Assessing the risks to embankment dams in the Caribbean from climate change

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Table of Contents

Table of Figures

Table of Tables

Table of Appendices

Abstract

Embankment dams are essential for the water management schemes in many countries within the Caribbean, providing for water utility, flood control and agricultural needs among many other purposes. However, the impact of climate change on these structures and the water management systems in the region is becoming more evident as time progresses, with extreme weather events increasing in both frequency and intensity. Therefore, it is necessary to quantify the effects that climate change has on embankment dams in the region as a way to improve the risk management of these assets.

This study aimed to develop a means whereby the effect of climate change on the embankment dams in the Caribbean can be quantified. This was done by developing a fragility curve utilizing past dam failure information from previous case studies. The study focused on the key failure mode that occurs under climate change, which is external erosion via overtopping. The three target islands utilized for the study are Antigua and Barbuda, Jamaica, Trinidad and Tobago. The study also separated the assets into two classes: large and small. All assets were evaluated utilizing similar design criteria to ensure relative uniformity.

The results of the analysis revealed that climate change will result in varying increases for each island up to the year 2100. For Antigua and Barbuda there will be an increased risk of +17% for small dams and +10% for large dams. For Jamaica there is an increased risk of +21% for small dams and +11% for large dams. For Trinidad and Tobago there will be an increased risk of +24% for small dams and +20% for large dams.

Key words: Risk Management, Climate Change, Embankment Dams, Fragility Curve, Probability of failure

Declaration

I hereby confirm that this dissertation is my own original work unless referenced clearly to the contrary, and that no portion of the work referred to in the dissertation has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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Abbreviations

Abbreviation	Meaning
ACSLS	Adjusted Cost per Statistical Life Saved
AACSLS	Aggregated Adjusted Cost per Statistical Life Saved
CFRD	Concrete faced rockfill dam
CCRIF SPC	Caribbean Catastrophe Risk Insurance Facilty Segregated Portfolio
DEM	Discrete Element Modelling
EAP	Emergency Action Plan
FEA	Finite Element Analysis
GCM	Global Circulation Model
HET	Hole Erosion Test
IDF curve	Intensity-duration-frequency curve
IPCC	Intergovernmental Panel on Climate Change
ISV	Internal state variable
LEA	Limit Equilibrium Analysis
MNL	Maximum normal operating level
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
SWRC	Soil water retention curve

1 Introduction

1.1 Background

Embankment dams function as essential infrastructure in many water resource management systems globally. These structures provide for domestic, municipal, and industrial water needs, while also acting as flood control mechanisms to protect human life and property downstream (Choi, Jun, et al. 2020). In many cases, failure of a dam will not only result in damaged structural members and direct damage to property and people living downstream but will also have devastating consequences on the socio-economic fabric of the regions affected. For instant, the 1975 Banqiao Dam collapse in China resulted in widespread property damage and loss of life, causing over 171,000 casualties, and an estimated economic damage of RMB 10 billion (approx. US$ 1.4 billion) from the disaster and the epidemics that ensued (Encyclopaedia Britannica 1975, Xu, et al., 2008, Choi, et al. 2018).

In the Caribbean, dams, and dam-like structures form an essential part of the water management systems in several islands such as Antigua and Barbuda, Jamaica, St. Lucia, and Puerto Rico, to only name a few. As time has progressed, the water security provided by these structures has become more sensitivity to damage from both anthropogenic influence and the effect of environmental factors such as storms and droughts (Cole & Cashman, 2021). This is a major concern as many of the nations within the region are considered water scarce, with the water management system already stressed to meet the existing demand without the influence of climatic disasters (Cole & Cashman, 2021).

With climate change projected to increase the intensity and frequency of extreme weather events, the loading imposed on embankment dams is expected to increase (Choi, Jun, et al. 2020). It is therefore incumbent on the dam engineers, governments, and other stakeholders of the Caribbean to comprehend the implications of these increases and development adaptive mechanisms to address these concerns when developing new dams and appraising older structures.

Considering aged embankment dam structures were designed and built assuming static climatic conditions, it becomes necessary to assess the impact of changing weather phenomena on these sites to ensure they possess adequate structural capacity (Fluixa-

Sanmartin, Altarejos-Garcia, et al. 2018). In some cases, this may require decision makers to demolish some of these structures and design new more adaptive dam systems. It is also necessary to evaluate the effect of climate change through an integrative process which captures aspects such as the input hydrology, consequences of flood wave on downstream population and assets (Fluixa-Sanmartin, Altarejos-Garcia, et al. 2018).

Therefore, this study is geared towards developing the knowledge base on climate change associated risks for embankment dams within the Caribbean. The research will also develop tools that can be utilized in the Caribbean region to quantify the risk that climate change will have on embankment dams and dam-like structures such as levees, thereby providing critical means to improve the risk management for these structures.

1.2 Aims and Objective

The aim of this research is to evaluate and quantify the risks faced by embankment dam structures in the Caribbean due to climate change. To achieve this, the specific objectives have been laid out as follows:

- Establish the connection between climate change and embankment dam failure modes.
- Create fragility curves to quantify the probability of failure of embankment dams under the influence of climatic drivers.
- Extrapolate the information developed from these fragility curves to the dam structures in the Caribbean and incorporate future climate projections to quantify the evolution of risk during the life of these structures.

1.3 Scope

The scope of this research has limited the list of Caribbean countries evaluated to nations that are both members of the Caribbean Catastrophe Risk Insurance Facilty Segregated Portfolio (CCRIF SPC) and part of the insular Caribbean. The main reasons for this are:

- Scholarship requirement – As a scholarship recipient of the CCRIF SPC, approval for the research dissertation must be obtained from the CCRIF SPC and it must be in an area that CCRIF has an establish interest or is aligned to the CCRIF mandate and strategic objectives with a focus on the Caribbean.

- Economics – The countries evaluated are also either members or associate member countries of the CARICOM (Caribbean Community) association and are borrowing members of the CDB (Caribbean Development Bank). These organisations represent the major economic mechanisms that fund development and climate mitigation within the region, ergo, the data produced from this research will be relevant to economic decision making for these specific nations.

- Physical Characteristics – The countries form part of the insular Caribbean have a similar landforms and climatic conditions. These conditions are divergent for Caribbean Countries that form part of Central (Belize) and South (Guyana and Suriname) America.
    - Exposure to extreme weather-related disasters such as hurricanes, droughts are historically distinct for this region (The Climate Studies Group Mona UWI, 2020).
    - Rainfall Zones – As described above, the countries included have similar climatic conditions, which are quite distinct when compared to other Caribbean countries. It must also be stated that though the asset being evaluated (embankment dams) was not present in all islands listed, the information can be applicable if future assets are built in these countries. These zones and respective countries (as defined by the *"The State of the Caribbean Climate (2020)"*) are listed below:

Country	Rainfall Zone
Jamaica	3
The Bahamas	3
British Virgin Islands	4
Haiti	4
Anguilla	5
Antigua and Barbuda	5
Barbados	5
Dominica	5

Grenada	5
Montserrat	5
St. Kitts and Nevis	5
St. Lucia	5
St. Vincent and the Grenadines	5
Trinidad and Tobago	5
Cayman Islands	-
Turks and Caicos Islands	-

1.4 Outline of Dissertation

The structure of this dissertation is as follows:

CHAPTER 1 – Introduction – The preceding section; provides the general background and relevance of the study, including the aim, objectives, and scope.

CHAPTER 2 – Literature Review – provides an in-depth literature review on the existing research on the major concepts that define the risk faced by embankment dams worldwide and in the Caribbean.

CHAPTER 3 – Methodology – outlines the methodology applied to conduct the research for this specific project.

CHAPTER 4 – Data Analysis – presents information from the data analysis process; it illustrates the methods applied to the data input and presents the results obtained.

CHAPTER 5 – Discussion – provides a critical discussion of the results obtained, with detailed interpretation of applicability of the results and the limitations of the study.

CHAPTER 6 – Conclusions – presents the major findings of the study

CHAPTER 7 – Scope for future research – presents the major areas that should be investigated in future research.

2 Literature Review

2.1 Overview of section

The topic of the research paper - 'Assessing risks to embankment dams in the Caribbean region from climate change' is a relatively unexplored area, with little research existing that covers all the key themes in a synergistic sense. Therefore, it was necessary to conduct a wide-ranging literature review to establish the connections between all the concepts and the study location in a relevant way.

Key concepts reviewed included risk management of dam structures, structural failure mechanisms of embankment dams, methods of incorporating climate change impacts in previous research, the state climate change projections worldwide and the Caribbean, and the consequences of embankment dam failure. Given the structural engineering background of this MSc degree, the areas focusing on structural performance and integrity were given precedence. The literature review begins with a review of risk analysis procedure, followed by an exposition of the components of risk, with an examination of selected case studies, and concluding with the identified gaps in this research field.

2.2 Risk analysis of Dams

The type of methodology applied to previous research on the risks relating to the effects of climate change on dams varied based on the purpose of the research, the study area or region being assessed, the type and quality of the data set, and the desired outcomes. However, there are several commonalities that exist, particularly as it relates to the quantitative studies conducted on the topic. The quantitative studies typically utilized the general format of the risk analysis methodology to generate the projected risk profile for specific dams. The procedure involves the summation of three major concepts: what can happen (probability of an event or hazard – loads on the system), how likely is it is to happen (failure probability or exposure of system – system response) and what are the consequences or vulnerabilities that exist (casualties, socio-economic, ecological and other losses), represented by the formula shown below (Fluixa-Sanmartin, et al., 2021):

$$\textbf{Risk} = \sum_{e} \boldsymbol{p}(\boldsymbol{f}|\boldsymbol{e}) \times \boldsymbol{p}(\boldsymbol{e}) \times \boldsymbol{C}(\boldsymbol{f}|\boldsymbol{e})$$

$$p(f|e) - Failure\ probability$$

$$p(e) - Probability\ of\ event$$

$$C(f|e) - Failure\ consequences$$

With studies on climate change effects on embankment dams (and dams in general) being relatively nascent, the methodology applied is still in a developmental phase, with a significant number of studies being geared towards qualitative assessments as well. These qualitative studies, such as the research conducted by Hughes and Hunt (2012), cover a wider scope, and utilise an evidence-based approach to categorise risk but, although very instructive, are generally limited to screening analyses (Fluixa-Sanmartin, et al., 2018). As noted in Hughes and Hunt (2012), even though some general conclusions can be made, it is not possible to apply a prescriptive approach to dams on a generic basis due to the widespread differences between and intricacies related to each dam system.

