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FINAL REPORT

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Assessment of Downstream Hazard Potential for Dam Failure in Rhode Island

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CHAPTER 1: INTRODUCTION

Potential failure of dams poses a real threat to public safety, carries environmental risks, and has a significant economic impact on public and private property and infrastructure (roads, bridges, etc.). This threat has not gone unnoticed. The Rhode Island Department of Environmental Management (RIDEM) through the Dam Safety Program is responsible for inventory and inspection of state-owned dams across the State of Rhode Island. RIDEM descriptively classifies dams by size (small, medium or large) and hazard (high, significant or low). However, the hazard classifications were assigned nearly 25 years ago and may no longer provide an accurate assessment of the downstream hazard potential since many communities have continued to grow. As a result, a major effort has been underway to inventory all dams in the state and inspect those which pose a major threat to public safety.

Moreover, the current hazard rating scheme is solely qualitative and may not fully account for various societal categories that would be adversely affected in the event of a dam failure. These categories include the impact to first response facilities, major roadways and bridges, economic impact due to the loss of residential dwellings and local business, and demographics of affected communities.

The goal of this study is to investigate the safety of dams in terms of a hazard classification based on a quantitative measure of the extent of damage or disruption imposed on surrounding communities. The study uses a geographic information system (GIS) to represent geospatial data including the location and properties of nearly 500 dams and of their surrounding areas. A case study of a hypothetical failure of the Hughesdale Pond Upper Dam located in Johnston, Rhode Island is also presented. The Simplified Dam Break Analysis (SMPDBK) hydrology model is used to estimate the extent of the flood area. The inundated area is then combined with the GIS model and US Census Block data to evaluate the impact on the infrastructure and population of the affected communities and ultimately quantify the hazard potential of the dam.

1.1 Background

Notable dam failures have highlighted the need to reevaluate dam hazard ratings for increased safety. The recent failure of the Whittenton Pond Dam located in Taunton, Massachusetts in 2005 has reemphasized the importance of dam safety and the need for identifying risk and developing a management plan. The 173-year old dam buckled under heavy rain and forced the evacuation of 2,000 residents. It was projected that collapse of the dam could send 6 feet of water through downtown Taunton, causing major flooding and destroying homes, businesses, and schools (5). Failure would further affect the integrity of any downstream dam and could create a dangerous chain reaction.

The threat of dam collapse has also been experienced by Rhode Islanders. The 1998 failure of the low hazard California Jim's dam in South Kingstown triggered the creation of the Dam Safety and Maintenance Task Force by then-Governor Almond to review the State's Dam Safety Program (19). The Task Force primarily focused on the legislative nature of the State's dam safety law, financial impact on government and private dam owners, and the emergency plans in event of dam failure. In 2001, the Task force reported that Rhode Island's dam safety and maintenance laws were out-of-date having been first adopted in 1896 and last amended in 1956. It was also reported that average cost of dam repair could be as much as $800,000 per dam resulting in a major investment by state officials.

The dam inspection structure established by the RIDEM has historically relied on a High-Significant-Low hazard rating classification that is assigned to each dam. The hazard classifications are defined by the consequence of failure or misoperation as follows:

- **High Hazard** - probable loss of more than a few human lives or excessive economic loss.
- **Significant Hazard** - probable loss of a few human lives or appreciable economic loss.
- **Low Hazard** - no probable loss of human life and minimal economic loss.

The structure, also used by the Federal Emergency Management Agency (FEMA), however, does not necessarily associate a rating with a specific level of safety (16). New Jersey, New York, New Hampshire, and Massachusetts currently rely on similar hazard rating systems with structural integrity categorized by visual inspection (24, 27, 28).

In 2004, there were 618 inventoried dams in Rhode Island with 17 dams classified as high hazard and 41 as significant hazard. Most of the dams, however, were categorized in the late 1970's and early 1980's. In 2006, the Dam Safety Program reported a total of 674 dams with 83 dams (12%) as high hazard and 90 dams (13%) as significant hazard (11). This represents nearly a 400% and 120% increase in classification of high and significant hazards, respectively, in only two years. However, many of these classifications may no longer be valid since communities have continued to develop downstream of many dams. As a result, a major effort is underway to inventory all dams in the State and inspect those which pose a major threat to public safety.

1.2 Objectives

The objective of this study is to provide a quantitative measure of the extent of damage a disruption imposed on a surrounding community in the event of a dam failure. In addition, several viable risk assessment methods for hazard ratings of dams are investigated. Risk-based approaches to dam safety have been recognized as vital tools due to the inability of aging dams to satisfy current flood and earthquake loading criteria, increased downstream development, public's demand for greater protection from natural and man-made hazards, and the government's trend toward performance-based budget justification (9).

This overall objective will be accomplished by (1) conducting a comprehensive review of literature from the academic, government, and private sectors to identify types of uncertainty, means of assessing risk, and various analysis and management plans for dam safety; (2) identifying various risk assessment techniques and tools to be used for assessing the downstream hazard potential of dams; and (3) developing a geographic information system (GIS) based model that accounts for various dam parameters including location, geometry, and proximity to vulnerable populations and facilities of first responders, evacuation routes, and other important infrastructure. A case study will also be performed on a selected Rhode Island dam to examine the extent of the impact on nearby communities as a result of a dam break using the GIS-based model and US Census block data.

1.3 Organization of Report

This report is organized into five chapters. This chapter has introduced the current structure used for classifying the hazard potential for dams located in Rhode Island and discussed some of its shortcomings. Chapter 2 presents more detailed information on safety assessment of dams including the various components of dam design and possible failure modes. A review of various risk assessment methods as well as a general introduction of risk is presented in Chapter 3.

Chapter 4 introduces the use of GIS as a tool for developing a dynamic model for dams located in Rhode Island. This model allows for the consideration of several factors that affect the hazard level of a dam such as proximity to various community components (i.e. businesses, homes, schools, senior-citizen centers), facilities of first responders (police, fire, hospitals), and roads and bridges along major evacuation or emergency routes; design characteristics such as material type, size, and capacity; maintenance records from inspection reports; and the identification of downstream dams that may be affected by for surging demand levels in the event of a dam failure. This graphical representation of the State's dams is also suitable for simulation of various failure scenarios, both natural and man-made, and for the assessment of various management plans. This chapter also includes details of a dam break case study for a selected Rhode Island dam.

Finally, Chapter 5 presents a summary of the research work and presents conclusions and recommendations for future work.

CHAPTER 2: LITERATURE REVIEW

In recent years, the safety of dams has been a focus in the State of Rhode Island due to near failures in Rhode Island and Massachusetts. Dams are located in almost every community throughout the State and range in material type (i.e. earthen, concrete, masonry or stone), purpose (i.e. recreation, flood control and municipal or industrial water supply) and age with the Hope Valley Mill Pond Dam constructed in 1750 being the oldest in RI (Hopkington, RI) (29). Rhode Island dams also exhibit quite a large range of values of length, height, discharge, and maximum storage as shown in Table 2.1.

Table 2. 1 Range of characteristics of inventoried dams located in Rhode Island (29)

Characteristic	Name of Dam	Location	Value
Length, feet	Bouchar Farm Pond Dam Easton Pond South Dam	West Warwick Near Newport	7 9708
Height, feet	Brown Sawmill Pond Dam Gainer Memorial Dam	Johnston Scituate	3 109
Maximum Discharge, ft^3/sec	Camp Aldersgate Pond Dam Albion Dam	Glocester Cumberland/Lincoln	6 138,000
Maximum Storage, acre-foot	Knibb Farm Pond Dam Gainer Memorial Dam	Burrillville Scituate	1 164,850

2.1 Hazard Classification of the Rhode Island Department of Environmental Management

The State of Rhode Island began inspecting dams in 1883 as a duty of the Commissioner of Dams and Reservoirs. Today, the Rhode Island Dam Safety Program (RI DSP) implemented by the RIDEM, inspects and catalogs all dams within the State and publishes an annual inspection report. In RI, dams are inspected based on their hazard classification with higher hazard dams inspected more frequently. Any dam can also be inspected at the request of an abutter or a municipality.

The RI DSP performs inspections based on the guidelines developed by the United States Army Corp of Engineers (USACE) in 1976 for the National Program for Inspection of (Non-Federal) Dams (11). All inventoried dams are classified based on size, categorized as small-medium-large, and hazard potential, categorized as low-significant-high hazard. RIDEM has also determined major components of a dam that are to be annually inspected. These components include the spillway, embankment, and low-level outlet. Each component is visually inspected using the following qualitative condition rating:

Good – properly maintained, no irregularities, and meets minimum guidelines
Fair – requires maintenance
Poor – has deteriorated and no longer functions properly, needs replacement

In general, condition rating of such dam components does not directly affect the overall hazard classification of a dam but provides an indication of the overall structural integrity of the dam. Based on the findings of an inspection, an overall hazard rating is assigned as high, significant, or low. For example, a high hazard rating may be assigned to a dam that could result in probable loss of more than a few lives or excessive economic loss in the event of failure or misoperation. On the other hand, if the dam is located in a rural area with few residents, life loss is uncertain and a significant hazard rating is assigned. If no loss of life is expected and minimal damage or interruption is anticipated, the dam is assigned a low hazard rating. This rating is then reported to the owner with recommendations for improving the condition of deficient dam components.

Since there has been continual population growth and economic development in areas located downstream of many dams, these classifications, determined during the 1970s and 1980s, have become outdated. In addition, the classification structure does not consider various site parameters within the region of a dam in the event of a failure. These include the proximity of a dam to community components such as homes, business, schools, senior-citizens, facilities of first responders (i.e. police, fire, hospitals) and major roadways and bridges particularly along an evacuation route.

2.2 Hazard Classification of the United States Army Corp of Engineers

The United States Army Corp of Engineers (USACE) uses a dam hazard potential structure developed in the early 1970s largely based on ratings for life, lifeline, property and environmental losses (39). Table 2.2 presents the four major components of the potential hazard classification system used by USACE. Generally, if a dam is located in a heavy residential or commercial area and at least one fatality is expected as a result of a dam breach, a high hazard classification is assigned. If loss of life in the downstream area is uncertain or is not expected, a significant hazard and a low hazard rating is assigned, respectively.

Property losses are evaluated based on direct and indirect losses experienced by the downstream population. Direct losses include property damaged by the flood wave whereas indirect losses include loss of services provided by the damaged dam or other damaged downstream infrastructure such as loss of power or water. Loss of lifelines include inaccessible bridges or roads and disruption of major medical facilities. If disruption of or loss of access to essential or critical facilities is expected, a significant or high hazard rating is assigned. Otherwise, if such facilities experience cosmetic damage that is rapidly repairable, a low hazard rating is assigned instead. Environmental losses resulting from a dam failure are also considered. If major or extensive mitigation costs are incurred, the dam is classified as significant hazard and high hazard, respectively.

Table 2. 2 United States Army Corp of Engineers (USACE) Hazard Classification System (adapted from 39)

Category	Low	Significant	High
Direct loss of life	None expected (due to rural location with no permanent structures for human habitation)	Uncertain (rural location with few residences and only transient or industrial development)	Certain (one or more extensive residential, commercial, or industrial development)
Lifeline losses	No disruption of services; repairs are cosmetic or rapidly repairable damage	Disruption of or loss of access to essential facilities	Disruption of or loss of access to essential facilities
Property losses	Private agricultural lands, equipment and isolated buildings	Major public and private facilities	Extensive public and private facilities
Environmental losses	Minimal incremental damage	Major mitigation required	Extensive mitigation cost or impossible to mitigate

2.3 Hazard Classification of the Federal Emergency Management Agency

The Federal Emergency Management Agency (FEMA) has defined a hazard potential structure as "a system that categorizes dams according to the degree of adverse incremental consequences" (16). Incremental consequences include downstream impacts greater than what would be experienced from a normal flooding condition. The hazard classification system adopted by FEMA also uses a High-Significant-Low level rating scheme to represent adverse incremental consequences of a dam failure as shown in Table 2.3.

This classification structure accounts for an increased hazard potential for dam failures that may cause loss of life regardless of other losses (i.e. economic, environmental or lifeline losses). As a result, if the loss of one or more lives is expected, a high hazard rating is assigned and a more conservative design of the dam would be necessary. If other losses are expected, a significant hazard rating is assigned. Otherwise, the dam is classified as a low hazard.

This classification system was created to be used for the failure or misoperation of a dam for both normal and flood flows. A dam is rated assuming a worst case failure mode scenario. However, for high hazard dams, other failure modes may be considered to determine the possibility of higher incremental consequences. In any case, failure modes should be realistic and should conform to FEMA guidelines including the *Earthquake Analyses and Design of*

Dams (FEMA 65) and *Selecting and Accommodating Inflow Design Floods for Dams* (FEMA 94).

Table 2. 3 Federal Emergency Management Agency (FEMA) Hazard Classification System (adapted from 16)

Hazard Potential Classification	Low	Significant	High
Loss of Human Life	None expected	None expected	Probable, One or more expected
Economic, Environmental, Lifeline losses	Low, generally limited to the owner	Yes	Yes, but not necessary for this classification

2.4 General Dam Design

The major types of dam construction utilize earth, concrete, and masonry materials. A typical cross-section of an earthen dam is shown in Figure 2.1. The design of dams requires the investigation of many factors including material used for construction, foundation characteristics of the existing site, climate, shape and size of the existing valley, river characteristics, wave action, timeline for dam construction, function of the reservoir, and presence of seismic activity (34). In addition, consideration is given to the availability of dam construction materials near the proposed site. Table 2.4 presents the different onsite soil types that may be used for different zones of the dam.

The effect of ground water level and the line of saturation (i.e. the level of material considered to be saturated in an earthen dam) and proper placement of the core-wall are also important factors that should be considered (23). The line of saturation represents the highest point water will reach when traveling through the dam. The location of the line of saturation greatly influences the design and selection of materials used for an earthen dam. A safe design would maintain the line of saturation well below the downstream face of the dam. If fine materials are used for construction, such as fine sands or loams, boils can form and piping will develop if the line of saturation is too close to the surface of the dam. The position of the line of saturation is affected by several factors including upstream and downstream soil properties, soil porosity and grain size distribution, depth of foundation soils, flow characteristics, depth of the ground water table, and the use of core walls and drains to prevent seepage. The slope of the line of saturation is also affected by material type with a gradual slope in the case of impervious materials and a steeper slop for pervious materials.

