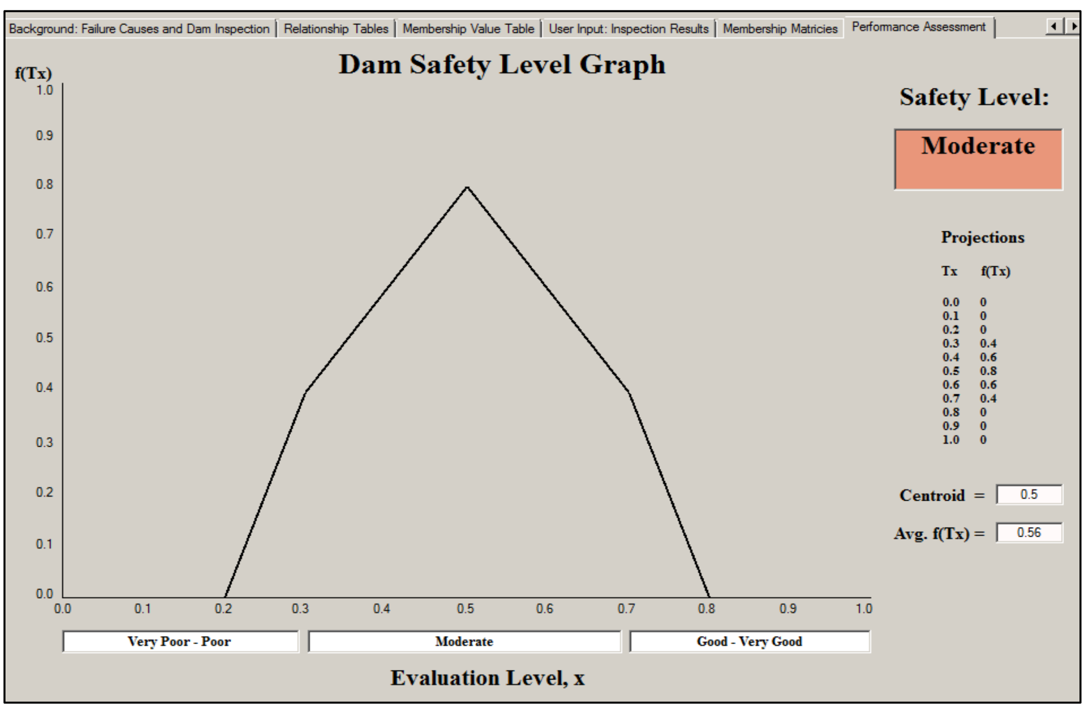


Figure 4-13: Example of a "Moderate" Saftey Level Evaluation

Figures 4-14 and 4-15 on the followin page show sample user inputs and the corresponding safety level graph for a theoretical dam with a “Moderate to Unsafe” Safety Evaluation repectively.