Given its focus on specificity and detail, the quantitative risk analysis approach is preferred by the research community, though there is a substantially larger need for comprehensive data on dam and reservoir basin characteristics. Preponderantly the impact of climate change on dam risk is analysed separately, with most studies focusing on its impact on hydrological loads, while discounting other aspects (Fluixa-Sanmartin, et al., 2018). However, the dam risk models adopted in more recent studies have sought to utilize a more comprehensive approach to addressing the effects of climate change, from input hydrology to the calculation of downstream consequences of flooding (Fluixa-Sanmartin, et al., 2018). A sample flow chart of this approach utilizing the hydrologic scenario is shown in Figure 2-1.

Also, these studies are beginning to incorporate aspects of time-sensitivity, due to variable nature of the climate, and changing conditions such as aging assets, population growth, and migration; components which are also interconnected (Fluixa-Sanmartin, et al., 2019). This approach even extends to end of service life, with researchers Lee & You (2013) proposing a framework to evaluate the risk of dam overtopping due to climate change with a view of determining the optimal time to cease dam operations and possibly remove the infrastructure.

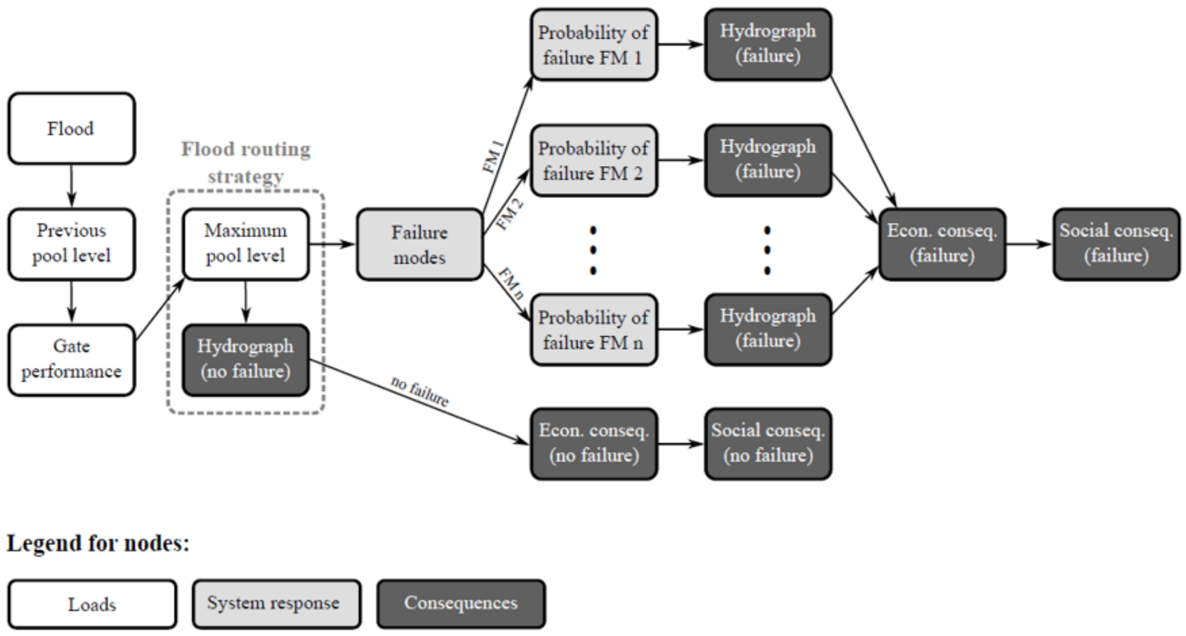


Figure 2-1: Risk model for the hydrologic loading scenario (Fluixa-Sanmartin, et al., 2018)

The metrics most often utilized in these risk analyses to determine the recommended course of action is the probable human casualties and economic impact, with casualties subsumed under the economic criteria in some cases to unify the assessment. An example of this is the use of Adjusted Cost per Statistical Life Saved (ACSLS – applicable to short-term analyses) and Aggregated Adjusted Cost per Statistical Life Saved (AACSLS – applicable to long-term analyses) by Fluixa-Sanmartin, et al. (2020), which calculates the total cost of a statistical life saved across a specific time interval, inclusive of economic, and societal risks paired with risk reduction mitigation. In this case, Fluixa-Sanmartin, et al., (2020) evaluated the changing impact of four mitigation measures over a period of 50 years (2019-2069) for the Santa Teresa Dam measured against the base case – the do-nothing approach. The four measures included the following:

- Measure A - Implementation of Emergency Action Plan (EAP) (Non-structural):
- Measure B – Construction of continuous concrete parapet wall (1.5m high) along dam and auxiliary saddle dam (structural):
- Measure C – Increase spillway capacity by lowering 1.5m its crest level (structural) most effective measure in the long term
- Measure D – Establish better maintenance program for spillway gates:

The assessment established that Measure A proved highly reasonably in the short term (up to 28 years) but was less justifiable as the end of the period, while Measures B and C proved to be the inverse; Measure D represented the least profitable route throughout the entire time period (Fluixa-Sanmartin, et al., 2020). This information is represented by the relative priority listing based on cost in Table 2-1 and graphically in Figure 2-2.

Table 2-1: Resulting AACSLS and ACSLS indicators for the four risk reduction measures (Fluixa-Sanmartin, et al., 2020)

Measure	AACSLS	Priority (Based on AACSLS)	ACSLS	Priority (Based on ACSLS)
A	62.25M€/life	3	160.77M€/life	1
B	27.55M€/life	1	169.47M€/life	2
C	57.32M€/life	2	197.20M€/life	3
D	175.42M€/life	4	1,115.30M€/life	4

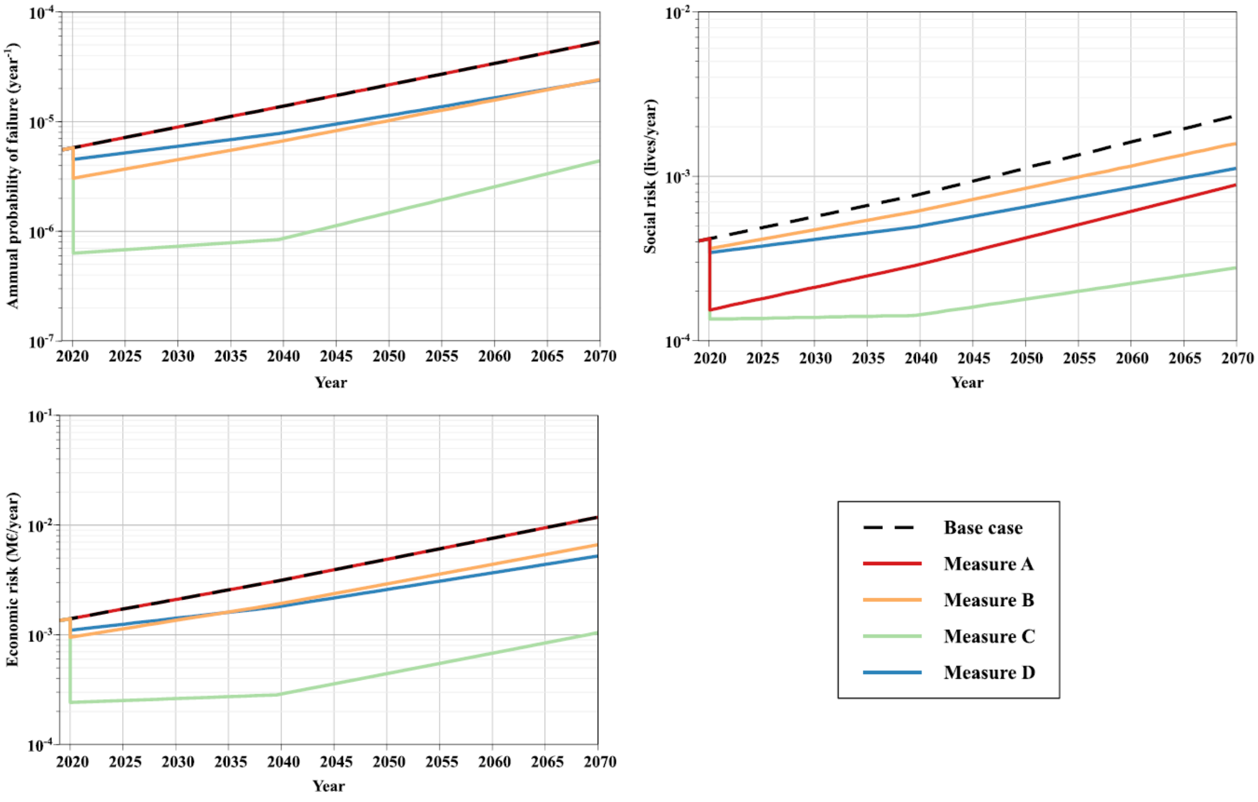


Figure 2-2: Development of failure probability (top-left), social risk (top-right), and economic risk (bottom-left) considering the application of mitigation measure (Fluixa-Sanmartin, et al., 2020).