A core wall, often constructed of concrete, steel or masonry, can be used to control the line of saturation by preventing water flow through a dam. The core wall, frequently placed upstream from the centerline of the dam cross-section, must penetrate foundation soils far enough to cause a significant drop in the line of saturation which results in greater overall stability. Increased stability can also be attained by offsetting the core wall which reduces the amount of the cross-section that is saturated. Additionally, extending the core wall above the surface of the dam can be used as a wave protection measure for the upstream face.

Table 2. 4 Soil types used for dam design (adapted from 34)

Onsite Material Type	Dam Type/Components
Impervious	Homogeneous small amount of pervious material are used for internal seepage control
Pervious	Non-homogeneous impervious core or membrane are added
Various types	Zoned dam finer material placed as core, more coarse material placed downstream to aid drainage
Erratic soil conditions	Random zone dam is constructed using any material placed in any location (may result in larger embankments)

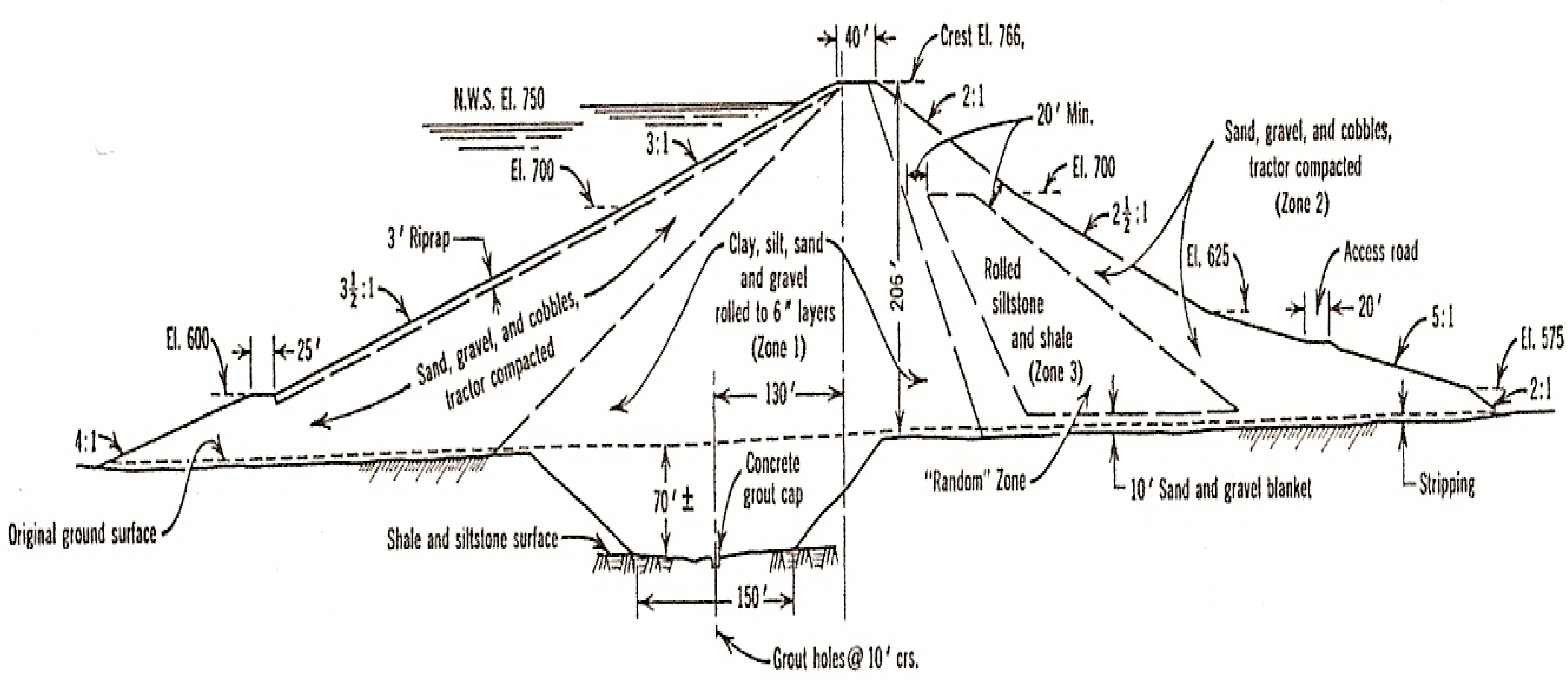

Figure 2. 1 Typical cross-section of an earthen dam (34)

A number of other considerations include wave action, construction details (i.e. joints, water stops, drains, stop logs, flashboards, and gates) and material variability. For example, a pocket of weaker material introduced in an earthen dam originally designed to be impervious would represent a conduit through the embankment and would change the intended design characteristics of the dam. Other soil-type concerns that should be considered are low shear strength for foundation soils, settlement and differential cracking, and the presence of loose sands which may lead to liquefaction. The goal of a well designed and constructed dam should be to minimize uncertainty with complete consideration of all factors. Every site is unique and requires a thorough site investigation. The risk of an unsuccessful design is a function of the structure itself and the site location (2).

Generally, wave action can result in direct and indirect damage through erosion of the upstream face of a dam or through the impact of debris that is carried by large waves. Wave action is affected by surface size of impounded water and wind velocities and can be significant for larger dams (i.e. square miles). Most commonly, rip-rap is incorporated into a design as the most cost effective solution for wave action protection.

2.5 Type and Consequence of Failure

Natural events that can cause a dam failure are referred to as external initiating events and include floods, earthquakes, and failure under normal operating conditions. Once an external initiating event occurs, a number of circumstances related to the malfunction of a dam can follow. These internal responses can include loss of external or internal stability, malfunction of electrical or mechanical systems, or loss of capacity. Table 2.5 presents some possible internal responses for three external initiating events. For example, as a result of a flood, a dam can suffer damage through wave action, erosion or exceedance of wall/gate capacity.

Table 2. 5 Internal Responses for Possible External Initiating Events

External Initiating Events		
Flood	**Earthquake**	**Normal Operating**
External/Internal Stability	External/Internal Stability	Foundation sliding/piping
Flood capacity	Loss of capacity	Dam stresses
Wall/gate capacity	Appurtenances	Reservoir rim stability
Erosion	Spillway design	Appurtenances
Outlets	Gate/pier capacity	Outlets/ gates piping
Electrical/Mechanical systems	Outlets	Slope stability
Obstructions	Liquefaction	Deterioration of Materials
Piping	Deformation	
Wave action	Fault movement	
Leakage		

The major types of a structural dam failure are due to foundation defects (36%) and overtopping by flood (33%) as outlined in Table 2.6. Other causes of failure include sinkholes, transverse or longitudinal cracking, erosion, vegetation, settlement, crest defects, poor drainage, seepage, spillway problems, outlet pipe defects, leaking valves, or failure of an outfall structure as shown in Figure 2.2.

Table 2. 6 Major Causes of a Dam Failure

Initiating Event	Frequency of Occurrence (%)
Foundation Failure	36
Overtopping	33
Cracking	7
Slides (along banks or dam slopes)	5
Incorrect Calculations	1
Unknown Reasons	18

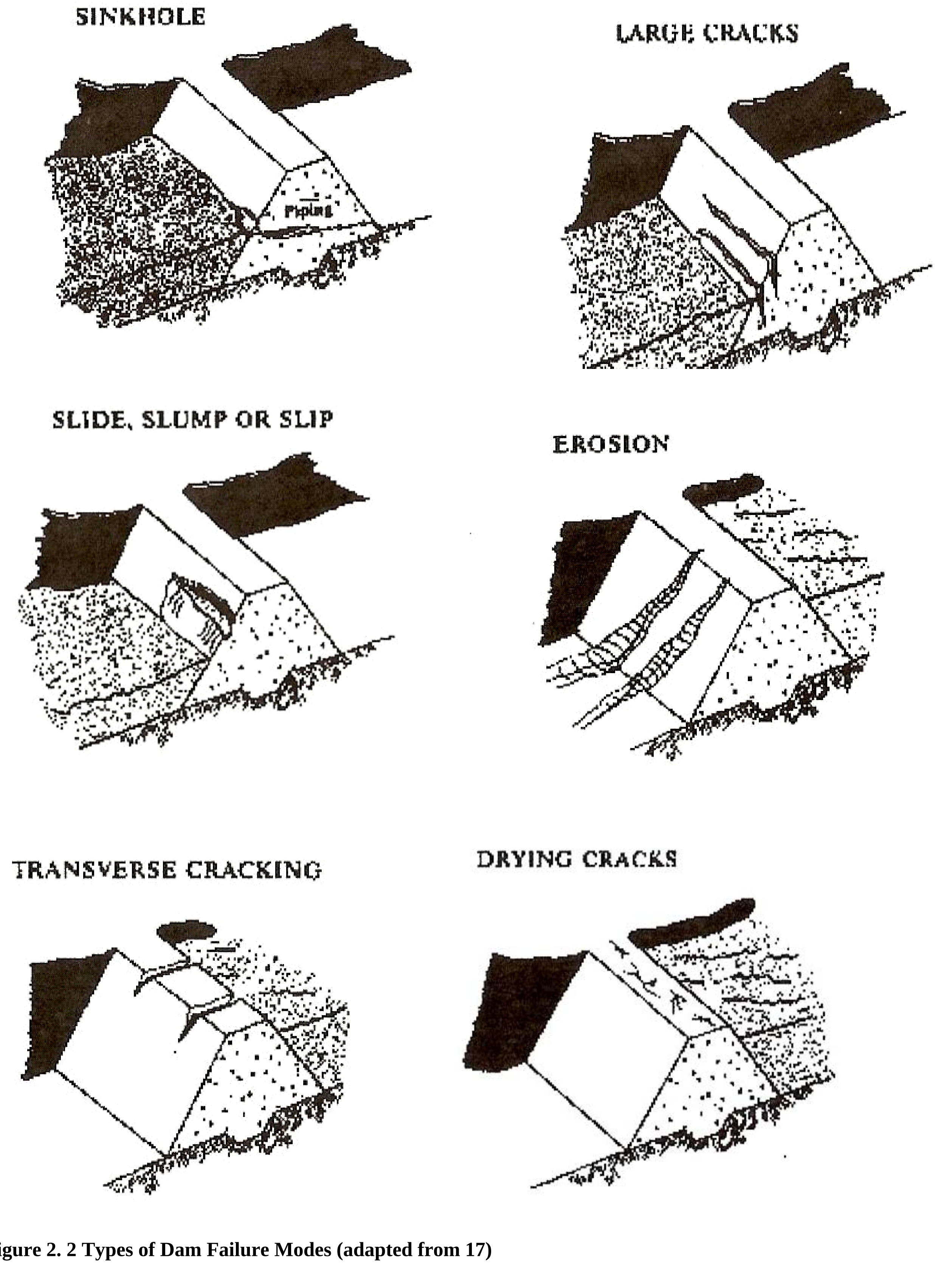

Figure 2. 2 Types of Dam Failure Modes (adapted from 17)

As of 2006, there were a total of 674 inventoried dams in Rhode Island; 83 high hazard, 90 significant hazard, and 456 low hazard dams. However, since 1889, there have been only seven notable dam failures in the State of Rhode Island as listed in Table 2.7. Although this number may seem relatively low, an aging infrastructure is likely to increase the probability of failure. In addition, expanding community development near the location of a dam increases the severity of the consequences incurred as a result of a dam break.

Table 2. 7 Summary of Rhode Island Dam Failures (26)

Dam ID	Dam Name	Incident Date	Incident Type
RI00306	Spring Lake Dam	1889	Piping
RIS00004	Randall's Pond Lower	1901	Inflow flood, Hydrologic event
RI04258	Burton Pond Dam	1991	Concrete Deterioration
RI00003	Unnamed Dam	1991	Not Known
RI03201	Peace Dale Pond Dam	1998	Inflow flood, Hydrologic event
RI04389	Mill Pond	2000	Embankment Erosion
RIS00006	Sweet's Mill	2002	Biological Attack, Embankment Erosion

Consequences of failure are determined based on a physical reality and usually represent a loss or a negative impact from a particular hazard. Consequences of a structural failure and the post condition of the dam are assessed by evaluating the downstream affects to a community. These consequences will depend on the population densities as well as site conditions surrounding the failure. Table 2.8 lists a number of variables that are often considered for different failure scenarios. These include the time of day, weather conditions, and the presence of a warning system.

There are several possible consequences of a dam failure including loss of life, displaced persons, and economic, social, and environmental effects as outlined in Table 2.9. Consequences may also include political and legal issues which are generally more qualitative and subjective and are independent of a hazard potential classification (16).

Once the consequences have been identified, a "damage value" for each consequence can be determined (32). The value of an outcome can simply be defined by using a binary system or through consideration of more complicated but relevant parameters such as loss of life, economic loss, or environmental damage. Evaluation of consequences can also be interpreted in terms of an incremental effect which implies consequences above those that would occur if a failure or misoperation did not occur.

The USACE evaluates economic consequences based on an exceedance level of a probability density function to obtain an expected annual damage estimate. The USACE established a *Consequence Team* in the aftermath of Katrina to estimate life loss and property damage resulting from maximum inundation depth of flood waters. Life loss estimates were developed using probability distributions and property damage was determined to be a best estimate with a 90% confidence interval (38).

Table 2. 8 Various scenarios of downstream dam failure affecting consequences (adapted from 12)

Failure Scenario	Number of Selections	Selections
Type of failure	3	a) Sunny day b) Rainy day c) Earthquake
Warning time prior to breach	Range	Varies
Time from onset of failure to peak breach discharge	Range	Varies
Number of dams	≥ 2	a) Subject dam only b) Dam(s) in cascade upstream of subject dam
Antecedent flow downstream	2	a) Sunny day on adjacent catchments b) Extreme rainfall on adjacent catchments as well as subject catchment
Time of day	3	a) At night, most people are asleep at home b) During daytime, most people are at work c) Evenings and weekends, most people are shopping or a recreational sites
Nature of population	Range of young to old, fit to unfit, etc.	Varies

Table 2. 9 Possible consequences for various failure modes (adapted from 17)

Failure Mode	Possible Consequence
Sinkhole	Piping can empty reservoir through a small hole in the wall or can lead to failure of a dam as soil pipes erode through the foundation
Large Cracks	Indicates upset of massive slide or settlement caused by foundation failure
Slide, Slump, or Slip	A series of slides can lead to obstruction of the outlet or failure of the dam
Transverse Cracking	Settlement or shrinkage cracks can lead to seepage of reservoir water through the dam. Shrinkage cracks allow water to enter the embankment. This promotes saturation and increases freeze thaw action
Erosion	Can be hazardous if allowed to continue. Erosion can lead to eventual deterioration of downstream slope and failure of the structure.
Drying Cracks	Heavy rains fill cracks and cause small parts of the embankment to move internally

CHAPTER 3: RISK ASSESSMENT METHODS

There are a number of different definitions of risk depending on the context but in general risk often refers to the hazard associated with the outcome of uncertain events and would include consideration of the probability of an event occurrence, the expected outcomes or consequences and the context of the situation. Early applications of studying risk are derived from reliability theory and can be attributed to the insurance industry which often estimates risk in terms human survival probabilities. Today, Risk assessment techniques have been employed in a variety of industries including aerospace, electronic, nuclear, chemical, and structural engineering.