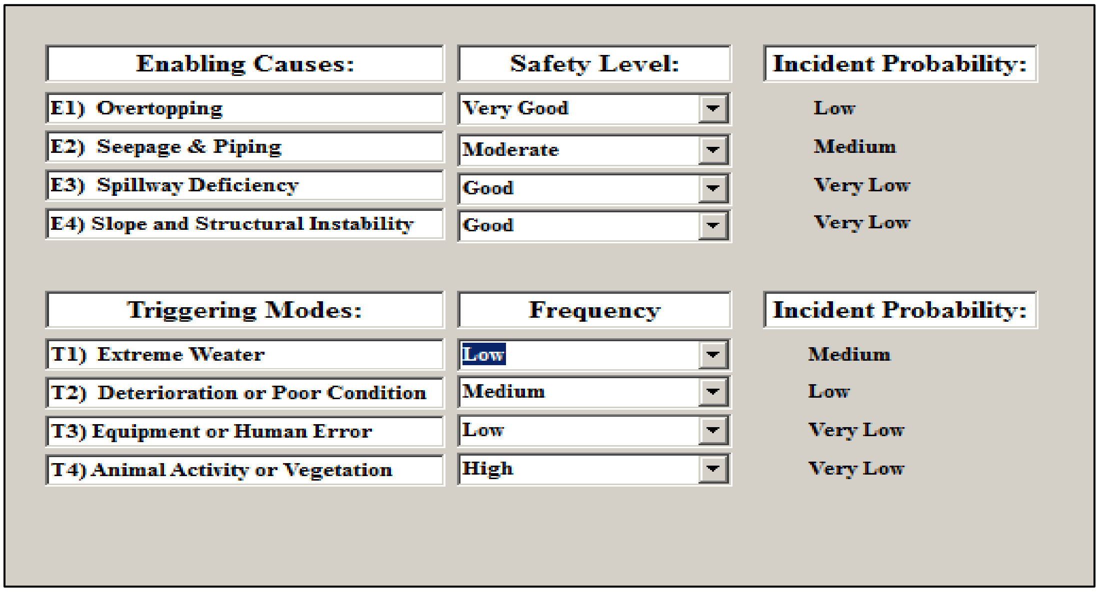


Figure 4-14: Sample Inputs for a “Moderate - Safe” Evaluation

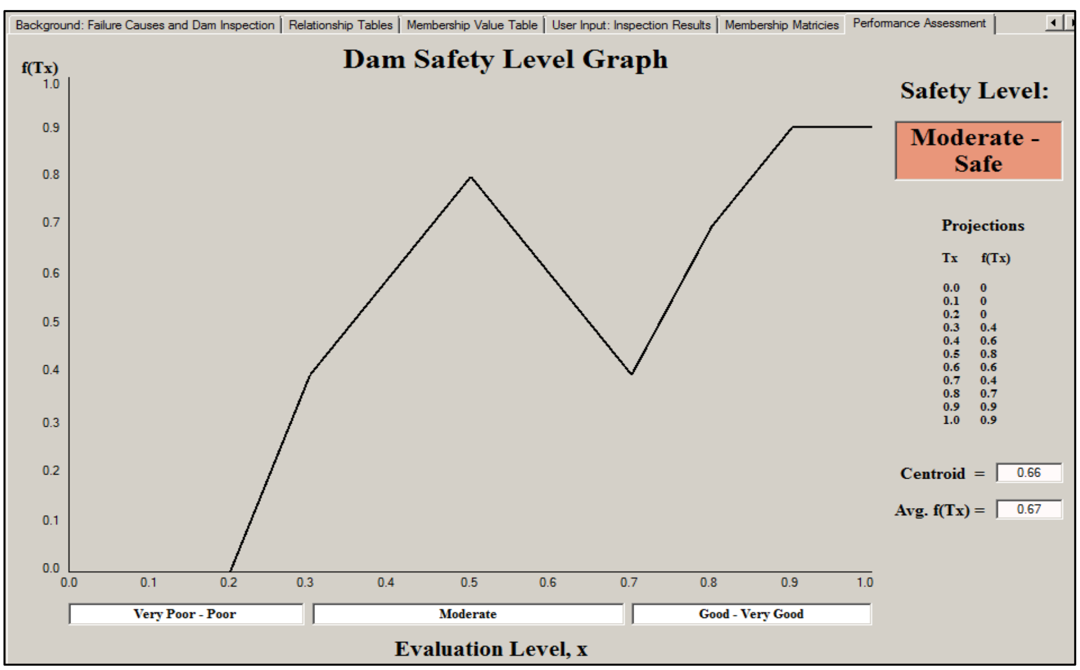


Figure 4-15: Example of a “Moderate - Safe” Safety Level Evaluation

Figures 4-16 and 4-17 show sample user inputs and the corresponding safety level graph for a theoretical dam with a “Very Safe” Safety Evaluation repectively. It is important to note that there are many input combinations that can create a similar overall evaluation. A graph with a “Safe” Evaluation closely resembles a “Very Safe” graph, but the centroid and average f(Tx) values would be different.