With the general approach to risk analysis covered above, each component of climate change induced risk on embankment dams is further examined in the preceding sections.

2.3 Failure probability (System response) – p (f |e)

The failure probability corresponds to the different failure modes that the dam may undergo and is highly dependent on the structural characteristics of the dam (Fluixa-Sanmartin, et al., 2018). Therefore, it is essential to understand the engineering mechanisms and construction techniques utilised for each dam system to evaluate the modes of failure that could be affected by climate change. Subsequently, the risk assessment can proceed, with some studies utilizing complex computation finite element analysis (FEA) to capture the engineering behaviour, provided adequate information is available, and other studies utilizing more simplified analysis techniques like Limit Equilibrium Analysis (LEA) for embankment dam structures (Preziosi and Micic 2012).

Another major point garnered from previous research on the topic is the scope of failure being evaluated. In some instances, such as the research conducted by Fluixa-Sanmartin, et al. (2019), failure refers to any event that results in adverse effects on dam performance, inclusive of interruptions to service and possible structural damage. In other cases, like the studies conducted by Tatalovich & Harris (1998), a failure refers to a physical breach of the dam structure that results in a release of the material being stored in the reservoir, while any other event that threatens the structural or performance integrity of the dam is referred to as an accident or incident. Given the second definition is more relevant to structural engineering, this classification was utilized to contextualize the failure mechanisms evaluated in the other reference materials.

Embankment dams, many of which are designed utilizing empiricism, rely on the proportion of the slopes to provide stability, with design prescriptions geared towards preventing rotational slips, erosion, and piping failures (Fell, et al., 2015). These structures are constructed utilizing earth and rockfill as the main constituents, with the use of other materials such as asphalt or concrete as surface protection layers or as the impermeable mid-layer. The cross-sectional view of the various prototypical types is illustrated in Figure 2-3, ranging from simplistic designs that utilize a homogenous soil structure to more intricate construction types such as zoned earthfill and concrete-face rock-fill (CFRD).

Though all classed as embankment dams, each type has a different range of applicability, with design selection being heavily reliant on material available and capital costs.

Notwithstanding, homogeneous dams have generally performed more poorly than the other types of embankment dams. An in-depth statistical study produced by Foster, et al. (2000) revealed that homogeneous dams failed at a much higher rate than other types of embankment dams, with failure due to piping being approximately five times higher than the average of all other dams combined. The causitive factor proposed for this high failure was the lack of adequate seepage control. This is catered for in the other designs by zoning, or free draining material which allows a clear and defined drainage path through the structure (Foster, et al., 2000). Given this defect, the other embankment types have gained more popularity, but homogenous dam construction has continued in many regions internationally.

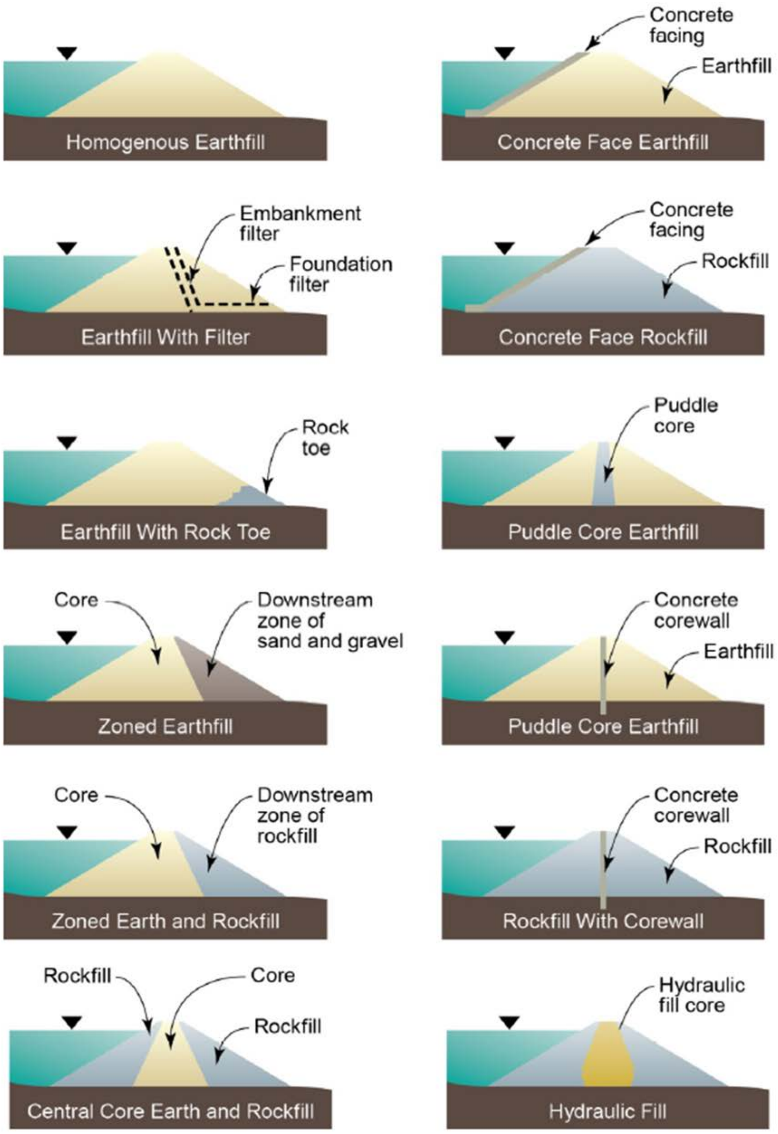


Figure 2-3: Cross-section of different types of Embankment Dams (FEMA, 2013)

Another major design concern is the prevention of overtopping, primarily through the use of outlet release systems, overflow spillways, emergency pumping or a combination of these systems. A typical example of this is shown in Figure 2-4 which illustrates the plan view of the Tooma Embankment Dam in Australia, where the water is transported to the Tooma River whenever the inflow to the reservoir exceeds its capacity limits.

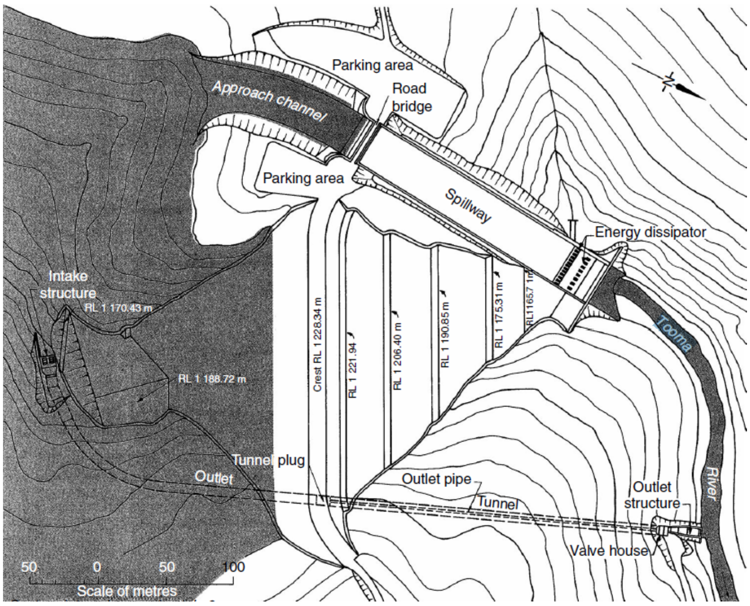


Figure 2-4: Plan view of Typical Embankment Dam utilizing Tooma Embankment (Fell, et al., 2015)

Though overtopping risk is not exclusive to embankment dams, the other major dam type - concrete, is more resilient to structural failure under this design load case. For concrete dams, also referred to as gravity dams, the structure relies primarily on its weight to achieve stability and resist imposed loading, with design prescriptions geared towards preventing more monolithic forms of failure such as overturning, uplift and sliding. Given these fundamental differences, embankment dams are far more susceptible to climatic drivers, mainly due to their vulnerability to erosion.

This is reflected in the case study history as the failure rate of embankment dams is significantly higher than those for concrete dams (Atkins 2013, Kostecki and Banasiak 2021). It was, however, very noteworthy that concrete faced rock fill dams (CFRD) have a very high operational safety in this regard, with very little breaching failure occurring for this embankment type (Zhong, et al., 2021). In fact, two of the detailed case studies for CFRD failures that exist, the 1993 Gouhou dam failure and the 2005 Upper Taum dam failure, have widely been recognized to have several defects in the design and construction, although a hydrological event was the triggering event (Zhong, et al. 2021, Schleiss & Boes, 2011, Rogers, et al. 2010).

Historically, the most common failure modes of embankment dam include overtopping, sliding and piping/internal erosion, with overtopping being the most widespread (Fluixa-Sanmartin, Altarejos-Garcia, et al. 2018, Kostecki and Banasiak 2021). Foster, et al. (2000) estimates that of all the large embankment dam failures worldwide up to 1986 (not including Japan pre-1930 and China), 48% of dam failures are due to Overtopping, 46% attributable to piping or internal erosion, 5% due to structural faults and 1% due to earthquakes (refer to Figure 2-5).