Albeit simple, risk can be controlled in one of two ways, namely by consistently over-designing a system or by carefully assessing the risk levels. The former requires a significant allocation of resources in terms of material and money while maintaining the same effort in design while the latter requires more effort during design but may lead to reduced costs. The latter approach has been formalized as the study of risk and has led to several methods for assessing and managing risk.

3.1 Risk

Generally, risk of an unfavorable event (i.e. damage or collapse) can be defined as the systematic process of identifying and quantifying possible outcomes and their associated probabilities. Oftentimes, risk is expressed as:

$$\begin{aligned}\text{Risk} &= \text{Probability of Occurrence} \times \text{Consequence} \\ &= \int_{0}^{\infty}\int_{-\infty}^{\infty} x(t)P\big(x(t)\big)\,dx\,dt\end{aligned} \tag{3.1}$$

where X is a random variable representing possible events that describe the adverse consequence and $P(x)$ is the probability density function of such consequences. Many consequences and their associated probabilities are time-dependent and therefore, risk must be evaluated based on current conditions.

3.1.1 Probability of Occurrence

Probability can be generally categorized into three groups, namely structural, frequentist, and subjective. Structural probability relates to the structure or physical characteristics of a system and represents an occurrence of unwanted structural behavior whereas frequentist probability represents probability in terms of relative frequency of a large sample. Probability can also be represented as subjective or objective. Subjective probability is based on a personal interpretation of the likelihood of events with minimal direct evidence of event outcomes. Use of subjective probability is common among planners and is also used to describe information from an "expert witness." Objective probability, on the other hand, is based on observed events or events with a certain frequency. This type of probability can also be examined in terms of *a priori* and *a posteriori* observations. An *a priori* observation represents a decision before the facts are known with deductive reasoning (i.e. a coin toss) while *a posteriori* observation represents after the fact estimation of probability. Historical stream flow gage data is an example of an *a posteriori* objective probability but is only reliable with a large amount of data samples (20).

The probability of failure (P_f) is often defined as one minus the reliability (R) as given by Equation 3.2. Reliability represents the probability of safety or proper performance of a system over a given period of time.

$$P_f = 1 - R \tag{3.2}$$

Recently, a probability of unsatisfactory performance (P_r) has replaced the terminology for the probability of failure, particularly for maintenance projects of existing dams in order to better distinguish between the severity of events (37).

3.1.2 Consequence

The consequence of an event is often measured based on a value system. The value of an outcome can be simply defined by using a binary system or through consideration of more complicated but relevant parameters such as loss of life, economic loss, or environmental damage. Estimate of consequence probabilities can often be subjective in nature and depends on expert judgment. When life loss is considered, a monetary value assignment to consequence can be extremely difficult to quantify and raises many ethical questions.

3.1.3 Context

Risk assessment should always account for the context or point of view of the entities involved. Entities which affect a risk assessment include all parties involved on a state, local, and federal level and any political, social, legal or financial influences which would affect the assessment. The goals and objectives of the organization performing the risk assessment will also affect a risk assessment outcome. A clear sense of why the risk assessment is being performed must be known. The system under consideration should be well defined and all factors not considered as part of the analysis should be fully understood (35).

3.2 Types of Risk

There are a number of different types of risk, namely perceived, calculated, and "real" risk. Perceived risk is the risk that a person or a group of persons thinks is the case. Perceived risk may or may not correlate with "real" risk but nonetheless must be considered in any risk assessment study.

Table 3.1 lists a number of factors that influence the level of perceived risk including the degree to which risk is voluntary, familiarity with the situation, number of people involved, nature of communication, duration of exposure, and the immediacy of the consequences. Oftentimes, people will assume a higher level of risk for events they have voluntarily participated rather than for situations that happen *to them*. This is because a person often feels a certain level of control and reliance in one's own skill level during events for which they willingly become involved.

Familiarity with a situation often tends to relieve some otherwise perceived risk associated with new and unfamiliar practices. A person becomes more comfortable in situations with which positive past experiences have been gained and, as a result, perceives less risk. The number of people that may potentially be affected is also a key factor. The public often perceives more risk associated with disasters that claim the life of a large group of people as compared with the same number of deaths occurring individually as a result of smaller incidences. This may be contributed in part to media coverage of large tragic events which tends to sensationalize such disasters. Hence, communication of risk also affects the perception of risk.

Finally, the influence of time to the severity of perceived risk is an important factor. Long-term exposure to hazardous situations is often perceived as more serious as short-term exposure to the same hazard. In addition, when consequences of an event are immediately experienced, the level of risk is perceived to be greater than if one is subjected to the same consequences in the future. Smoking is a good example of this. A number of scientific studies have highlighted the dangers of smoking yet smokers accept the associated risks since the consequences are not immediate and the "benefits" or pleasures are seen to outweigh the risks.

Calculated risk, on the other hand, is the risk level that is obtained from a quantitative risk assessment process. This often does not correlate with perceived risk but is rather based on mathematical models derived from available data, approximations, and various assumptions. As a result, each numerical model has some inherent level of uncertainty and will seldom account for all possible aspects of a system. Oftentimes, numerical models will underestimate the level of "real" risk since the model can not account for all contributors to failure such as human error. Nonetheless, if risk must be assessed, numerical models provide the analyst the tools to do just that with the acknowledgment that no model is truly a perfect reflection of reality.

The concept of "real" risk is often disputed but it is often described as the calculated risk if all relevant information about the primary components of risk is known (i.e. probability of failure, consequence, and context). In this case, the perceived, calculated, and real risk would all be one in the same.

Table 3. 1 Characteristics of Risk (adapted from 4)

Hazard:

- natural or man-made
- avoidable or unavoidable
- controllable or uncontrollable
- local or global
- continuous or periodic
- familiar or unfamiliar
- old or new
- known or unknown
- certain or uncertain
- predictable or unpredictable
- changing or unchanging
- stable or unstable

Exposure Characteristics:

- voluntary or involuntary
- compensated or uncompensated
- occupational or non-occupational
- continuous, periodic, or discrete
- controllable or uncontrollable
- equitable or inequitable

Characteristics of Possible Outcomes:

- likely or unlikely
- minor, major, disastrous, or catastrophic
- personal, group, communal, or societal
- national, international, or global
- known or unknown
- normal or dreadful
- familiar or unfamiliar
- permanent or temporary
- controllable or uncontrollable
- reversible or irreversible
- immediate, cumulative, or delayed
- equitable or inequitable

Characteristics of Associated Benefits:

- known or unknown
- certain or uncertain
- essential or non-essential
- equitable or inequitable

3.3 Acceptable Risk

Risk is generally categorized as acceptable, tolerable, or unacceptable as shown in Figure 3.1. Acceptable or a *de minimus* risk is an upper threshold that society is willing to live with in their daily lives. Acceptable risk is generally established by a government agency that judges various risks and develops regulations to prevent extreme risk. Examples of events that have an acceptable level of risk include natural disasters and lightening strikes (35). Acceptable risk is generally associated with an annual fatality of less than 10^{-6}.

Tolerable risk is non-negligible risk that is considered to be a potential hazard but for which the benefits of an occurrence out-weighs the risks. Events of tolerable risk are those that provide some benefit to society, have a noticeable chance of occurring, but for which the risk could be reduced through monitoring and continued improvements to the technology. An automobile accident is one example of an event for which risk is often tolerated. Although driving a vehicle provides many benefits, the likelihood of an automobile accident is not negligible but with more safety studies of driving conditions and improved design of vehicles, the consequence of accidents can be reduced. Unacceptable risk, on the other hand, is often associated with events that can cause harm with a high likelihood of occurrence.

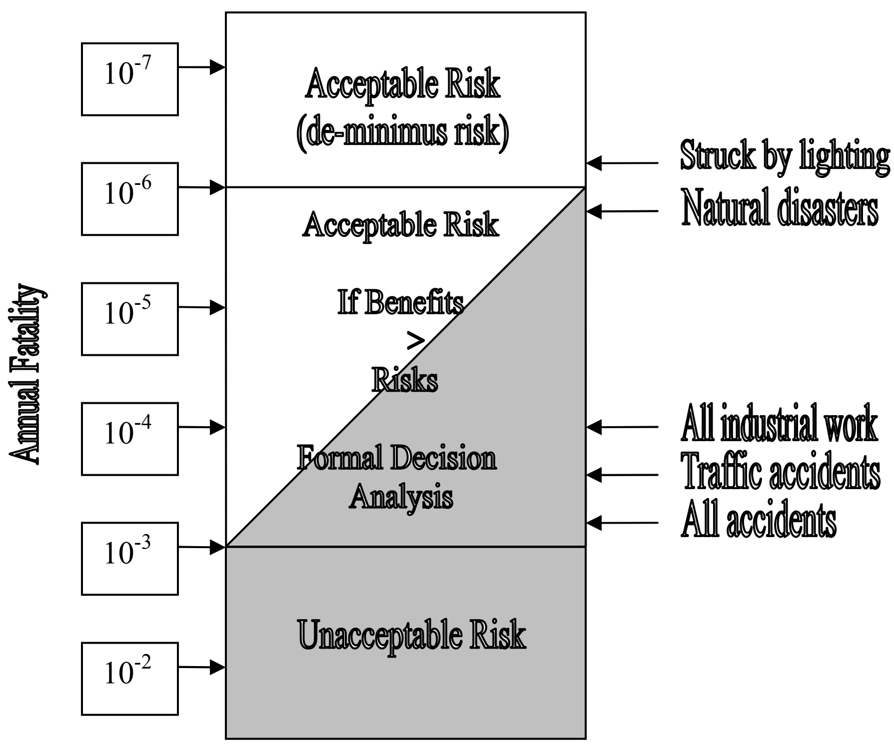

Figure 3. 1 Risk acceptance criteria (adapted from 35)

Tolerable risk levels can be determined by using the As Low as Reasonably Practical (ALARP) principle. The ALARP principle or the As Low as Reasonably Attainable (ALARA) principle as it is sometimes called, establishes a subjective level of risk that is as low as possible based on consideration of the impact to society and economic impacts of further risk reduction. A point of diminishing returns is eventually reached when additional expenditures result in increasingly smaller risk reductions (6). Figure 3.2 depicts the region of ALARP risk in comparison to unacceptable and acceptable risks. During a risk investigation, tolerable risk can be evaluated and compared to ALARP risk levels to determine if the principle has been satisfied. The ALARP principal can also be used to evaluate all structural and non-structural risk reduction methods (7).

Most safety decisions will involve several system components that need to be analyzed. Each component should be evaluated separately to determine if the ALARP risk level has been achieved. In addition, the risk status of various system components should be continually updated as additional information is obtained and future assessments are performed (6). For example, most regulating agencies use data based on past experiences to form expectations of reasonable risk levels. These acceptable risk levels need to be revised periodically to reflect unexpected events and new technologies and information (35).

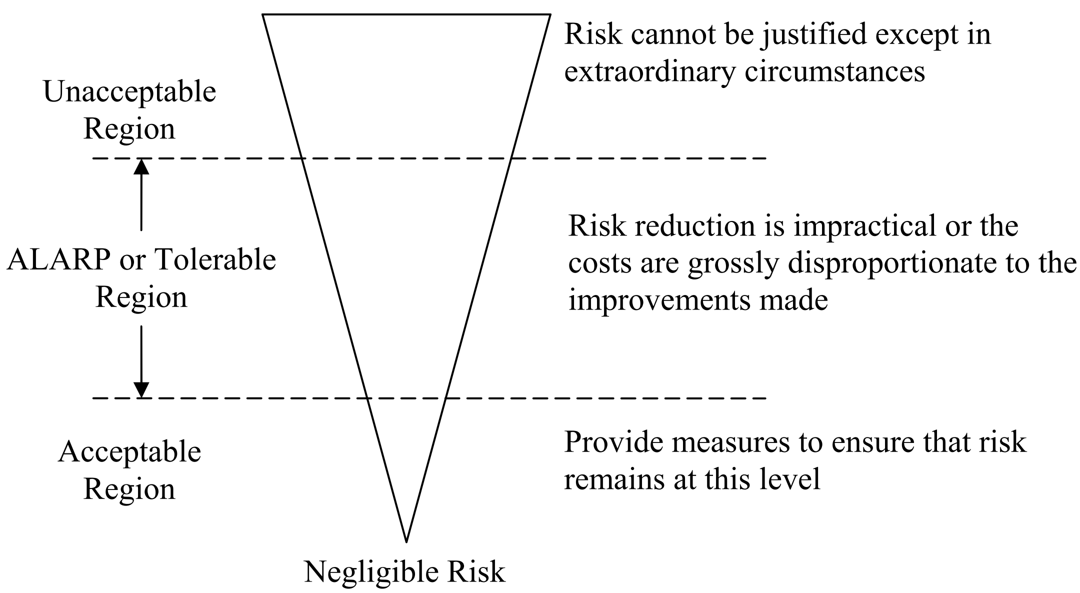

Figure 3. 2 As Low as Reasonably Practical (ALARP) Risk Principal (35)

3.4 Elements of Risk Assessment

Depending on the source, there may be several representations of the risk assessment process. Generally, however, a risk assessment process includes a clearly defined context, risk criteria, hazard identification, risk analysis, sensitivity analysis, treatment of risk, and monitoring of future risk (35). The context of an assessment represents the individuals involved with the risk assessment and the reason for the assessment. Social, cultural, legal, financial, and other factors must be clearly understood by all parties involved.