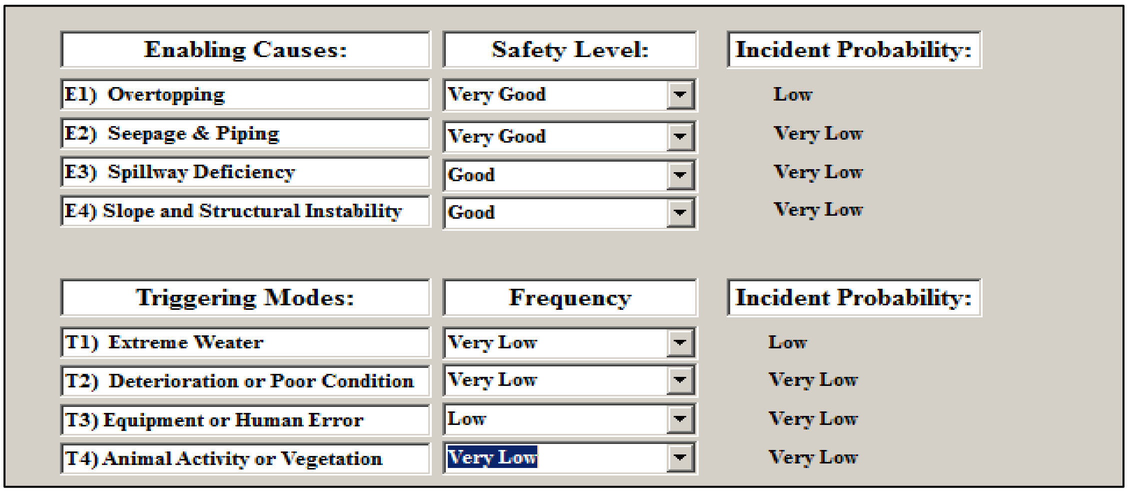


Figure 4-16: Sample Inputs for a “Very Safe” Evaluation Level

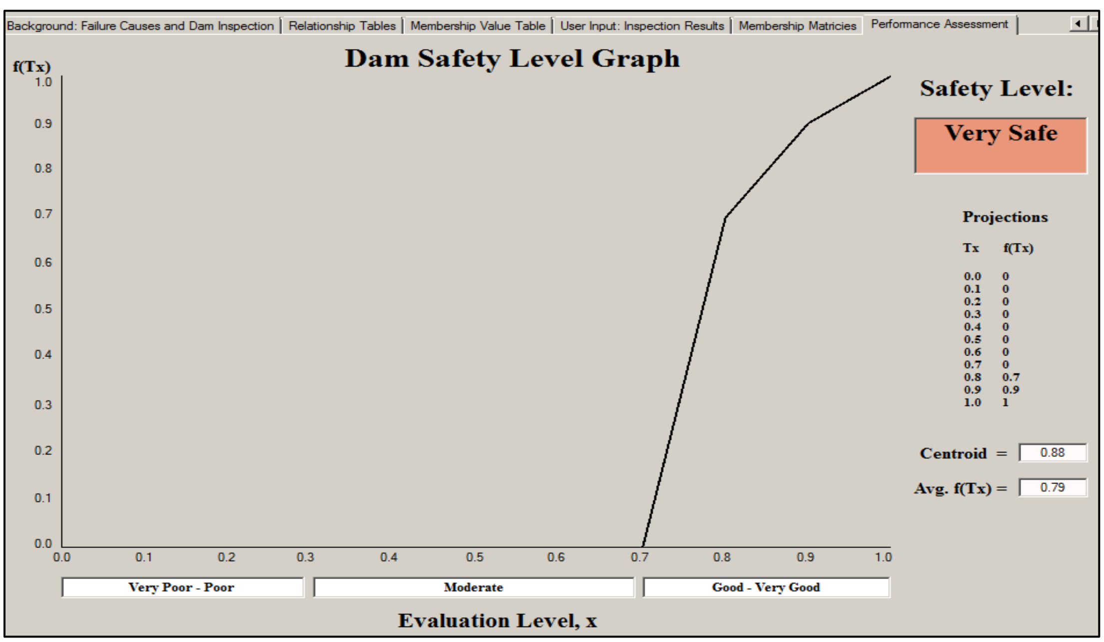


Figure 4-17: Example of a “Very Safe” Evaluation Level

Chapter 5) Recommendations and Conclusions

5.1) Summary and Conclusion

Dams are an extremely important part of our nations infrastructure serving numerous economic, agrigultural, environmental, and recreational purposes. Dam safety is becoming an increasingly important issue because countless U.S. dams are deficient and at risk of failure. A dam failure can be a catastrophic event with dangerous consequences to the downstream area and the surrounding environment. In many locations, if a dam fails it can cause massive damage to property, the economy, the environment, and can result in fatalities.