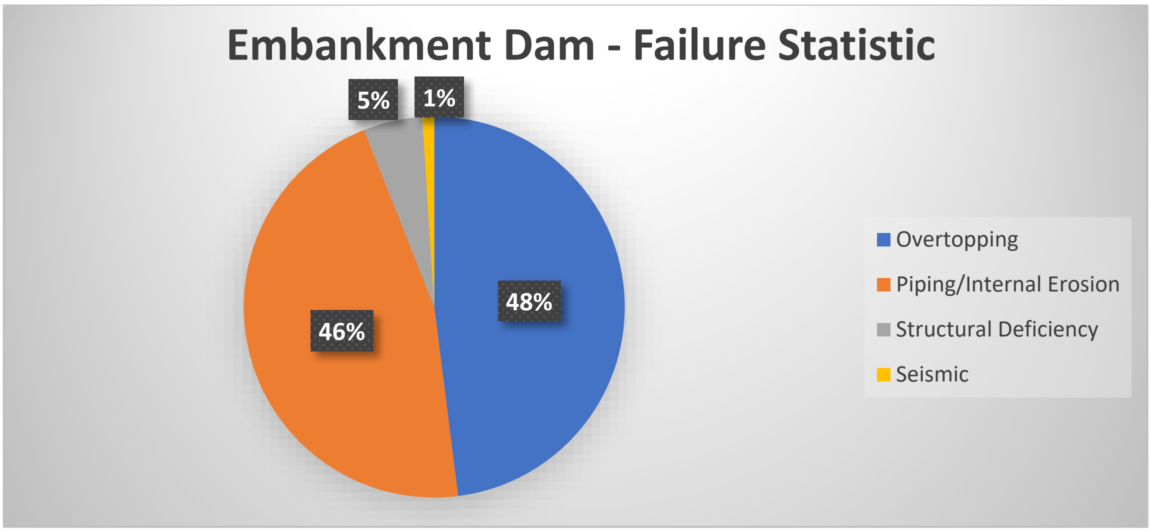


Figure 2-5: Failure statistic for large embankment dams (Foster, et al., 2000)

Though the specific statistics on dam failure vary between different studies, the trend strongly indicates that overtopping and piping/internal erosion are the two major causes of dam failure. Given the overwhelming influence of these modes of failure, further research was conducted on the specifics of each loading scenario and its connection to climate change.

2.3.1 Key Failure Mode 1: Overtopping

Overtopping in the case of dam engineering describes any event where the material being stored in the reservoir overflows the top of the dam structure. This failure mode has several potential triggers, including, but not limited to, significant hydrologic events, human errors, problems with gate performance or other equipment issues. In alignment with the failure criteria outlined previously, overtopping is only considered a failure if it results in significant external surface erosion and breaching of the dam structure. Otherwise, it is referred to as an overtopping incident, inclusive of cases where there could be significant damage to other parts of the dam infrastructure such as the spillway, training walls or other machinery.

Figure 2-6 illustrates the breaching process under the influence of overtopping forces, with part (a) showing the initiation of erosion at the toe of the downward slope, and its continual progression to the upward slope in part (b). This process can continue until an entire section of the embankment 'gives way' or breaks, forming a breached section. Figure 2-7 presents this breaching process utilizing real images captured from a controlled field experiment captured by West, et al. (2018).

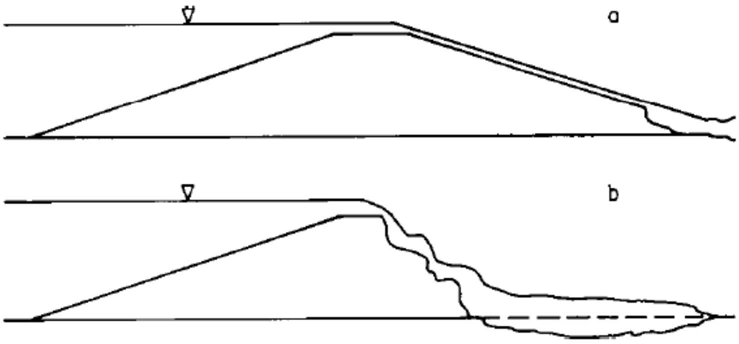


Figure 2-6: Dam Breach Progression due to Overtopping (Wahl, 1998)

Figure 2-7: Overtopping failure breach progression of a cohesive embankment (West, et al., 2018)

It is notably that this type of failure is gradual and does not usually result in a complete or sudden failure, unlike concrete dams, where large monolithic sections fail abruptly (FEMA, 2013). From a risk management standpoint, this can be a potential benefit as the time between observing the first serious defects and breach failure can be used to enact emergency procedures, provide warning, and evacuate personnel.

As previously mentioned, the design component that caters for the overtopping risk is the outlet system that expels excess water when the reservoir is above acceptable levels, with the emergency spillways being the most critical element of this system (Charles, et al., 2011). Traditionally, the approach adopted by dam engineers involves the use of deterministic means to conduct the hydrological analysis of the dam, whereby a design flood hydrograph is obtained and routed through the dam reservoir (Gabriel-Martin, et al., 2017). These design flood conditions are determined based on the relative importance of the dam and the level of risk a breach event can have on the downstream. For instance, in countries like Norway, there are different flood return periods for each class of dams, with Class 2-4 dams required to handle 1,000-year floods, Class 1 – 500-year floods, and Class 0 dams having no specific flood event constraints, only a recommendation of a 200-year flood event.

Some of the assumptions of this analysis include a constant reservoir level prior to flood arrival, typically estimated at the maximum normal operating level (MNL) and presuming a static maximum design event (Gabriel-Martin, et al., 2017). However, climate change studies have highlighted gaps in these design assumptions, primarily as it relates to the variable nature of both the reservoir and the maximum flood event. To assess the impact of climate change on the maximum design flood events, researchers generally utilize two approaches, the use of an extreme precipitation analysis and a flood frequency analysis, with the results of both being compared with each other and check against the historical flood levels (Chernet, et al., 2014).

Chernet, et al. (2014) has found that in the case of many dams in Norway, there will be more frequent and increased precipitation on rapid stream flooding and longer duration riverine and lake flooding, with variations in the timing of peak flows and flood events. Specifically, it is recommended that a 20% increase in the design flood for the 500-year and 1000-year event be introduced to cater for these changes in some dams, like those within the Sogn-og Fjordane County. In some areas of the country, climate projections also indicate that the 100-year flood hazards may become twice as likely, essentially changing to 50-year or less flood hazard (Chernet, et al., 2014).

Though precipitation and flood projections are the major issues covered in most climate studies, emerging research has also investigated the state of the reservoir prior to the arrival of floods. Gabriel-Martin, et al. (2017) evaluated the effect of initial reservoir level and gate performance, utilizing a Monte Carlo framework to capture the stochastic nature of these two factors (refer to Figure 2-8).

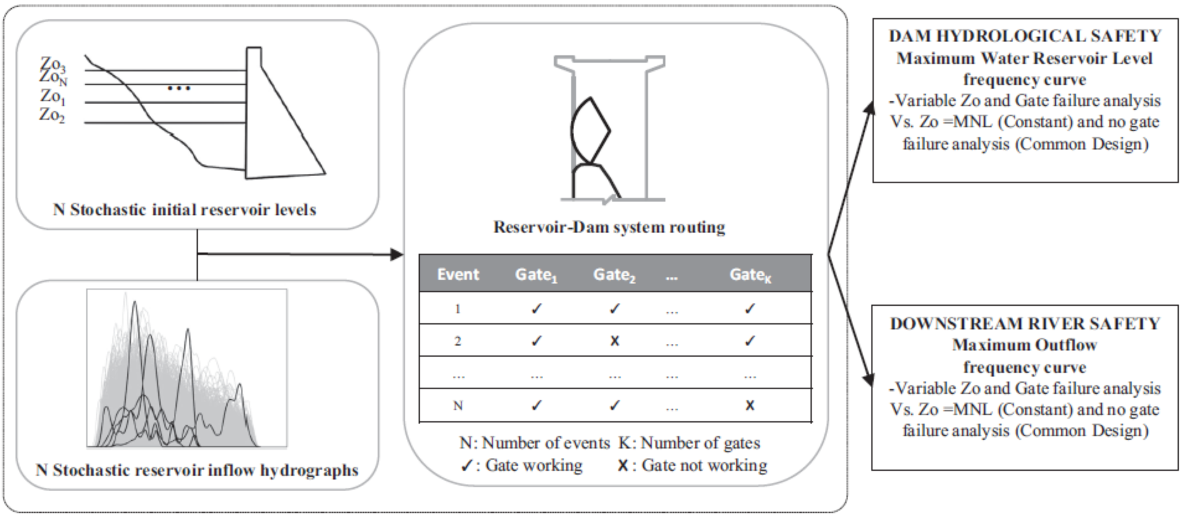


Figure 2-8: Methodology for stochastic model to capture gate performance and variable reservoir level (Gabriel-Martin, et al. 2017)

The general conclusions drawn from the analysis were that accounting for the variable initial levels was critical to dam safety, particularly for irrigation dams, and gate performance was also important, with the higher the return period of maximum water levels resulting in a higher effect of gate performance. Gabriel-Martin, et al. (2017) did note that the analysis was only tested utilizing one case study, Riaño Dam (northern Spain), and that the experiment should be expanded to other systems to validate the results. Atkins (2013), though qualitatively, also highlighted the importance of these factors to dam climate safety, while also adding the importance of monitoring maintenance regimes, sedimentation (which can significantly reduce reservoir capacity), dam settlement and mechanical deterioration.

2.3.2 Key Failure Mode 2: Piping (and Internal Erosion)

Piping and internal erosion are words often utilized interchangeably, but there are subtle differences in the mechanisms behind each. Piping, as described by McCook, (2004), is “the intergranular seepage that occurs through a soil body with no preferential flow paths”, while internal erosion, also defined by McCook, (2004), is “a result of water flowing through defects or cracks within a compacted fill, foundation, or at a contact between a fill and foundation”. Another distinction provided by (FEMA, 2013), and probably a more perspicuous description, is that internal erosion originates internally, while piping originates externally, typically from the downstream face. Albeit, like many other references, the term piping will be used to decribe either type of failure for pratical purposes, as the mechanisms are highly similar under the influence of climatatic drivers.