Hazard identification is the process by which all possible failure modes of a system are identified. This process involves several steps beginning with dividing the overall system into several smaller sub-systems. For each sub-system, different hazard scenarios are determined using brainstorming sessions, databases, and checklists (35). Each hazard is then analyzed to determine the likelihood of each scenario as well as the severity of its affects.

Several approaches may be employed for analyzing the risk associated with each hazard scenario including qualitative ranking procedures as well as quantitative methods. Minor risks are often eliminated from the analysis with preliminary risk analysis methods such as Preliminary Hazards Analysis (PHA). PHA is used to identify only the basic elements that can lead to a potential accident and, although it is often used in preliminary stages of a risk investigation, it can also be used to evaluate new hazards that may occur after completion of a design. Other, more risky scenarios are then analyzed in detail, the extent of which is determined by the required results. For a quantitative analysis, probabilities of occurrence are estimated based on combined data and model assumptions while consequences are often largely based on expert judgment.

For complex systems, a sensitivity analysis is often useful for identifying influential parameters and for estimating the extent of influence. Model variables are varied within some appropriate, pre-specified range for each scenario and the risk level is re-assessed. Large variation of model output signals to a more significant factor. However, whether or not a sensitivity analysis is performed, the risk level from each hazard scenario should be compared to established risk criteria including acceptable and unacceptable levels of risk. If the risk is determined to be greater than those within an acceptable range, several methods may be undertaken to mitigate the excess risk. These include avoidance, reduction, transference, and acceptance.

Risk avoidance abandons an entire system or sub-system. Risk reduction involves reducing the probability of occurrence or changing the consequences of an event by using an early warning system. A reduced probability of occurrence can be achieved through increased condition monitoring, implementation of operation guidelines, and enforcement of routine inspections. Risk transfer refers to shifting some of the risk to a third party and lowering the risk levels experience by the main system (i.e. through contract documents or by sale agreements). Finally, risk acceptance permits excess risk either for a short period of time or on a more permanent basis (i.e. insurance) (7).

Finally, once risk levels have been determined for each hazard scenario that is identified, a monitoring process must be established. Risk is time-dependent and, as a result, the level of risk (and the level of safety) will change over time due to variations in site conditions, seasonal characteristics, and structural capacity. A dynamic process is therefore required to create a "living document" that is capable of reflecting the presence of new information as well as to changing conditions (35).

3.5 Risk Assessment Methods

There are several methods available to analyze risk depending on the desired output. Some of the more common methods are summarized in Table 3.2. In general, risk assessment methods may be considered to be qualitative or quantitative, although some methods such as Fault Tree Analysis (FTA) provide enough flexibility to be used for either approach.

A qualitative method is an approach which relies mostly on tables and descriptors including expert knowledge to assess the risks of a system. Qualitative methods provide a general sense of the major risks which, once ranked in likelihood of occurrence or severity of consequences, can then be more closely analyzed using quantitative methods and compared with acceptable risk criteria. Oftentimes, however, risks identified using qualitative methods can only be relatively compared to one another. As a result, qualitative methods do not provide an absolute value for the risks considered and lack the capacity to compare risk levels between different sources (35).

A quantitative approach, on the other hand, relies on point estimates to assess system risk and performance (10). For event tree or fault tree analysis, for example, probabilities of occurrence are estimated based on the available information and assigned to each branch to reflect the best estimate of the likelihood of an occurrence to a particular outcome.

Several industries including the US Department of Defense have moved toward a more risk-based analysis for assessment needs. RAM-D was developed as a methodology to assess dam security and defined risk in terms of system effectiveness (25). RAM-D is similar to the Portfolio Risk Assessment (PRA) method which uses screening to eliminate unrealistic threats, fault trees for risk analysis, and updating to create a live document. The PRA method uses a decision-based framework, engineering assessment, risk assessment, and prioritization to determine an outcome for a risk investigation of a group or portfolio of dams.

Table 3. 2 Summary of risk assessment methods

	Method	Abbreviation	Primary Decision Tool?	Source	Qua[L]itative or Qua[N]titative
1	Preliminary Hazards Analysis	PHA	No	[35]	L
2	Failure Mode and Effects Analysis	FMEA	No	[35]	L
3	Hazard and Operability Studies	HAZOP	No	[35]	L
4	Failure Mode Identification	FMI	No	[10]	L
5	Management Oversight Risk Trees	MORT	Yes	[1]	L
6	Safety Management Organization Review Technique	SMORT	Yes	[1]	L
7	Failure Mode and Effect and Criticality Analysis	FMECA	Yes	[35]	N
8	Probable Failure Mode Analysis	PFMA	Yes	[14]	N
9	Cause Consequence Analysis	CCA	Yes	[1]	N
10	Fault Tree Analysis	FTA	Yes	[13]	N

3.5.1 Preliminary Hazards Analysis

Preliminary Hazards Analysis (PHA) is mostly used in the preliminary stages of a risk investigation to identify and formulate appropriate measures of dealing with various hazards. A PHA can provide several benefits including a safely operated system, cost saving measures since modifications of a system are less expensive and easier to implement at earlier stages of design, and a decreased design time by reducing the number of unknowns.

A PHA examines critical events and their effects on individuals within a system. The analysis is best represented in table form with input information often gathered from past experience and expert knowledge. These tables (or checklists) allow the analyst to identify the most potentially hazardous events and implement appropriate remedial measures (13). A PHA often involves the following steps (1) identify known hazards, (2) determine the cause(s) of hazards, (3) determine the effects of hazards, (4) determine the probability that an accident will be caused by a hazard, and (5) establish initial design and procedural requirements to eliminate or control hazards.

Hazard severity classifications are often classified by the following descriptors

- Catastrophic – causes multiple injuries, fatalities, or loss of a facility
- Critical – may cause severe injury, severe occupational illness, or major property damage
- Marginal – may cause minor injury, minor occupational illness, or minor property damage
- Negligible – probably would not affect the safety or health of personnel but is still in violation of a safety or health standard

Estimates of probabilities of occurrence are often categorized by the following descriptors based on expert knowledge and past experience:

- Probable – likely to occur immediately or within a short period of time
- Reasonably Probable – probably will occur in time
- Remote – possible to occur in time
- Extremely Remote – Unlikely to occur

An example of a PHA for a corrosion hazard of a pressure tank is shown in Table 3.3.

Table 3. 3 Example of a Preliminary Hazards Analysis (adapted from 35)

Hazard	Cause	Effect	Probability of Accident due to Hazard	Corrective or Preventative Measures
Corrosion Rust forms inside a pressure tank	Contents of a steel tank are contaminated with water vapor	Personnel injury and damage to surrounding structures if the operating pressure is not reduced	Pressure tank rupture	Use a stainless steel pressure tank and locate the tank at a suitable distance from equipment

3.5.2 Failure Modes and Effects Analysis

Failure Modes and Effects Analysis (FMEA) has been used in the aerospace, nuclear, electrical, and manufacturing industries as a systematic approach of identifying failure modes. A FMEA is an inductive process that starts with the outcome of a particular event and regresses to possible causes (35). A table listing the function of various system components, failure modes, outcome of component failure, failure detection methods, and action to be taken is used to summarize results of a FMEA. An example of a FMEA for a nonfunctioning valve of a valve-regulated feed water flow to a steam generator is presented in Table 3.4.

A probability of occurrence for each failure mode and effect can also be shown in a FMEA table. This would allow for total system representation of probabilities of failure with summation of the probabilities of critical effects (13). Some shortcomings of the FMEA approach include the inability to detect combinations of failure events that may lead to complete system failure as well as the amount of time required to consider all possible failure modes. On the other hand, a FMEA offers the most specificity compared to other qualitative hazard evaluation methods (21).

Table 3. 4 Example of a Failure Mode and Effects Analysis (adapted from 35)

System Component	Component Function	Failure Mode	Possible Causes of Failure	Effects on the System	Detection Method	Action
Valve 031VD	<u>Function</u> Regulates feed water flow to the stream generator (SG1) produced by motor-driven pump MDP 021P <u>State</u> Normally open	Valve stuck wide open	Internal mechanical defect Defect of control air system Loss of control air to motor Loss of control power	The flow rate supplied by SG1 by MDP 021P cannot be controlled from the control room In case water or steam pipe break or SG tube break, SG1 cannot be isolated from control room	Limit switch is on SG1 supply flow rate Exceptionally high flow rate alarm sounds Possibly high flow rate alarm threshold is reached	Position the valve locally Stop operation of MDP 021P Close valve 031VD locally

3.5.3 Hazard and Operability Studies

The Hazard and Operability Studies (HAZOP) method primarily examines a design for potential hazards and their effect on the overall system. This qualitative method also uses a table format to present various hazards by identifying different components, change in system behavior, cause and effect of change, and possible corrective measures.

The HAZOP method also makes use of guide words or action words to describe a change in the behavior of a component from normal operating conditions. Example of guide words include "more of", "part of", "other than", "no or not", and "reverse". An example of the use of some guide words in a HAZOP analysis for a pipe in a chemical plant is provided in Table 3.5.

3.5.4 Failure Mode Identification

Failure Mode Identification (FMI) method is used to identify the sequence of events leading to a particular failure mode. FMI is similar to a PHA in that it is primarily used as a preliminary analysis tool but differs in the format of the analysis; FMI uses an event tree whereas PHA uses a table. In addition, FMI is often used in combination with a standards-based approach for risk assessment.

Table 3. 5 Example of Hazard and Operability Studies Worksheet for a pipe failure in a chemical plant (adapted from 35)

Possible Causes	Consequences	Actions Required
NONE		
(1) No hydrocarbon available at intermediate storage	Loss of feed to reaction section and reduced output. Polymer formed in heat exchanger under not flow conditions	(a) Ensure good communications with intermediate storage operator (b) Install low level alarm on settling tank LIC
(2) K1 pump fails (motor fault, loss of drive, impeller corroded, etc.)	same as consequences for (1)	same actions required as (b)
(3) Line blockage, isolation valve closed in error, or LCV valve fails	same as consequences for (1)	Same actions required as (b)
	J1 pump overheats	(c) Install kickback on J1 pumps (d) Check design of J1 pump strainers
(4) Line fracture	same consequences as for (1)	same actions required as (b)
	hydrocarbon discharged into area adjacent to public highway	(e) Institute regular patrolling and inspection of transfer line
MORE OF		
(5) LCV fails open or LCV bypass open in error	Settling tank overfills	(f) Install high level alarm on LIC and check sizing of relief opposite liquid overflowing (g) Institute locking off procedure for LCV bypass when not in use
	Incomplete separation of water phase in tank, leading to problems on reaction section	(h) Extend J2 pump station line to 12” above tank base

3.5.5 Failure Mode, Effect and Criticality Analysis

A Failure Mode, Effect and Criticality Analysis (FMECA) uses information from a FMEA analysis to further rank critical failure modes by severity and recommend appropriate measures to minimize risk. A FMECA analysis generally includes identifying various failure modes and their effects on the system, outlining existing and proposed remedial measures, and documenting the findings. Additionally, both FMEA and FMECA analyze only one failure mode at a time in the context of the overall system and therefore can not analyze combinations of component system failures.

FMECA uses probability and consequences of a critical failure mode to calculate a failure mode importance. A criticality number (C_m) for each severity level (m) can be used as one form of a FMECA and is given by Equation 3.3.

$$C_m = \sum_{i=1}^{N} \beta_i \alpha_i \lambda_p t \tag{3.3}$$

where, α and β represent the failure mode ratio and a conditional probability of a loss for a failure mode, respectively, λ is the component failure rate, t is the time period under consideration, p denotes the component under consideration, and N is the number of component failure modes.

Another variation of a FMECA is more qualitative and characterizes possible failure modes based on the likelihood of occurrence. This approach uses four levels to represent increasing severity of consequences for a specified failure mode

- Level 1 maintenance – minor consequence
  (i.e. trees growing on top of an earthen dam might lead to minor consequences of decreased strength of the embankment over time due to decay)

- Level 2 delays – significant consequence
  (i.e. heavy rain increasing the impoundment leading to the significant consequence of increased water pressure on the upstream face of the dam)

- Level 3 out of order – critical consequence
  (i.e. cracks forming in the embankment of a dam might lead to the consequence of a weakened structure capable of failing if the upstream height of water is increased)

- Level 4 loss of life – catastrophic consequence
  (i.e. a complete dam breach would inundate the downstream area and greatly increase the likelihood of fatalities as a consequence)

Once the outcome of each failure mode has been categorized in one of the four levels, probabilities of occurrence are assigned as very low, low, medium or high using a table format

(35). Probabilities of occurrences for the various levels can also be obtained from literature. Table 3.6 presents probability estimates for five severity levels that range from frequent to extremely unlikely.

Table 3. 6 Probability of Occurrence Values (adapted from 36)

	Severity Level	Frequency of Event	Probability of Occurrence
A	Frequent	High Probability	$p \geq 0.20$
B	Reasonably Probable	Moderate Probability	$0.10 \leq p < 0.20$
C	Occasional	Marginal Probability	$0.01 \leq p < 0.10$
D	Remote	Unlikely Probability	$0.001 \leq p < 0.01$
E	Extremely Unlikely	Rare Event	$p < 0.001$

3.5.6 Probable Failure Mode Analysis

Probable Failure Mode Analysis (PFMA) is a seven step process that analyzes possible failure modes and is estimated to take several months to fully execute. A PFMA generally includes assembling a team of analysts, collecting information about the dam, performing the failure mode analysis, considering risk reduction options based on the most likely failure modes, and documenting the findings. A traditional PFMA involves investigation of all potential failure modes that are categorized into different groups depending on the significance and likelihood of occurrence as outlined in Table 3.7.

Table 3. 7 Failure mode categories for Probable Failure Mode Analysis Failure Analysis (adapted from 14)

	Level of Importance	Description
I	Potential failure modes for further analysis with the highest priority	Failure modes recognized as a significant threat. They are reasonably likely and credible.
II	Potential failure modes considered for further analysis, secondary to those of Category I	A Failure mode which is of lesser significance and likelihood than Category I.
III	More information is needed to classify a failure mode with this level of importance	Failure modes that are not well described or lack information required to classify into one of the other three categories.
IV	Potential failure mode ruled out	These failure modes are understood to be insignificant and highly unlikely

3.5.7 Fault Tree Analysis

Once all possible sources of risk are identified for each component, logic diagrams can be used to evaluate overall system risk. Logic diagrams can include fault trees, event trees or decision trees. Fault tree analysis (FTA) focuses on identifying critical states of the system as well as the various ways each critical state may occur. As a result, a complete list of all possible system failure modes is not analyzed since only critical states are considered (35). In addition, construction of fault trees first require a preliminary analysis such as FMEA, FMECA, or HAZOP to obtain an initiating event (13).