The dam safety community is currently facing critial issues and if they go unsolved, can result in a crumbling of the U.S. dam infrastructure. Many dams were constructed in the early 1900's and suffer from the effects of aging, deterioration, and poor engineering standards. Dams that were built decades ago had undeveloped, highly agricultural downstream areas. With the increase in population, many of these areas are now heavily populated making the safety of the upstream down critical.

This study is designed to improve the safety and sustainability of the U.S. dam infrastructure. It is a goal to increase situational awareness of dam owners, regulators and inspectors. This studysupports this goal by analyzes the SIR database to gain insights on recent dam failures and incidents. The SIR database is a relatively new endeavor taken on by the ASDSO and the Department of Homeland Security Office of Infrastructure Protection. This database of recent dam failures and incidents is one of the first of its kind. Much can be gained by examining and analyzing its contentsto find useful statistics and trends in the variables.

This report also compiles important background information on dams to help with public awareness. Reviewing and understanding the different dam materials, designs, failure causes, and proper inspection techniques is crucial to creating feasible solutions to the nations dam safety crisis. Inspections and safety level evaluations of existing dams can help prevent future disasters. This study creates a dam safety level evaluation tool to help meet the challenges of uncertainties and dam failure prevention.

The dam safety community is starting to show great signs of improvement and initiative. It is imparative that people become aware and active to find dam safety solutions which can revitalize the nations infrastructure.

5.2) Recommendations

An important part of this study was to provide recommendations and possible improvements for the future of SIR reporting and dam safety level evaluating. There is more analysis than can be done using the SIR database than what was presented in this study. It would be informative to find trends and correlations of other variables as the database continues to expand. The KBES safety evaluation program for dams can also include other aspects such as dam type, state, and hazard level. This study provides the crucial research and development for incorporating SIR statistics into an aplicable safety evaluation tool. This program is therefore a prototype that can be expanded and improved on in the future.

5.2.1) SIR Database Recommendations

Recommendations for the SIR include improvements of reporting methods and standards, and further analysis which can be utilized. The following is a list of recommendations for SIR reporting and future analysis:

- The method of clarifying an “Extreme Weather Event” is needed so it does not become a blanket incident cause. Most dam failures deal with heavy rainfall and high water levels, but everything should not be classified as an extreme weather event. It may be advisable to limit the definition of an “Extreme Weather Event” to a hurricane, earthquake, or flooding beyond the spillway design standards for that dam or hazard level.
- Make sure the incident reporting group is diligent and includes all known entry inputs for an incident. Many variables in this study were unknown due to non-response for a particular input. For example there were 123 reports that did not include what Hazard Level the dam was. Non-response, especially in smaller datasets, creates skewed and bias results.
- As the SIR grows, it would be beneficial to look at trends in the data over time. This is helpful in studying the effects of climate change and differences in engineering standards.

- The SIR statistics should be compared with statistics in the National Inventory of Dams (NID). This would give a better picture for analyzing things such as dam types.
- In order to get a better indication why some states have more incidents than others, it would be beneficial to compare state incidents with the number of flood disasters in that state.
- Compare state incidents with that states corresponding design standards and hazard level descriptions

5.1.2) Possible Improvements to the KBES

The analysis of the SIR database includes many variables and statistics, while the KBES only incorporates failure causes. As this is the most important factor when determining risk, other factors would help strengthen the program. Some KBES recommendations and continued work are listed below:

- Incorporation of different risk levels for each enabling and triggering cause based on the different dam types. Currently the KBES relies solely on the judgment and experience of the inspector, which leaves many uncertain variables. The more the program can do on its own, the more reliable it becomes.
- Include the state as an input so the program could take into account the design standards and climate for that states region.
- Incorporate Hazard Level into the final evaluation for further prioritizing safety level and the determination if immediate action is needed.

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Appendix A: Mathematical Notations

f(x) : Membership Function

Λ : Conjunction

∩ : Intersection

V : Disjunction

o : Composition