Figure 2-9 illustrates the progression of a breach mechanism caused by piping, with part (a) showing the initiation of piping at the downstream face of the dam, followed by part (b) the progression towards the upstream face of the dam, with part (c) occuring when the pipe that expanded overtime, allowing larger amounts of water and sediments to be transported to the downstream end, eventaully resulting in significant resevoir reduction and possible breach collapse of the dam. A diagram of internal erosion is not explicitly illustrated as it would result in a similar failure mechnism. Figure 2-10 presents this breaching process utilizing real images captured from a controlled field experiment captured by West, et al. (2018).

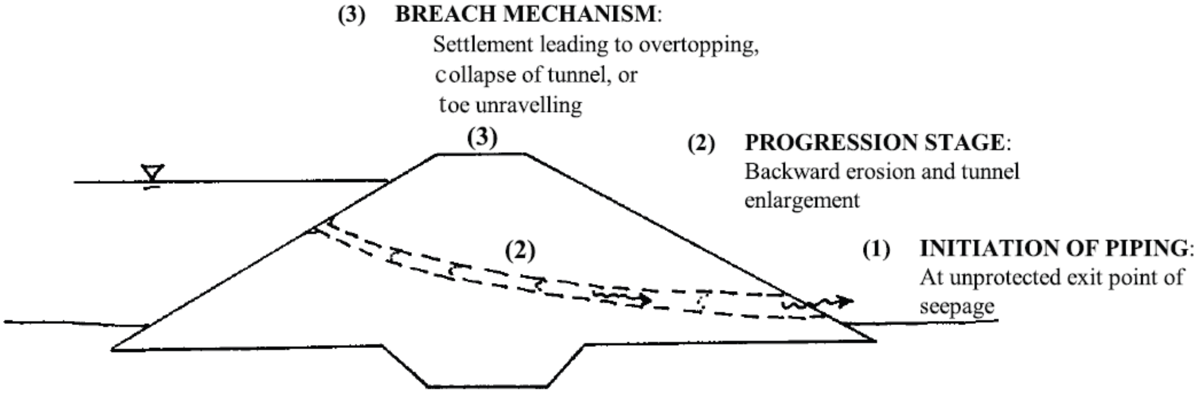


Figure 2-9: Stages of Piping (Foster, et al., 2000)

Figure 2-10: Internal erosion failure and breach progression of an embankment dam (West, et al., 2018)

As previously mentioned, piping is the second highest cause of embankment dam failure, responsible for approximately half of the failures where the mode of failure is known (Fell, et al., 2015). However, what is not immediately obvious, is that approximately two-thirds of all piping failures and half of the incident occur at the first filling or the dam or within the first 5 years of dam operation (Fell, et al., 2015). This demonstrates that, dissimilar to overtopping events, the vast majority of piping failures are not due to extreme weather events such as storms. In fact, Zhong, et al. (2021) points to the fact that it is not necessary for water levels to reach the top of the dam for piping erosion to cause a breach.

Still, the impact of climate change can be seen in more subtle ways, such as alterations in the shear strength and cracking, factors that have a more gradually change over time. In this context, research has focused mainly on the impact of extreme temperature variations, particularly those related to prolonged drought periods. During droughts embankment dams are susceptible to developing dessication cracks due to shrinkage of the soil mass under the influence of evapotranspiration (Khandelwal, 2011). These cracks increase the likelihood of failure under piping and seepage by (Khandelwal, 2011):

1. Providing a preferential path to water flow, thereby inducing high pore-water pressure and,
2. Forms part of the slip surface by significantly reducing the shear strength of the soil matrix (reduced shear strength to negligible levels – essentially zero)

Figure 2-11 illustrates the proposed stages of desiccation cracking, initiated by loss of moisture that induces shear stresses in soil that progress to shrinkage cracks. Figure 2-12 illustrates a real image of the desiccation cracks on the surface of a model embankment dam tested by Khandelwal (2011).

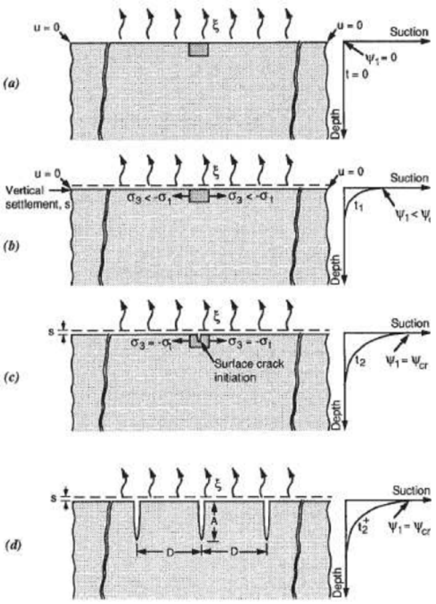


Figure 2-11: Schematic illustration of stages of desiccation cracking (Khandelwal, 2011)

Figure 2-12: Desiccation cracks on a scaled clay embankment after a drying cycle (Khandelwal, 2011)

While climate change projections have indicated that some regions are expecting increased precipitation and a higher number of cool days, many regions, such as the Caribbean, are expecting the inverse (Cole and Cashman 2021, The Climate Studies Group Mona UWI, 2020). Therefore, the drought or dry weather condition is more critical for some countries and region, with this reduction not only affecting the structural integrity of embankment dams but also services such as water utility and energy production (Chernet, et al., 2014).

Unfortunately, the research on drought effects on embankment dam structures is far more limited in comparison to data on flood effects, with very little information on quantitative measurements for its effect on cracking (Atkins , 2013). This has been attributed to some difficulties related to the concept of desiccation cracking in soil, with Khandelwal (2011) listing the following limitations:

1. Absence of a reliable theory to explain the phenomenon of desiccation cracking, formation, and progression,
2. Difficulty in measuring the geometry of the cracks,
3. Lack of numerical tools to simulate the effect of cracks in soil and,
4. Limited understanding on the uncertainty-based determination of the embankment’s integrity

To address some of these limitations, Khandelwal (2011) conducted finite element analyses to numerically capture the impact of water flow through the cracks, which was then validated utilizing a scaled physical model. This study reveal that a 2-D finite element model of the dam can adequately simulate the transient fow of water through the cracks in an unsaturated embankment (model produced in CODE_BRIGHT).

The research by Jalil & Benamar (2021) also sought to quantify the effect of desiccation cracks on soil behaviour, particularly in relation to piping failure. They did this by conducting phyical hole erosion test (HET) on 3 sample taken from 3 separate dam sites in Morocco – Kaudiat El Garn (Lean Clay with sand), Mazer (Fat Clay) and Moulay Boucheta (Fat Clay). A HET involves introducing a controlled seepage through in a preformed cylidrical logitudinal hole or 'pipe' drilled into the soil specimen to measure the erosion kinetics, with the primary aim of evaluating the core soil erodibility at varying hydraulic pressure before and after desiccation.

The results of the experiment revealed that erosion kinetics were low prior to desiccation, but experienced a significant increase after, particularly for the Koudiat El Garn and Mazer dam samples. This was visually evident in the appearance of the test models, illustrated in Figure 2-13, with significant erosion taking place for the the Koudiat El Garn and Mazer dam samples. The sensitivity of this change was quantitatively accounted for in a plot of erosion rate, ε, versus applied shear stress, τ (refer to Figure 2-14 and Figure 2-15).

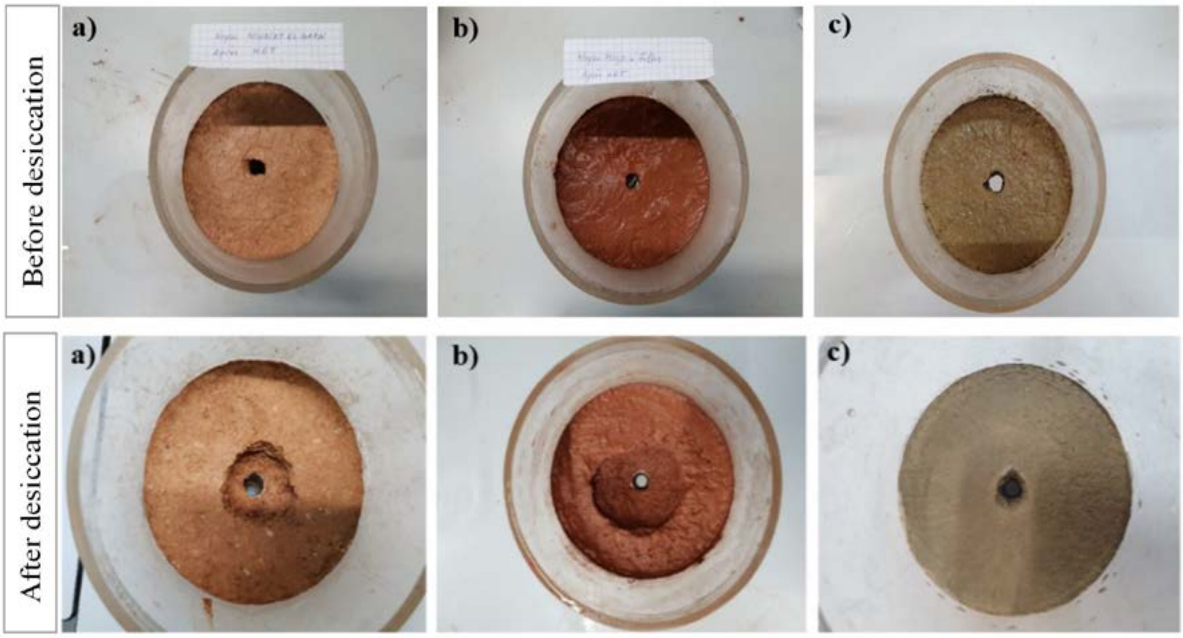


Figure 2-13: Pictures of hole shape at the end of hole erosion test, before and after desiccation from (a) Koudiat El Garn, (b) Mazer and (c) Moulay Boucheta dams (Jalil & Benamar, 2021)