The development of fault trees starts with a failure mode (critical state) and deductively progresses to possible causes. Fault trees use symbols (squares, circles) and logic statements (and-, or-statements) to represent different events. Each branch of a fault tree represents a success or failure of a particular event and is connected to other branches through 'gates' which allow passage to the next event if certain criteria are satisfied.

Event trees, on the other hand, start with an initiating event and lead to the consequences of such an event. The initiating event is often identified using another analysis method such as FMECA, FMEA, or HAZOP. Event trees can sometimes become overwhelming when all possible outcomes are considered. As an alternative, truncated event trees may be used to represent only the success or failure of an event.

An example of an event tree and fault tree are shown in Figures 3.3 and 3.4, respectively. Figure 3.3 presents a truncated event tree for a dam failure caused by aging. Simple commands of "Yes" and "No" are used to determine the most probable consequences of a dam failure. Each branch is accompanied by a probability (P) that represents the likelihood of occurrence. The likely failure modes are presented at the end of the diagram with the associated mathematical probability for each branch of the event tree.

Figure 3.4 presents a fault tree analysis for a failure mode as a result of a system power loss. The analysis starts with the failure mode (i.e. power loss) and progresses to the consequences of a power outage, loss of grid power, loss of standby power supply and battery power failure. The diamond symbols of the fault tree represent completed events that will not further result in other consequences. Rectangular symbols represent initiating events that are likely to occur while circles represent conditional events that may occur. Fault trees also use gates to separate primary events. The gates used in this example represent connectivity "AND" and "OR". Events that result from an "AND" connection will occur if all the input events occur while events resulting from an "OR" connection will occur if at least one of the input events occurs.

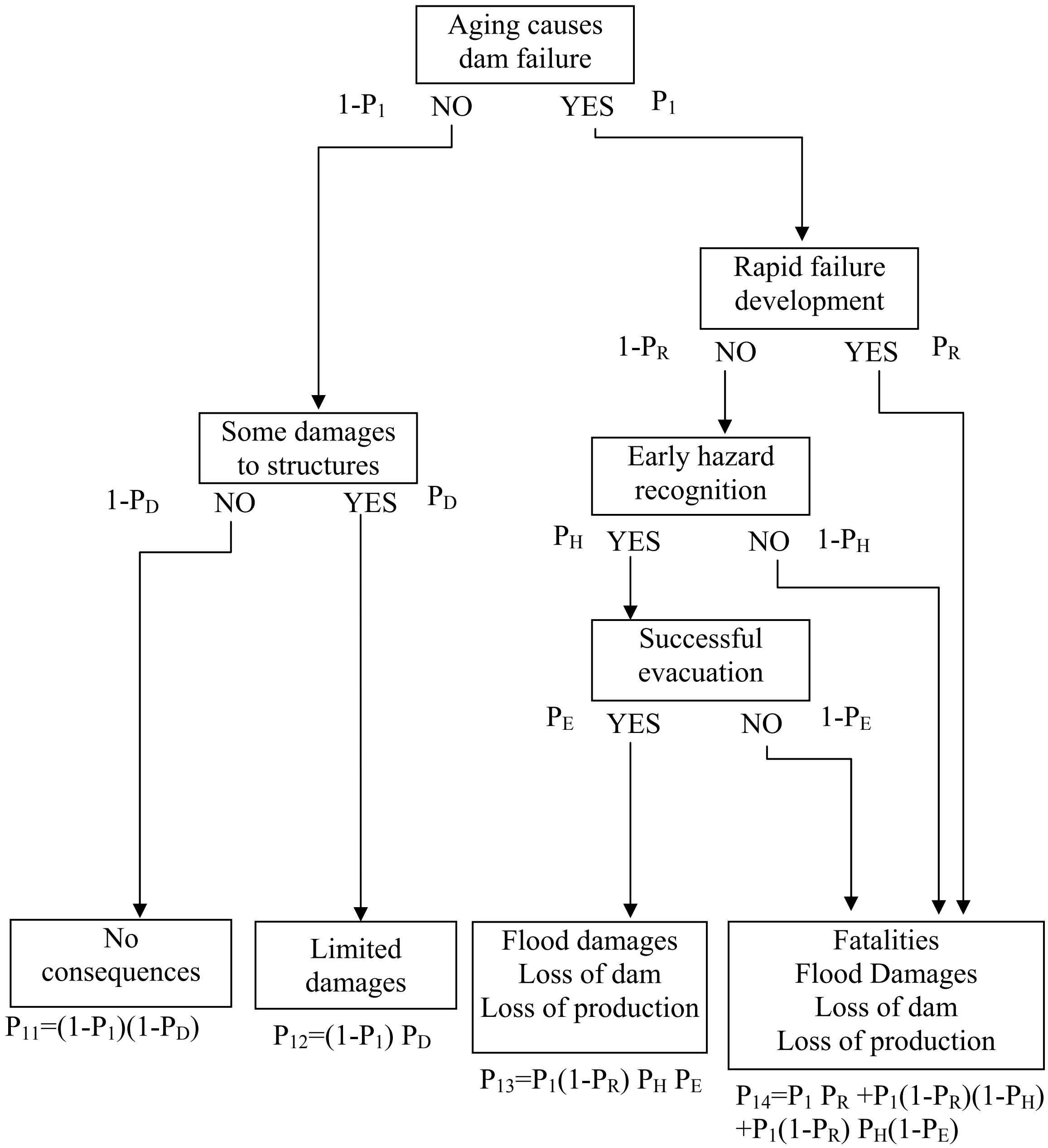

Figure 3. 3 Example of an event tree analysis (adapted from 31)

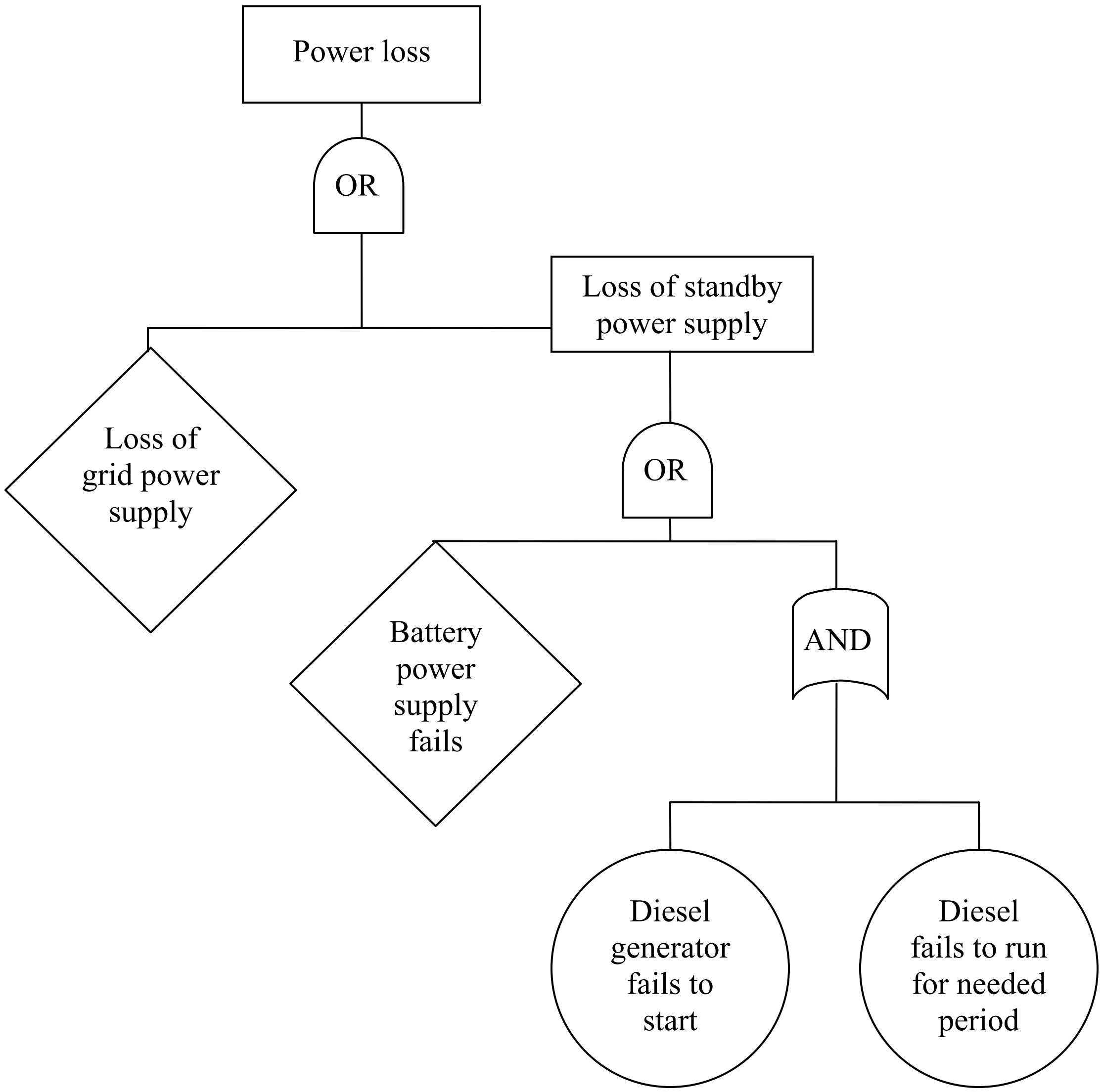

Figure 3. 4 Example of a fault tree (adapted from 35)

3.5.8 Cause-Consequence Analysis

Cause and Consequence Analysis (CCA), sometimes referred to as an expanded event tree analysis, combines both event and fault trees as shown in Figure 3.5. This figure illustrates how two different types of logic can be used to gain the most information. A fault tree starts with possible failure modes and leads to possible causes as shown on the left side of Figure 3.5. The output of the fault tree is then used as input in the event tree analysis which starts with possible causes and leads to a number of probable consequences as shown on the right side of the figure.

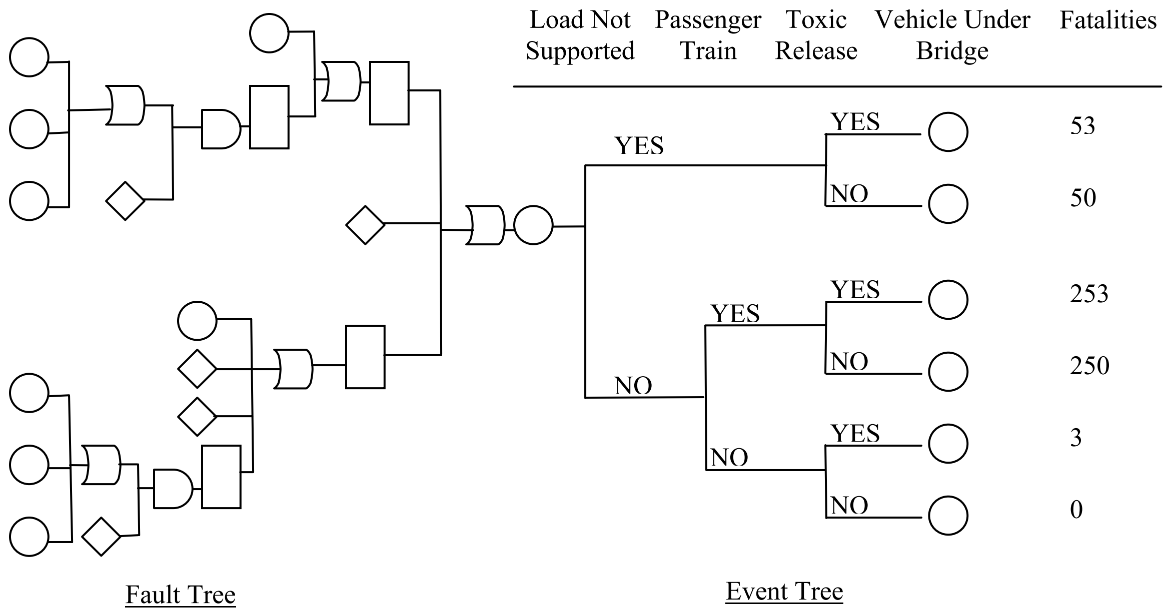

Figure 3. 5 Example of an event tree developed from a fault tree (adapted from 35)

3.6 Risk Management

Risk management deals with creating a balance between risk and available resources as to achieve the lowest possible overall risk for a given investment. Risk management combines risk assessment and risk analysis to control long-term risk as depicted in Figure 3.6. A dam safety management program should include an ongoing review and improvement component. A review component involves maintenance and operation of the dam, continuous monitoring for potential problems, periodic review of operation policies, and development of an emergency response plan. An improvement component, on the other hand, deals with implementing long-term change including examination of dam safety issues and remedial actions to solve such problems (8).

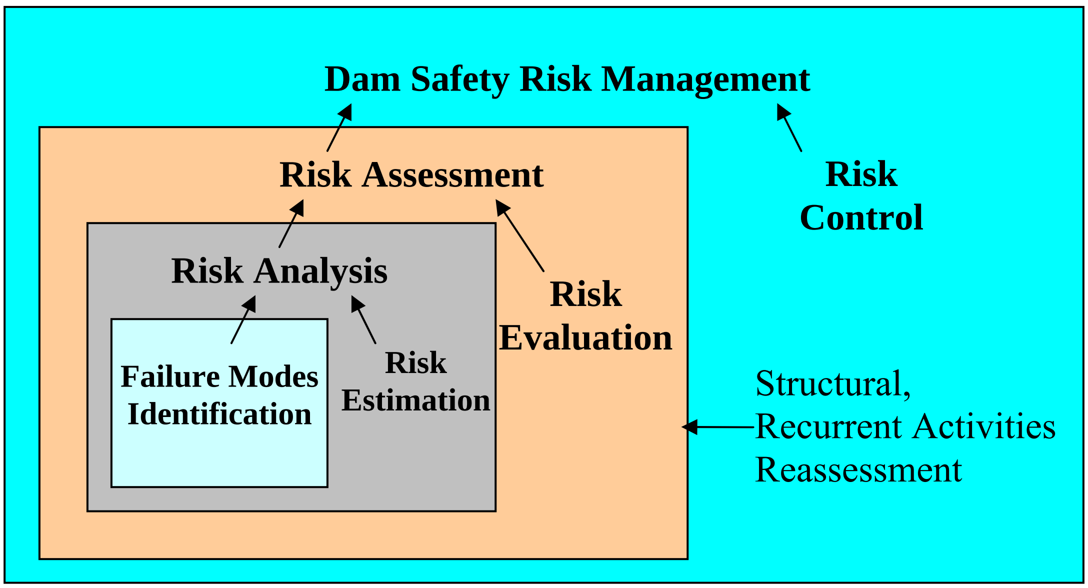

Figure 3. 6 Components of risk management (adapted from 10)

CHAPTER 4: GIS-BASED MODEL AND CASE STUDY

A computerized model of the effects of a dam break requires integration of spatially-referenced data on a topological model. The model will specify the physical connectivity of dams to other infrastructure such as roadways and bridges, residential and commercial buildings and integrate relational databases throughout the network using a geographic information system (GIS). GIS is a spatial database of stored mathematical coordinates expressed as separate geographical layers. For example, coordinates and attributes of a dam structure such as location, capacity, and dimension can be expressed on a separate layer than a roadway network which includes information of travel direction, number of lanes, and roadway type. This flexibility allows for a broad range of spatial and network analyses. GIS provides the capacity to organize, combine, and analyze geospatial data for network analysis, asset management, and decision making (22).