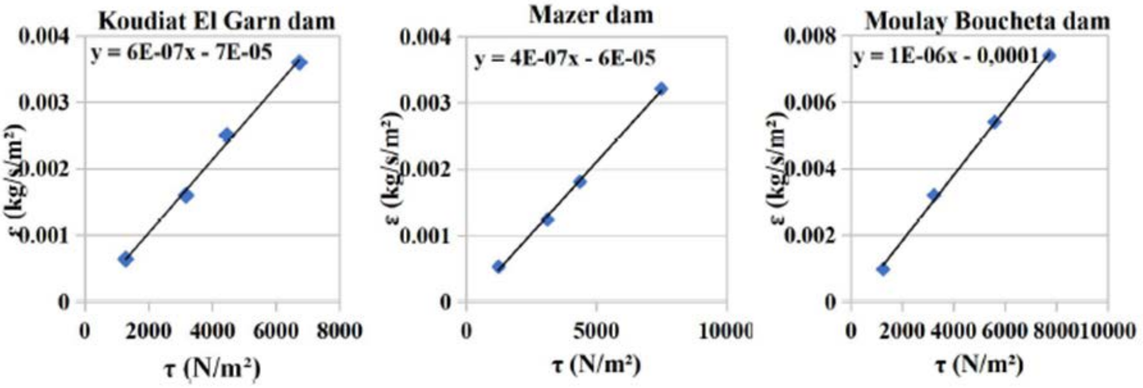


Figure 2-14: Evolution of erosion rate with applied shear stress before desiccation

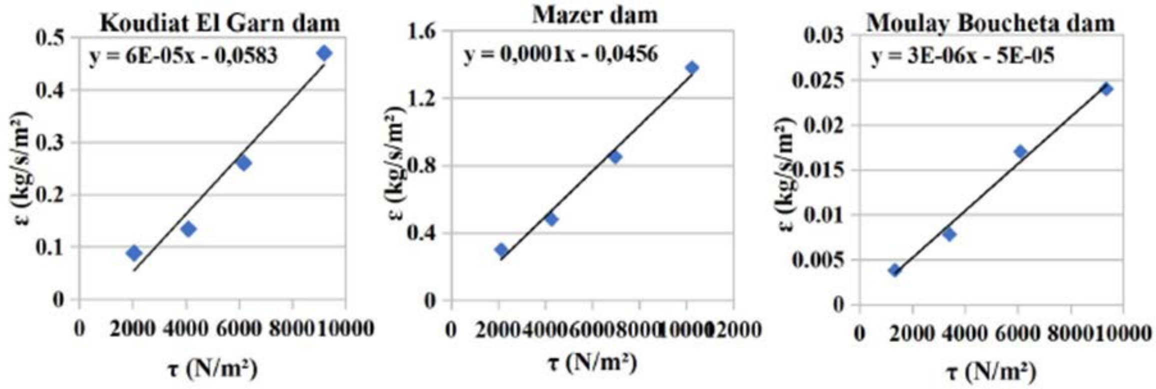


Figure 2-15: Evolution of erosion rate with applied shear stress after desiccation

Though the results of these studies are very important to the growing knowledge base, there still remains several points that require further exploration, such as:

- The effect of desiccation on a macroscale, as the physical models developed are at a much smaller scale compared to real life dams
- The effect of the desiccation cracks in the out-of-plane direction, as most studies only focus on the in-plane behaviour.
- Some soils self-heal and even close when rewet, a process that is very difficult to model (Bottema, et al., 2021).

Although the contribution of droughts on desiccation crack development is evident, only a minute number of dams and levee failures have been directly attributed to these effects, such as the 2005 Wilnis dike failure (Netherlands) (Bottema, et al., 2021). Emerging research has begun to consider these drought effects, especially considering its' potential to increase the embankment's vulnerability to other failure modes such as rotational and shallow slides, erosion by overtopping, and piping (Bottema, et al., 2021).

2.3.3 Cascading events

One of major observations revealed through the literature is the importance of cascading or combined effects of droughts and precipitation. The combination of these two events can result in very detrimental effects like failure when they occur within a short time of each other, even if the magnitude of the component events is smaller than a major singular event (Mortezaei, et al., 2019). This phenomenon works whereby drought conditions effectively weaken the soil structure, through mechanisms such as desiccation cracks, and then the high rainfall or flood conditions produce large hydrological loads in a short space of time, essentially producing shock loading and resulting in catastrophic failure in many cases (Mortezaei, et al., 2019). Figure 2-16 illustrates how these cascading effects can couple to collectively reduce the structural integrity of dam and levee structures.

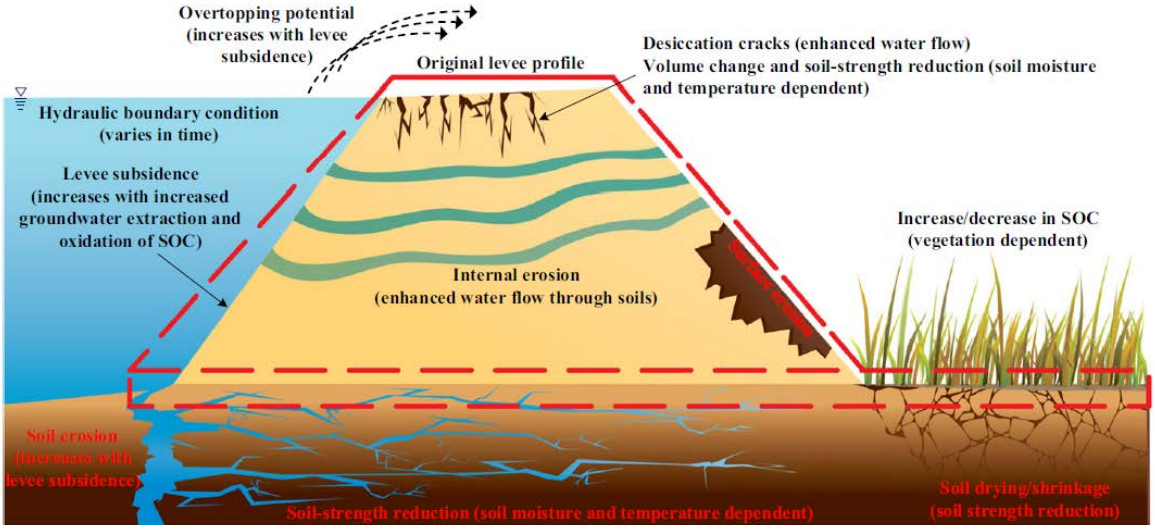


Figure 2-16: Conceptual model of coupling effect of cascading events mechanisms imposed on dams and levees (Robinson & Vahedifard, 2016)

Mortezaei, et al. (2019) identified the Oroville Dam incident in 2017 as one such event, where a drought period was superimposed with an extreme hydrological flood event, resulting in the failure of several earthen structures and significant damage to the spillway. The Wilnis dike failure of 2005 is also noted as being caused by this cascading effect, as the embankment has the reduced density and increased infiltration, resulting in a sudden failure when the heavy rainfall occurred (Bottema, et al., 2021).

Research on the topic has typically separated these events, but climate change studies increasingly project that both other these events will occur with closer proximity as time progresses, increasing the risks faced by these structures (Robinson & Vahedifard 2016, Mortezaei, et al. 2019, Bottema, et al. 2021). Researchers have noted that there are significant challenges to implementing this type of analysis as information on drought effects are still being developed and the problem involves very long- and multiple-time scales (Mortezaei, et al. 2019).

This becomes even more complicated for dams that may have conflicting performance requirements, such as drought protection and flood prevention. For example, the 2018 drought experienced by India after the Kerala floods was worsened due to the reservoirs being drawn down in anticipation for floods (Ward, et al., 2020). Though this represents a performance type failure, its impact on the overall dam risk resulted in significant detrimental effects on the nation.

2.4 Probability of an event (System loading) – p (e)

The probability of an event in this context covers the loading criteria that the dam will undergo. This is mainly focused on the upstream characteristics of the dam, with the major loading being imposed by the hydraulic force produced by incoming floods (Fluixa-Sanmartin, Altarejos-Garcia, et al. 2018). This component is highly dependent on the hydrology of the river basin, which is itself controlled by factors such as the precipitation regime, temperature variations, soil saturation and snowmelt (Fluixa-Sanmartin, Escuder-Bueno, et al. 2021).

For this aspect, most of the research relied on the use of probabilistic climate models as opposed to deterministic models. Given the inherent variability that exists in climate predictions, probabilistic models are implemented as they can capture the natural uncertainties presented by these ever-evolving climate scenarios (Fluixa-Sanmartin, Escuder-Bueno, et al. 2021). It is however noted by Preziosi and Micic 2012, that some aspects of the design, such as snowfall rate, latent heat flux, wind speed and soil moisture, cannot be estimated by probabilistic models, with deterministic properties being utilized for these components.

These probabilistic climate models are typically based on either the use of either Global Circulation Models (GCMs), which provide climate projection data on the global scale or Regional Climate models (RCMs), which provide climate projection data on a smaller regional scale (The Climate Studies Group Mona UWI, 2020). In cases where the spatial resolution of the data for the GCM is too low for some regions, statistical downscaling techniques are utilized, with Regional Climate Models (RCMs) incorporated to downscale large scale weather based on the observed local-scale weather within the study region in some cases (Chernet MSc., Alfredsen and Midttomme 2014).

As it relates to the Caribbean, statistically downscaled GCM data is utilized to define the climate projections for the region on a whole, with these models being the primary schemes whereby projections relating extreme events of short duration, such as hurricanes and storms are defined (The Climate Studies Group Mona UWI, 2020). These models use the Representative Concentration Pathway (RCP) scenarios as adopted by the IPCC, which represent the aggregate measure of human induced greenhouse gas emissions and range from +2.6 to +8.5 W/m^2 (The Climate Studies Group Mona UWI, 2020).

The RCM data, however, is utilized to define the climatic variations in the rainfall groups within the Caribbean, whereby the projections in relation to long-term climatic conditions such as daily rainfall and temperature are defined at a smaller scale (The Climate Studies Group Mona UWI, 2020). These models use the Special Report on Emissions Scenarios (SRES), specifically the A1B (thought to be the most probable case), which represent future greenhouse gas emissions based on several accumulated assumptions relating to population increase, energy use and other factors (The Climate Studies Group Mona UWI, 2020).

A key point identified by The Climate Studies Group Mona UWI (2020) is that the overall trend revealed by these two approaches is the same – an overall drier Caribbean, with increased intensity for extreme rainfall events such as hurricanes and storms through to the end of the 21st century (Year ending in 2100). In fact, both models results in near identical projections under the SRES A1B scenario and the RCP 8.5 scenario for the time scales between 2020 through to 2060 and then RCP 6.0 through to 2060 to 2100). A graphic representing the carbon emission and carbon dioxide present in the atmosphere for each model type is illustrated in Figure 2-17.

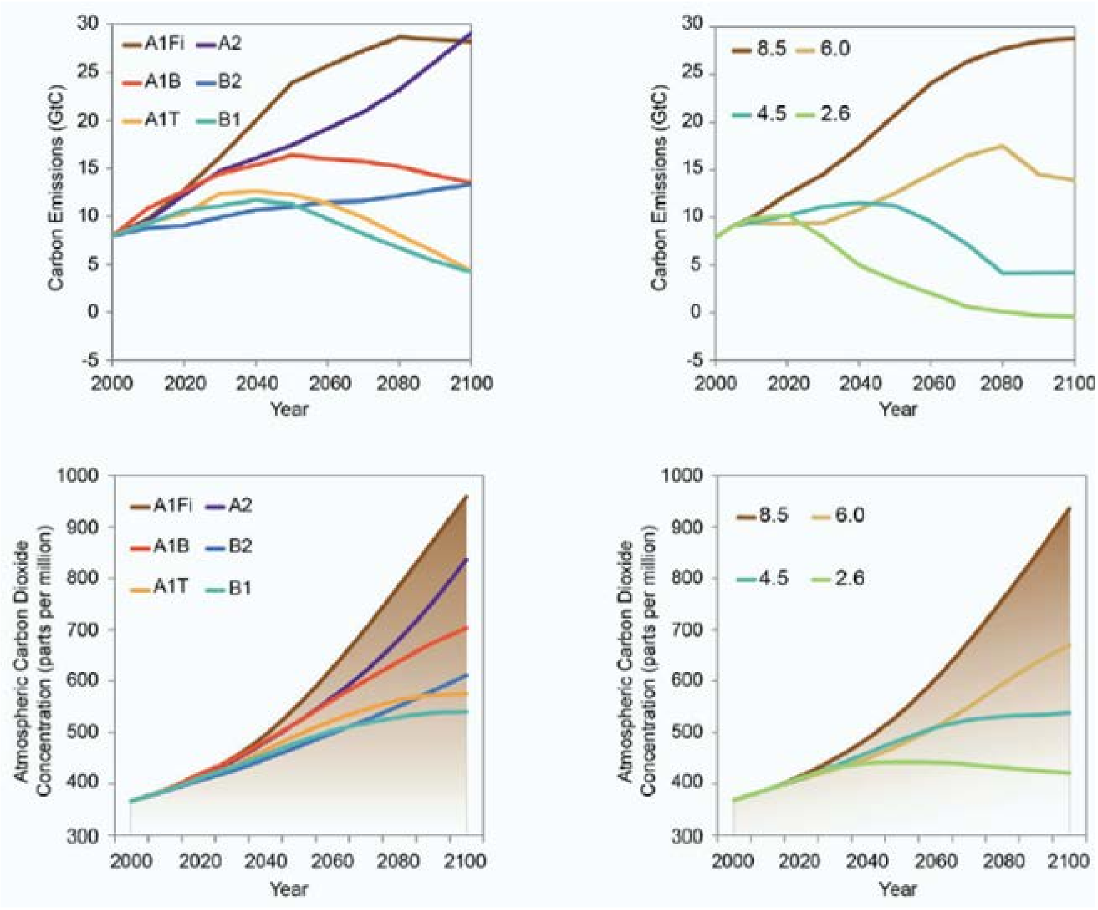
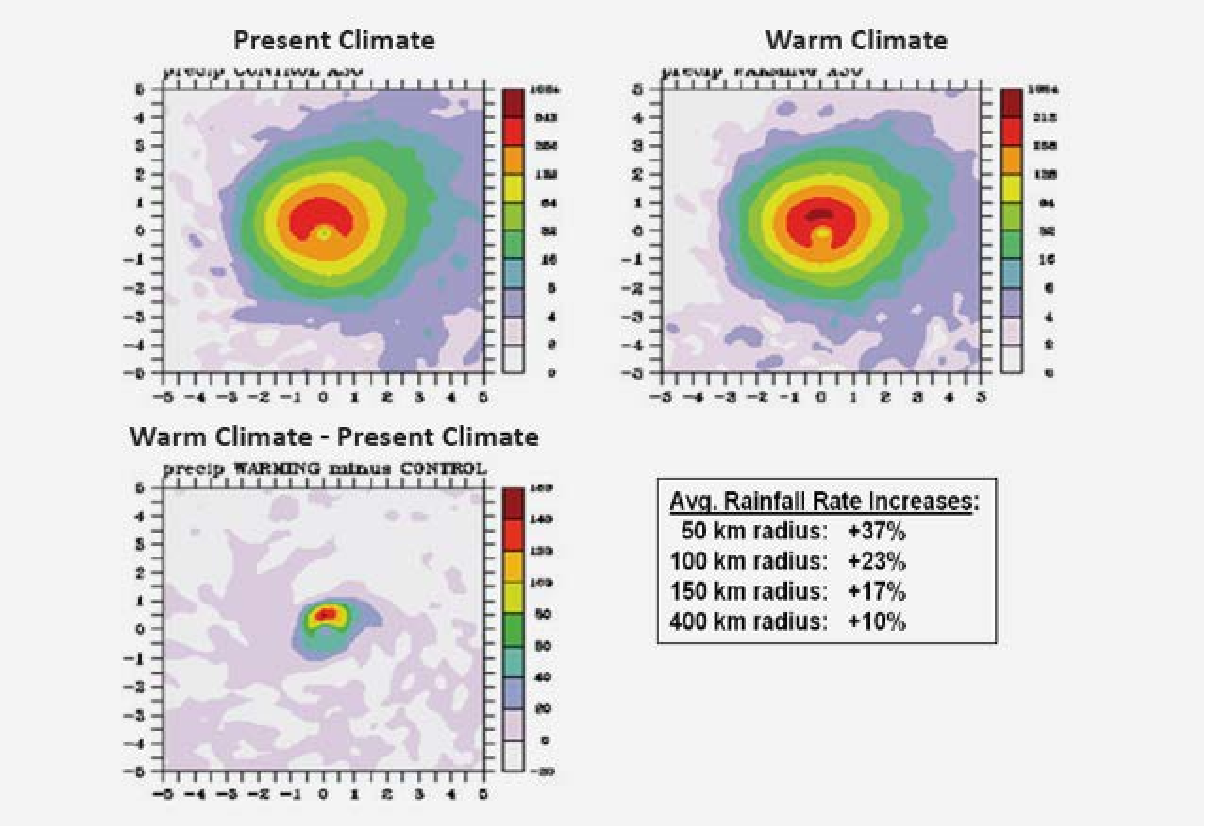


Figure 2-17: Comparison between the two types of scenario systems utilizing (i) annual carbon emissions and (ii) carbon dioxide equivalet levels in the air (The Climate Studies Group Mona UWI, 2020)

Specific relating to the projections reported by The Climate Studies Group Mona UWI (2020) are (measured against the 1986-2005 baseline):

- The region will be expected to undergo more droughts in the future. This is because of a reduction of approximately 20% for annual rainfall across the region according to the GCM and 25 to 35 % according to the RCM. There will also be a mean increase of 0.83 – 3.05^{o}C by 2100 for all scenarios in the GCM and an increase in warm days of 51 - 251 days and warm nights of 24 – 360 nights under RCP 8.5
- There is low confidence in the predictive schemes of the models relating to hurricane and storm systems, with no established consensus on the change in frequency of event occurrence hurricane and storm frequency. This is because hurricane intensity is also affected by many other climatic conditions in the Caribbean region such as (i) El Niño-Southern Oscillation phenomenon (ii) African Easterly Waves which cross the Atlantic Ocean during June – October and account for half of all Atlantic hurricanes

(iii) Weak easternly trade winds (iv) High Sea Surface Temperatures (>26^{o}C) and (iv) low vertical wind shear. However, there is agreement that the impact of climate change could cause increased rainfall intensity could ranging from anywhere between 10 – 30%, depending on the location proximity to the centre of the storm (refer to image Figure 2-18).