Today, GIS serves as a powerful tool for engineers, planners, researchers, as well as scientists to better understand the complex inter-relation between variables. In fact, GIS has been used in several areas including management of pavement and bridge maintenance (33), disaster response plan modeling, flood predictions, risk assessment and risk management, and traveler information system analysis (15).

For the purpose of this study, a GIS model is developed for assessing the effects of dam failures in the State of Rhode Island. A database is complied with geospatial information obtained from the Rhode Island Geographic Information System (RIGIS) managed by the Environmental Data Center (EDC) of the Natural Resource Science Department at the University of Rhode Island (www.edc.uri.edu/rigis). The model accounts for several important parameters such as the type and size of the affected population (i.e. senior-citizens and school-aged children), extent of property damage (i.e. residential and commercial), mileage of roadway damage particularly of evacuation routes, and location of emergency response facilities (i.e. police barracks, fire stations, and hospitals). The model also provides the flexibility of examining the effects of different failure scenarios of increasing severity. Attributes are also added to the dam database to reflect current RIDEM inspection report ratings.

Details of the analysis of the hypothetical failure of the Hughesdale Pond Upper Dam (ID 313) are presented as a case study. The Hughesdale Pond Upper Dam is located on Dry Brook in the Township of Johnston, Rhode Island. The immediate downstream area primarily consists of undeveloped, wooded land. However, the Hughesdale Pond Lower Dam, approximately 1,400 ft downstream of the Upper Dam, is located in a considerably developed area with mixed residential and commercial land usage. This dam is likely to be affected in the event of a dam break of the Upper Dam (30).

A dam break analysis, provided by RIDEM, is used to estimate the peak outflow, peak water surface elevations, and the timing of the flood wave. The analysis is performed using the National Weather Service (NWS) Simplified Dam Break (SMPDBRK) model (30). An inundation map of the land area that is expected to flood is then coupled with the GIS model and US Census block data to characterize the affected population as well as the surrounding community. The level and severity of the impact can then be used for hazard classification of the dam.

4.1 Development of a GIS Model

A GIS model is developed using the ArcView 9.0 software provided by ESRI (3). The model is created from databases that represent spatial and physical attributes for more than 500 dams under the jurisdiction of RIDEM as well as the characteristics of surrounding communities. The latter includes information on the location of police barracks, fire stations, roadways, bridges, and population demographics. The dam database includes information on the type, purpose, year, capacity, length, height, and location of each dam. The hazard rating of dams classified as high hazard is also added.

Spatial data is represented by points, lines, or areas as either thematic layers or discrete objects and stored as shape files. Each entity of a spatial model can be represented by either a vector or raster model in GIS. A vector model is used to depict unvarying parameters such as discrete state boundaries or roadways whereas a raster model is used to represent constantly changing geometric features such as the change in height of a mountain throughout a mountain range. GIS also uses coverages to store both primary and secondary features of a map. Arcs, nodes, and polygons are examples of primary features whereas tics, links, and annotations represent secondary features. A coverage typically represents a single layer such as that of a roadway.

In a GIS model, similar geometric objects are often grouped together into a feature class which can be part of a shape file or a coverage. An example of a single line feature class is a file containing all primary, secondary, and minor roadways. Within a GIS model, several functions can be performed with spatial data such as unions, intersections, feature extraction, and the creation of buffers. A combination of these functions can provide estimates of the characteristics of the community affected by different intensities of a dam failure.

4.1.1 Societal Parameters Considered in Dam Break Analysis

Parameters of the affected community that are considered in the analysis include emergency response facilities, roadways and bridges, vulnerable population, and economic impact including loss of residence or commercial buildings. Each parameter represents a societal category that would be adversely affected in the event of a dam failure and is considered in the evaluation of the Hughesdale Upper Pond Dam.

The affect on facilities of emergency responders such as police barracks, fires stations, and hospitals is considered to be of high value. Disruption to the operations of such facilities could compromise the level of medical care provided to victims since the response time would increase and injured persons may have to travel farther to seek medical attention. Access to major roadways and bridges is also an important consideration particularly in the event of an evacuation. Roadway detours may lead to traffic jams and congested collectors which can increase the travel time during a rescue operation.

Areas of high population density will undoubtedly have more people affected by a dam break. The demographics of the population including the age and capacity of individuals to evacuate are important factors that are considered in this study. An area with a high number of school-aged children or senior-citizen centers needs to be closely examined since this population may require additional resources in the event of dam failure.

Finally, the economic impact on nearby residences and commercial facilities is also considered. Displaced individuals may incur large costs due to damage and restoration of their homes as well as require temporary shelter, transportation, and in some cases, medical attention. Areas with a large number of businesses should also be considered in the analysis since employees, whether or not they are directly affected by a dam break, may experience loss of wages for some time.

4.1.2 Data Collection

Data is obtained from the Rhode Island Geographic Information System (RIGIS) website managed by the Environmental Data Center (EDC) of the Natural Resource Science Department at the University of Rhode Island (www.edc.uri.edu/rigis). Statewide data layers such as boundaries, demographics, economics, utilities, land use, and transportation are imported from the RIGIS library. In total, seventeen databases were imported into the GIS model from RIGIS as described in Table 4.1. Each dataset is also associated with a metafile that describes the contents of the respective dataset. Table 4.2 presents a portion of the metafile describing the entity and attribute information for the dam dataset. In addition, more than 100 orthophotographic (digital aerial imagery) images were imported into the model.

Besides information of RI dams that was available through RIGIS, inspection reports for dams rated as high hazard from 1999 to 2005 were also reviewed. The latest inspection ratings for embankment, spillway, and low level outlet dam components were added as attributes to the GIS model.

Table 4. 1 Data Layers obtained from the Rhode Island Geographic Information System Library (29)

	Data Layer	Description
1	Dams	Point dataset describing the general location of dams and related structures on rivers or streams within the state.
2	State Boundary	Rhode Island State boundary line including the coastline.
3	Medical Facilities	Hospitals and community health centers in Rhode Island.
4	Police Barracks	Police barrack tabular and geographic information for general emergency service, public safety, facility inventory, and mapping.
5	Fire Stations	Locations and major equipment for state and municipal fire stations for general emergency service, fire response, public safety and facilities inventory, and mapping.
6	Schools	Location and contact information for public and private schools from the preschool through the university level.
7	Roadways - All	All roads including paved, unpaved and track/trail with name attributes and annotation.
8	Bridges	All Bridges located with the State of Rhode Island.
9	Rivers	Rivers and streams derived from the 1997 National Grid_USA/RIDOT Orthophoto Project.
10	Ponds	Lakes and ponds derived from the 1997 National Grid_USA/RIDOT Orthophoto Project.
11	US Census data from 2000 Summary file 1 for Rhode Island	US Census 2000 source data of population and housing including age, sex, race, households and housing unit information to the Census Block level (Summary File 1).
12	US Census data from 2000 Summary file 3 for Rhode Island	US Census 2000 source data of population and housing including age, sex, race, households and housing unit information to the Census Block level (Summary File 3).
13	Economic Development Enterprise Zones	Economic development enterprise zones as delineated by US Census 1990 census tract boundaries.
14	Roadways listed in the state 911 database	Road centerlines based on the 1997 National Grid_USA/ RIDOT Digital Orthophoto Project with preliminary E-911 road/street name and address ranges (updated 12/04).
15	Driveways locations list in the state 911 database	Driveways and private roadways based on the 1997 National Grid_USA/RIDOT Digital Orthophoto Project with preliminary E-911 road/street name and address ranges (updated 12/04).
16	Roadways - Tiger	Road Centerlines with street name and address ranges from U.S. Census TIGER files 2005.
17	E911 Sites	Point features for buildings and other significant infrastructure features based on the 1997 National Grid_USA/RIDOT Digital Orthophoto Project with preliminary E-911 road/street name and address ranges (updated 12/04).

Table 4. 2 Entity and Attribute Description of the Dam Dataset (29)

Entity Type Label:	ri_dams.pat
Entity Type Definition:	point attribute table
Entity Type Definition Source:	RI Dept of Environmental Management

Parameter:	Description
ID	official state identification number
NAME	official state name
COUNTY	county where dam is located
NAT_ID	official national identification of dam
AKA	alternate dam name
TOWN	town where dam is located
RIVER	river or stream on which dam is located
NEAR_TOWN	name of nearest city or town that is most likely to be affected by floods resulting from dam failure
TYPE	dam construction and material
PURPOSE	purpose(s) for which reservoir or impoundment is used
COMPLETED	date of dams construction completion
DAM_LEN	length of dam in feet (to the nearest foot). Include spillway, fish passage, etc.
DAM_HGT	height of the dam in feet (to the nearest foot) from the lowest point in the original stream bed to the lowest point on the crest of the dam
MAX_DISCHG	number of Cubic feet per second that the spillway is capable of discharging when the reservoir is at its maximum designed water surface elevation
MAX_STOR	total storage space of the reservoir, in acre-feet, below the maximum attainable water surface elevation

4.2 Analysis of the Hughesdale Pond Upper Dam

The Hughesdale Pond Upper Dam (ID 313) is selected for this study because its hazard rating was recently upgraded from a Low to High by RIDEM. The Dam is located on Dry Brook in the Township of Johnston, Rhode Island in the vicinity of two major routes; Route 6 which provides east-west access to Providence, RI from Connecticut and Interstate 295 which provides north-south access from RI toward Boston, MA as shown in Figure 4.1. The Upper Dam is also located near Central Avenue, Scituate Avenue, and Atwood Avenue (Route 5) which has an 8-foot high by 10-foot wide culvert at the roadway crossing.

The immediate downstream area primarily consists of undeveloped, wooded land. However, the 250-ft long, 14-ft high Hughesdale Pond Lower Dam, approximately 1,400 ft downstream of the Upper Dam, is located in a considerably developed area with mixed residential and commercial land usage. Dry Brook eventually discharges into the North Branch of the Pocasset River approximately 3,700 feet downstream of the Upper Dam. Photographs of the two dams are provided in Figures 4.2-4.9.

Figure 4. 1 Orthographic Image of the Location of Hughesdale Pond Upper Dam (www.mapquest.com)


Figure 4. 2 The Hughesdale Lower Pond Dam


Figure 4. 3 Stone Masonry Crest of the Hughesdale Lower Pond Dam


Figure 4. 4 Earth Embankment of the Hughesdale Lower Pond Dam


Figure 4. 5 Impoundment of the Hughesdale Lower Pond Dam

Figure 4. 6 The Hughesdale Upper Pond Dam

Figure 4. 7 Earth Embankment of the Hughesdale Upper Pond Dam


Figure 4. 8 Woodland Banks of the Hughesdale Upper Pond Dam


Figure 4. 9 Impoundment of the Hughesdale Upper Pond Dam

The proximity of the Hughesdale Upper and Lower Pond Dams to facilities of first responders, major roadways and bridges, schools, senior-citizen centers, and residential and commercial buildings is considered. The dam is surrounded by a network of roadways of various capacities and importance. There are also several residences located along the banks of the Dry Brook between the two dams. Table 4.3 presents the distance of various parameters to the Hughesdale Upper and Lower Pond Dams.

Table 4. 3 Proximity of Critical Parameters to the Hugesdale Upper and Lower Pond Dams

Parameter	Name	Distance to Hughesdale Upper and (Lower) Pond Dams (miles)
First Responder Facilities		
Police Barracks	Johnston Police Department	1.63 (1.65)
	Cranston Police Department	2.30 (2.12)
Fire Stations	Johnston Fire Station	1.47 (1.52)
	Johnston Fire Station	1.40 (1.17)
Hospitals	Roger Williams Hospital	3.96 (3.75)
Vulnerable Population		
Schools	Kinder-Care at Work	0.50 (0.27)
Senior Citizen Centers		None
Roadways and Bridges		
Major Roadways	Route 295	0.40 (0.65)
	Route 6 and Route 6A	0.74 (0.70)
	Atwood Avenue	0.42 (0.19)
Collector Roadways	Central Avenue	0.06 (0.05)
	Scituate Avenue	0.20 (0.15)
	Simmonsville Avenue	0.44 (0.19)
Minor Roadways	Parrillo Circle	0.91 (0.25)
	Celcelia Drive	0.18 (0.14)
	Gesmondi Drive	0.28 (0.06)
	Ligian Court	0.36 (0.11)
	Alacar Drive	0.33 (0.07)
	Rotary Drive	0.45 (0.20)
	April Street	0.50 (0.24)
	Eldorado Drive	0.53 (0.28)

4.2.1 Dam Breach Analysis

A dam breach analysis of the Hughesdale Upper Pond Dam is obtained from RIDEM and used to create an inundation map of the expected flooded area (30). The map is then coupled with the GIS model developed for the area near the dams and used to identify various characteristics of the affected community. The dam breach analysis was performed using the Simplified Dam Break Analysis (SMPDBK) model which can predict peak flows, flood elevations, and downstream travel times with minimal data input. Peak flows estimated with SMPDBK are generally within 10 percent of values calculated with more rigorous hydrology models. However, SMPDBK does not account for downstream channel constrictions which may contribute to the reduced accuracy of the model (18).

SMPDBK was developed by the National Weather Service (NWS) in 1983 to predict the extent of downstream flooding from a dam failure. The SMPDBK model requires input of the reservoir area or volume, impounded surface elevation, breach formation time, and the final breach elevation and width. A partial dam failure, which tends to more closely approximate realistic failures, can also be modeled with SMPDBK by entering an average trapezoidal breach width or by entering the starting and ending breach elevations.

The maximum breach outflow $(Q_{\max})$ is calculated using the broad-crested weir equation as given by Equation 4.1. The flood peak discharge depends on a number of factors including the physical characteristics of the dam, breach dimensions, the depth and volume of stored water in the reservoir, time for breach development, and the inflow to the reservoir at the time of failure.

$$Q_{\max} = Q_o + 3.1 B_r \left(\frac{C}{\frac{t_f}{60} + \frac{C}{\sqrt{H}}} \right)^3 \tag{4.1}$$

$$\text{with,} \quad C = \frac{23.4 A_s}{B_r}$$

where,

A_S = Surface area of reservoir at the maximum elevation of the pool level (acres)

H = Elevation of maximum pool level – final breach bottom elevation (feet)

B_r = Average final breach width (ft)

t_f = Time to failure (minutes)

Q_o = Additional (non-breach) outflow at time t_f (cfs)

The expression of Equation 4.1 is the standard weir equation with the average final breach width (B_r) and the reservoir depth (H) corresponding to the width and head of the weir crest, respectively with a reduction factor that accounts for the reduction in reservoir level during breach erosion.

If a dam is determined to fail instantaneously, i.e. the time to failure is less than 1/1000 the dam height, Equation 4.2 is used to estimate the maximum breach outflow (Q_{max}). This alternate equation accounts for a wave that forms in the upstream direction in cases of an extremely rapid dam failure with.

$$Q_{b\max} = 3.1B_r(I_v I_n)H_d^{3/2} \tag{4.2}$$

where,

$$I_v = \left[1.0 + 0.148\left(\frac{B_r}{B}\right)^2 (m+1)^2 - 0.083\left(\frac{B_r}{B}\right)^3 (m+1)^3\right]^{3/2}$$

$$I_n = \left[\begin{array}{l} 1.0 - 0.5467\left(\frac{B_r}{B}\right)(m+1) + 0.2989\left(\frac{B_r}{B}\right)^2 (m+1)^2 - 0.1634\left(\frac{B_r}{B}\right)^3 (m+1)^3 \\ + 0.0893\left(\frac{B_r}{B}\right)^4 (m+1)^4 - 0.0488\left(\frac{B_r}{B}\right)^5 (m+1)^5 \end{array}\right]^{3/2}$$

B_r = Breach width (ft)
B = Valley topwidth at dam crest (ft)
H_d = Height of dam (ft)
m = Channel width vs. depth shape parameter used in a power function $\left(B = kh^m\right)$

$m = \dfrac{\log B_I - \log B_2}{\log h_I - h_2}$, where I represents a value for the channel width corresponding to the water depth and the subscript 2 represents a value for the second channel width and typically coincides with the top-bank depth (bank full) level of the cross-section.

The depth of flow is calculated using the Manning equation and is given by:

$$Q = \frac{1.486}{n} S^{1/2} A * R^{2/3} \tag{4.3}$$

where,

Q = Maximum discharge (cfs)
A = Wetted cross-sectional area (ft^2) and a function of elevation or depth associated with the maximum discharge
R = Wetted hydraulic radius A/B, where B is the wetted channel width (ft) and a function of elevation or depth associated with the maximum discharge
n = Manning roughness coefficient and a function of depth or water surface elevation
S = Total slope

Data from inspection reports of the Hughesdale Pond Upper Dam including the geometry of the dam (height, length, material type, etc.) and downstream channel characteristics (slope elevation, Manning roughness coefficients, etc.) are used in the SMPDBK model. The movement of the flood wave downstream upon dam failure depends on a number of factors including the channel bedslope, cross-sectional area, geometry, and roughness of the main channel and overbank areas, and the presence of storage floodwaters in off-channel areas. The Dam has an earthen embankment, a total length of approximately 200 feet, and a maximum height of 22 feet. The dam also has a stone masonry downstream face and an older low level outlet previously filled with earth and masonry. Various other structural and hydrologic characteristics of the dam used as input in the SMPDBK model include:

- A 34-foot wide broad-crested concrete spillway
- An approximate drainage area of three square miles with a normal pool storage capacity of 50 acre-feet
- Top of dam storage capacity of 55 acre-feet
- An immediate downstream area of mostly undeveloped woodland
- A flow from the Upper Pond Dam diverted into a 10-foot wide by 8-foot high culvert at Atwood Avenue (Rhode Island Route 5) approximately 2,400 feet downstream

The Hughesdale Lower Pond Dam (No. 312) is located approximately 1,400 feet downstream of the Upper dam. The lower dam also has a masonry downstream face and is 250 feet in length with a maximum height of 14 feet. Both the Upper and Lower dams are located on the Dry Brook reach which contains steep slopes and narrow valleys and discharges into the north branch of the Pocasset River approximately 0.7 miles downstream (30).

The analysis also compares the calculated flow depth with the reservoir water depth to determine if the depth of the water downstream is reducing flow through the breach. If the downstream water depth is reducing flow (i.e. tail water effect), a correction factor is applied by adjusting the head over the weir to compensate for this effect. The difference in the maximum tail water elevation and the final breach elevation is then compared with 67% of the head over the weir at the time of failure. If the difference in elevations is greater than the reduced head over the weir, another correction factor is applied to reduce the maximum discharge. The maximum breach outflow is calculated with the correction factor and re-calculated until the value converges (18).

The various input parameters used in the SMPDBK model are summarized as follows:

- An impoundment area equivalent to the top of the dam elevation is used
- Thirty minutes for breach formation
- A trapezoidal breach shape of 0.5 H: 1.0 V
- Average breach width of 66 feet, approximately three times the height of the dam
- Non-breach flow of 3.0 cfs
- Four cross-sections are used to represent downstream reach geometry
- Assumed Manning roughness coefficients based on the terrain at the four cross-sections
- Surface area of reservoir at time of breach is assumed to coincide with the top of dam elevation (elevation 212.0)
- The entire dam height is assumed breached for a final breach elevation of 190.0

A summary of the SMPDBK analysis for the Hughesdale Upper Pond Dam is shown in Table 4.4. The estimated peak breach outflow is approximately 1,700 cfs. This peak flood flow is approximately twice the FEMA 100-year flood flow and 1.4 times greater than the FEMA 500-year flood.

Table 4. 4 Simplified Dam Break (SMPDBK) Analysis for the Hughesdale Pond Upper Dam (30)

SIMPLIFIED DAMBREAK MODEL (SMPDBK) VERSION: 9/91

BY D.L. FREAD, J.M. LEWIS, & J.N. WETMORE - PHONE: (301) 427-7640
NWS HYDROLOGIC RESEARCH LAB W/OH3, 1325 EAST-WEST HIGHWAY,
SILVER SPRING, MD 20910

THE DATA FOR THIS DAM IS AS FOLLOWS:

Type of Dam	IDAM	EARTH
Dam Breach Elevation	HDE	212.00 FT
Final Breach Elevation	BME	190.00 FT
Volume of Reservoir	VOL	55. ACRE-FT *
Surface Area of Reservoir	SA	5.00 ACRES
Final Breach Width	BW	66.00 FT
Time of Dam Failure	TFM	30.00 MINUTES
Non-Breach Flow	QO	3.00 CFS
Distance to Primary Point of Interest	DISTTN	.00 MILES
Dead Storage Equivalent Manning Coefficient	CMS	.52

CROSS SECTION NO. 1

Flood Depth	FLD	2.00 FT			
ELEV.(FT)	HS	190.0	220.0	230.0	240.0
TWIDTHS(FT)	BS	66.0	300.0	350.0	500.0
INACTIVE TW(FT)	BSS	.0	.0	.0	.0
MANNING N	CM	.035	.065	.065	.065

CROSS SECTION NO. 2

REACH LENGTH	D	.15 FT			
FLOOD DEPTH	FLD	2.00 FT			
ELEV.(FT)	HS	170.0	174.0	180.0	190.0
TWIDTHS(FT)	BS	.0	20.0	100.0	200.0
INACTIVE TW(FT)	BSS	.0	.0	.0	.0
MANNING N	CM	.035	.035	.065	.065

CROSS SECTION NO. 3

REACH LENGTH (D)	D	.28 FT
FLOOD DEPTH (FLD)	FLD	2.00 FT
ELEV.(FT) (HS)	HS	144.0 148.0 150.0 160.0
TWIDTHS(FT) (BS)	BS	.0 20.0 100.0 300.0
INACTIVE TW(FT) (BSS)	BSS	.0 .0 .0 .0
MANNING N (CM)	CM	.035 .035 .065 .065

CROSS SECTION NO. 4

REACH LENGTH	D	.52 FT
FLOOD DEPTH	FLD	2.00 FT
ELEV.(FT)	HS	95.0 99.0 100.0 110.0
TWIDTHS(FT)	BS	.0 20.0 50.0 200.0
INACTIVE TW(FT)	BSS	.0 .0 .0 .0
MANNING N	CM	.035 .035 .065 .065

An asterisk (*) beside a parameter implies that a default value was computed

Name of Dam: HUGESDALE POND UPPER DAM NAME OF RIVER: DRY BROOK

Rvr Mile from Dam	Max Flow (cfs)	Max Elev (ft-msl)	Max Depth (ft)	Time (hr) Max Depth	Time (hr) Flood	Time (hr) Deflood	Time (hr) Depth (ft)
.00	1687.	192.24	2.24	.50	.42	.42	2.00
.15	1670.	177.36	7.36	.52	.04	.05	2.00
.28	1670.	150.67	6.67	.54	.06	.06	2.00
.52	879.	100.87	5.87	.57	.11	.13	2.00

ANALYSIS IS COMPLETE

4.2.2 Characteristics of Inundated Area

Results of the SMPDBK dam break analysis are used to create a buffer for the Dry Brook at the Hughesdale Upper Pond Dam in the GIS model. The othrophotographic images in the GIS model are examined for terrain information and approximately matched to the inundation area contours predicted by SMPDBK. The inundated area, approximately 0.04 square miles, is then represented as shape file and imported into the GIS model as shown in Figure 4.10.

The characteristics of the population located within the inundated area are estimated by intersecting the GIS buffer with US Census demographic data. In total, six US Census Blocks with excerpt data from the 2000 Summary File 1 and two US Census Blocks with excerpt data the from 2000 Summary File 3 are identified as shown in Figures 4.11 and 4.12. The US Census Blocks contain information on population age, gender, employment status, level of education, commute distance, household income, family size, and housing type. The characteristics of the affected community are presented in Table 4.5. An economic impact study from a potential dam failure can also be performed using tax assessment records. Property values of structures found to be within the inundation area represent a potential flood damage cost.

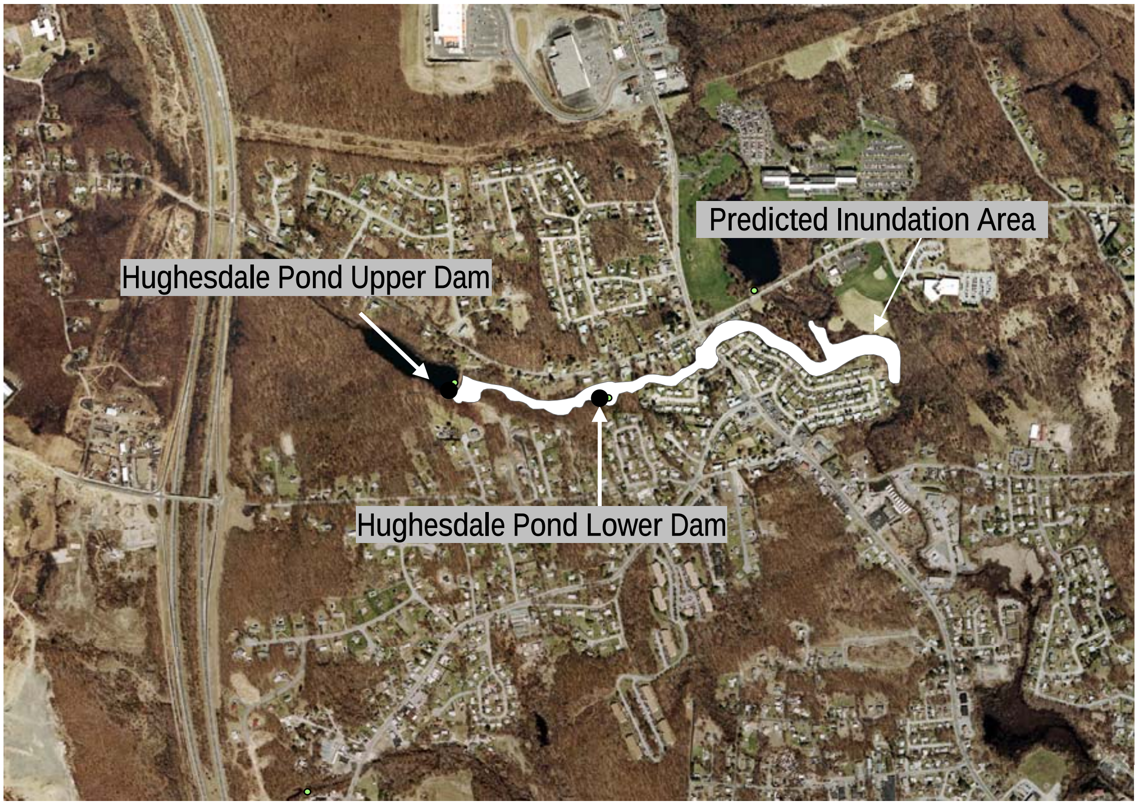

Figure 4. 10 Predicted Inundated Area for Failure of the Hughesdale Upper Pond Dam

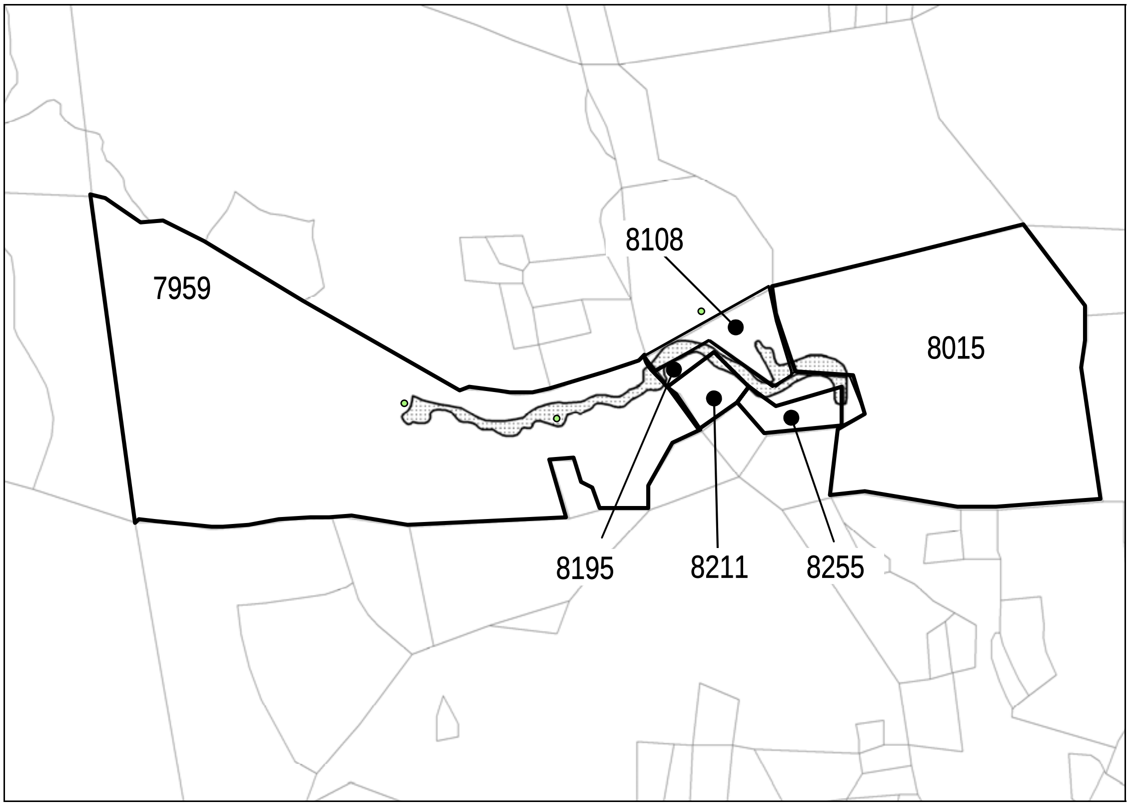

Figure 4. 11 Intersection of Inundated Area with US Summary File 1 Census Blocks

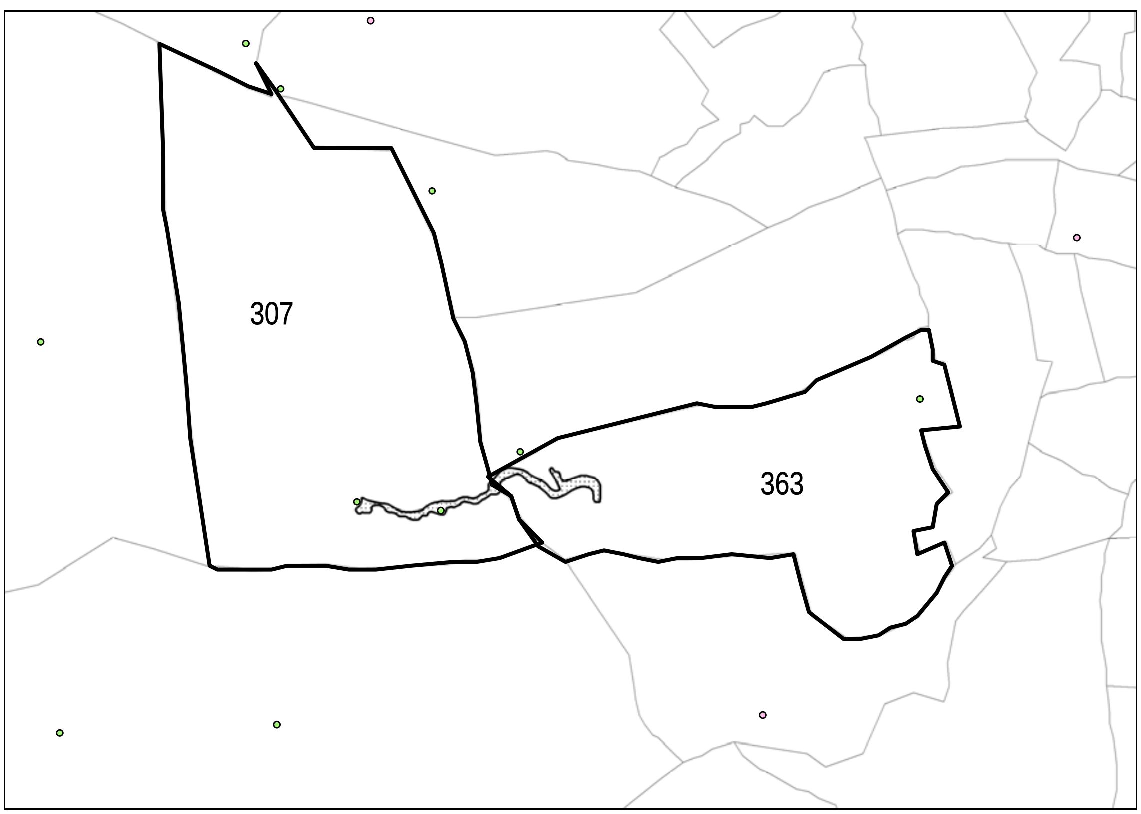

Figure 4. 12 Intersection of Inundated Area with US Summary File 3 Census Blocks

Table 4. 5 Characteristics of Community within Inundated Area

Census Block ID†	**307**	**363**	**7959**	**8108**	**8015**	**8211**	**8255**	**TOTAL**
Area within Inundation (sq. mile)	0.01	0.011	0.01	0.0037	0.002	0.0006	0.0005	0.04
Percent within Inundated area (%)	0.82%	1%	3.23%	18.5%	1.26%	6%	5%	
POPULATION								
Total Population	6.94	14.70	8.02	2.04	0.54	1.56	2.70	36.50
Gender								
Male Population	3.40	6.83	3.75	0.93	0.21	0.54	1.35	17.01
Female Population	3.55	7.87	4.27	1.11	0.33	1.02	1.35	19.49
Age								
Age 0-4	0.25	0.51	0.32	0.00	0.04	0.06	0.05	1.23
Age 5-17	0.49	2.03	0.87	0.00	0.09	0.06	0.30	3.84
Age ≥ 18 †	6.20	12.16	6.82	2.04	0.42	1.44	2.35	31.43
Age ≥ 65	2.54	3.22	1.81	2.04	0.09	0.12	1.15	10.97
Family								
Total families	1.83	4.28						6.11
Average Family Size			2.8	2.2	2.64	2.6	2.5	2.55
Families with children under 18	0.38	1.14						1.52
Language								
Persons ≥5 speak only English	6.24	12.32						18.56
Persons ≥5 speak English not well or at all	0.18	0.29						0.47
EDUCATIONAL LEVEL								
Persons age 3 and over in nursery and preschool	3.42	6.58						10.00
Persons age 16 to 19 employed and in school	0.07	0.06						0.13
Persons age 25+ who graduated high school	2.04	4.73						6.77
EMPLOYMENT								
Workers ≥16 y.o. in RI.	2.77	6.72						9.49
Workers≥16 y.o. outside RI	0.28	0.50						0.78
Persons ≥ 16 working in place of Residence	0.00	0.00						0.00

Table 4. 5 Characteristics of Community within Inundated Area (Cont'd)

Census Block ID	307	363	7959	8108	8015	8211	8255	TOTAL
INCOME								
Median household income in 1999 dollars	38462	45147						41805
Median family income in 1999 dollars	71136	53553						62345
Population with 1999 income below poverty level	0.14	0.91						1.05
Families below poverty with children under 18	0.00	0.07						0.07
Persons 65 and over below poverty level	0.14	0.18						0.32
RESIDENTIAL DWELLINGS								
Total Number of Dwellings	3.92	6.16	3.07	0.93	0.25	0.90	1.25	16.48
HU's built ≤1939	0.48	0.22						0.70
HU's built between 1940 to 1979	1.48	4.19						5.67
HU's built between 1980 to 1989	0.44	0.66						1.10
HU's built between 1990 to 1994	1.35	0.71						2.06
HU's built between 1995 to 1998	0.07	0.38						0.45
HU's built between 1999 to 2000 (March)	0.09	0.00						0.09
TRANSPORTATION								
Persons taking public transportation to work	0.00	0.00						0.00
Persons drive < 15 min. to work	0.69	1.88						2.57
Persons drive > 40 min. to work	0.26	1.09						1.35

† Census Block 8195 (0.004 sq. miles within inundated area) is entirely located in an undeveloped area and contains no dwellings or individuals

From Table 4.5, it is estimated that a total of thirty-seven (37) individuals will be directly affected by a potential failure of the Hughesdale Upper Pond Dam. This includes five (5) children under the age of 18 and thirty-two (32) adults including eleven (11) people over the age of 65. Consideration should be given to providing additional resources and care for the latter population during evacuation plans. Additionally, one individual within the inundated area is found to be living below the poverty level. This classification group should also be allotted additional resources such as transportation. Results also indicate that most of the people within the affected community speak English with perhaps only one individual not fluent in English. It is also estimated that seventeen (17) residential dwellings with a median household income of $41,805 will be affected by a potential dam break.

In general, hazard classification of a dam is often evaluated based on four components; loss of life, lifeline loss, property damage and environmental damage with the potential for loss of life serving as the primary indicator. Table 4.6 provides details of the downstream hazard classification structure of the Washington State Department of Ecology. By using this structure to classify the hazard potential of the Hughesdale Upper Pond Dam, a rating of ***High Hazard Level II*** is obtained. This is due to the high number of individuals, 37, as well as the number of dwellings, 17, estimated to suffer the consequences of a potential failure. The additional information including the breakdown of the population by age, educational background, income, and language, proximity of major roadways and bridges, and number and location of first response facilities such as police barracks, fire stations, and hospitals should also be used in the hazard classification and, in particular, in formulating an evacuation plan. Moreover, in the case of multiple dams on the same waterway, as in the case of the Hughesdale Pond Upper Dam, the hazard classification of the upstream dam must be as high as or higher than that of the downstream dam.

Table 4. 6 Downstream Hazard Classification Structure of Washington State (40)

<table>
<tr><th>Downstream Hazard Potential</th><th>Population at Risk</th><th>Economic Loss</th><th>Environmental Loss</th></tr>
<tr><td>Low</td><td>0</td><td><u>Minimal</u>
No inhabited structures. Limited agricultural development.</td><td>No deleterious materials in water</td></tr>
<tr><td>Significant</td><td>1 to 6</td><td><u>Appreciable</u>
1 or 2 inhabited structures. Notable agricultural or work sites. Secondary highway and/or rail lines.</td><td>Limited water quality degradation from reservoir contents.</td></tr>
<tr><td>High
Level I</td><td>7 to 30</td><td><u>Major</u>
3 to 10 inhabited structures. Low density suburban area with some industry and work sites. Primary highways and rail lines.</td><td rowspan="3">Severe water quality degradation potential from reservoir contents and long-term effects on life.</td></tr>
<tr><td>High
Level II</td><td>31 to 300</td><td><u>Extreme</u>
11 to 100 inhabited structures. Medium density suburban or urban area with associated industry, property and transportation features.</td></tr>
<tr><td>High
Level III</td><td>More than 300</td><td><u>Extreme</u>
More than 100 inhabited structures. Highly developed densely populated suburban or urban area.</td></tr>
</table>

CHAPTER 5: SUMMARY AND CONCLUSIONS

A potential dam failure poses a real threat to the safety of the public, can carry environmental risks and may have a significant economic impact on public and private property. The Rhode Island Department of Environmental Management (RIDEM) through the Dam Safety Program is responsible for inventory and inspection of state-owned dams across the State of Rhode Island. RIDEM descriptively classifies dams by size and hazard rating. However, the hazard classifications were assigned nearly 25 years ago and may no longer provide an accurate assessment of the downstream hazard potential for many of these dams since many communities have continued to grow. In addition, the current hazard rating scheme is solely qualitative and may not fully account for the various societal groups that would be adversely affected in the event of a dam failure.

This study has investigated dam safety with respect to the extent of damage or disruption imposed on surrounding communities due to a dam failure. Special consideration is given to the impact on first response facilities, major roadways and bridges, economic impact due to loss of residential dwellings and local business, and demographic characteristics of affected communities. A geographic information system (GIS) based model is developed for assessing the effects of dam failures. The model accounts for several important parameters such as the type and size of the affected population (i.e. senior-citizens and school-aged children), extent of property damage (i.e. residential and commercial), mileage of roadway damage particularly to evacuation routes, and location emergency responders (i.e. police barracks, fire stations, and hospitals). Attributes were also added to the dam database to reflect current RIDEM inspection report ratings.

Several risk assessment methods have also been introduced to evaluate possible causes and consequences of a dam failure including qualitative and quantitative techniques. Qualitative methods a Preliminary Hazards Analysis (PHA), Failure Mode and Effects Analysis (FMEA), Failure Mode and Effect and Criticality Analysis (FMECA), and Fault Tree Analysis (FTA). Risk management and its relationship to risk assessment, analysis, estimation, evaluation, and control are also examined.

Results from a hypothetical failure of the Hughesdale Pond Upper Dam (ID 313) were presented as a case study. A dam break analysis using the Simplified Dam Break (SMPDBRK) hydrology model is used to identify the boundaries of the inundated area. This boundary is coupled with the GIS model as well as US Census Block data to estimate the total effect on the affected community. It is estimated that a total of 17 residential dwellings and 37 individuals will be directly affected including 5 children under the age of eighteen and 11 senior-citizens. Additionally, 1 person living below the poverty level has been identified within the inundated area. These latter population groups may require additional resources such as medical care and transportation during an evacuation. Results also indicate that most of the people within the affected community speak English with perhaps one individual not fluent in English language. Given the number of individuals and residences that may be directly impacted in the event of a dam failure in addition to the proximity of the Upper Dam to facilities of first responders, major roadways, and a downstream dam (Hughesdale Lower Pond Dam), it is recommended that the Hughesdale Upper Pond Dam be classified with a ***High Hazard Level II*** rating.

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