Present Climate

Warm Climate

Warm Climate - Present Climate

Avg. Rainfall Rate Increases:
50 km radius: +37%
100 km radius: +23%
150 km radius: +17%
400 km radius: +10%

Figure 2-18: Rainfall intensity under simulated extreme event scenario (bottom graphic depicts future climate minus present) (The Climate Studies Group Mona UWI, 2020)

The rainfall intensity corresponding to extreme events such as storms is obtained via the use of intensity-duration-frequency (IDF) curves, which represent the rainfall intensity that is expected within a catchment based on select return period (Lumbroso, et al., 2011). As it relates to the Caribbean, Lumbroso, et al. (2011) has highlighted that many of the existing curves are inaccurate due to limited data availablity relating to short duration rainfall and the curves created for the islands are largely unavailble in the public domain. This has resulted in undersized hydraulic designs by some engineers that rely on designs for countries that have lower rainfall intensities (Lumbroso, et al., 2011).

2.5 Failure Consequence C(f|e)

This aspect of the risk evaluation is an estimation of the consequences arising from all the significant failure models, including the dam break modelling (Fluixa-Sanmartin, Altarejos-Garcia, et al. 2018). Previous research on this topic typically segregates this aspect under two major themes: Outflow hydrographs and Socio-economic consequences.

The outflow hydrograph captures the flow characteristics downstream and is evaluated under both dam non-failure and failure criteria, given climate change impacts are considered similar under both scenarios (Fluixa-Sanmartin, Altarejos-Garcia, et al. 2018). This is then used to define two major components of downstream hydrology: estimation of reservoir outflow hydrograph, which relates to the maximum water level in the reservoir and peak discharge, and the routing of the water, related to inundation maps for downstream zones (Fluixa-Sanmartin, Altarejos-Garcia, et al. 2018).

The socio-economic consequences evaluate the calculation of direct and indirect damage caused by a failure of the dam. This aspect is dependent on a combination of the exposure category and the vulnerability of the people, infrastructure and social systems impacted by the dam failure (Fluixa-Sanmartin, Altarejos-Garcia, et al. 2018). In additional to human casualties, other important impacts typically included in the consequence evaluation are geomorphic changes, plant biomass loss, biodiversity loss and water pollution (illustrated in Figure 2-19) (Zhang, et al., 2022).

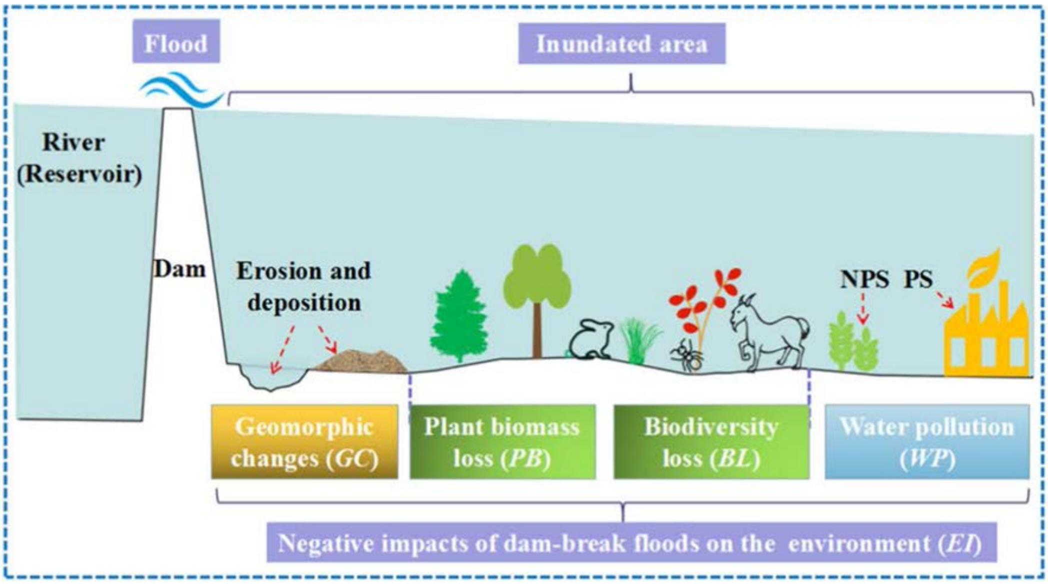


Figure 2-19: Illustration of some consequences of dam breach (Zhang, et al., 2022)

A key point extracted from the literature indicates that the losses predicted under long-term scenarios will be more dependent on increasing exposure of people and economic asset due to population and economic growth rather than climate change (Fluixa-Sanmartin, Altarejos-Garcia, et al. 2018, Fluixa-Sanmartin, Morales-Torres, et al. 2019). This also includes areas outside of the inundation area, as dam failure can have far-reaching consequences to persons that utilize the services provided by the dam, such as utility, electricity, and recreation (Atkins 2013, Fluixa-Sanmartin, Altarejos-Garcia, et al. 2018).

In cases where the assets below downstream are quantifiable, it may be possible to connect the economic loss to the peak outflow value, both for present and future scenarios (Fluixa-Sanmartin, Altarejos-Garcia, et al. 2018). Figure 2-20 illustrates one such plot illustrating this type of discharge-consequence curve.

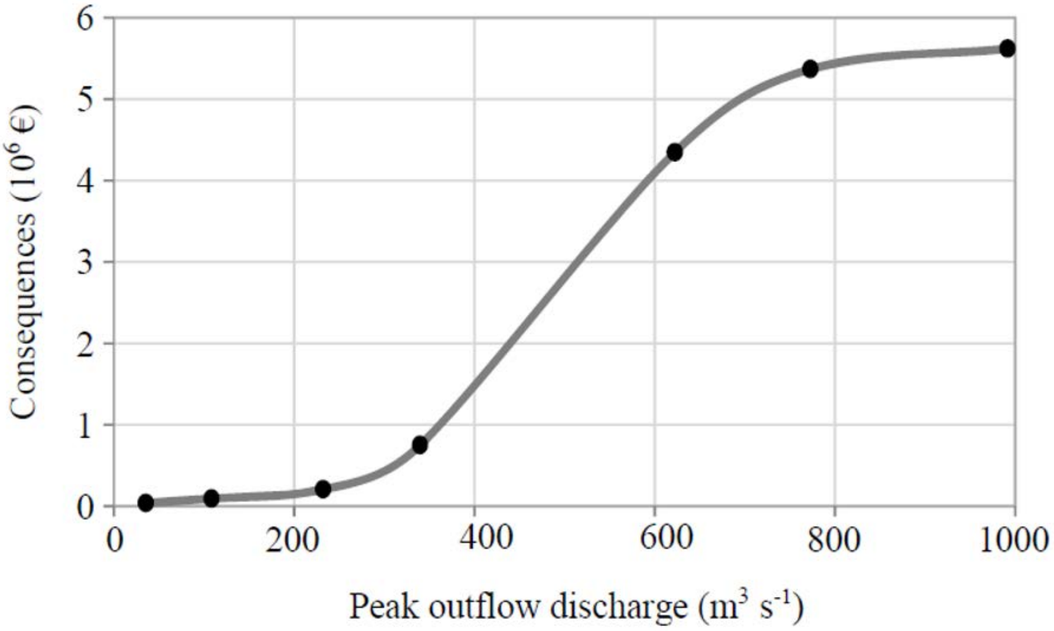


Figure 2-20: Sample discharge-consequence graph

2.6 Specific Case Studies (Recent Examples)

This section of the literature review captures some relatively recent dam incidents under hydrological flood loads to examine how climate change may have impacted these cases. It was important to review these case studies, as they provide a real-life scenario of dam performance. The case studies explored the major cause of failure at the Niedow Dam (breach occurred in 2010), Oroville Dam (incident occurred in 2017) and the Toddbrook Dam (incident occurred in 2019). As this section will be focusing on the structural failure mechanisms, consequences of dam failure on downstream zones were not captured.

Niedow Dam (August 7, 2010)

The dam structure suffered a breach after water levels exceeded the gate level of the hydroelectric station, inundating the power room. This prevented the on-site team from controlling the water release gates in the facility. This resulted in the overtopping of the dam crest, which was followed by embankment erosion. The concrete slabs and road above the embankment then collapsed due to the scour of the underlying support embankments. Other sections of the dam structure, such as the left training wall, collapsed after being subjected to increased hydraulic pressure (Kostecki & Banasiak, 2021)..

Prior to this incident the dam was monitored regularly and was stated to be in stable and good condition. The major causative factor in this scenario was due to catastrophic flooding, which correlated to an event with a return period of between 100-200 years. (Kostecki & Banasiak, 2021). Figure 2-21 illustrates the breached section of the dam.

Figure 2-21: Niedow Dam Breach Failure (Kostecki & Banasiak, 2021)

Oroville Dam (February 7-11, 2017)

The proposed failure mechanism of the main service spillway was caused by water injection through both cracks and joint in the chute slab during the flood event of February 7, 2017. This resulted in significant uplift forces beneath the slab that exceeded the structural capacity and caused a localized failure in the spillway. The failures in the emergency spillway (noted as being untested before this event) were due to poor ground conditions due to presence of highly erodible soil (Oroville Dam Spillway Incident Independent Forensic Team (IFT) 2018).

A peculiar aspect of this incident is that the failure occurred during a flood scenario which was within the prescribed design and operational limits of the structure (Koskinas, et al. 2019). The major causative factor in this failure event was noted as being due to inadequacies and defects in the structural system and dam management as opposed to loading caused by climate change, though the impact of cascading events may have played a significant role as well (Oroville Dam Spillway Incident Independent Forensic Team (IFT) 2018, Cole & Cashman, 2021). Figure 2-22 illustrates the damage to spillway and some of the earthen side slopes.

Figure 2-22: Oroville dam spillway damage (Oroville Dam Spillway Incident Independent Forensic Team (IFT), 2018)

Toddbrook Dam (August 1, 2019)

Like the spillway failure of Oroville 2017, a localized collapse of the slabs in Toddbrook embankment took place. The mechanism involved water penetrating through cracks within the slab, removing the underlying fill while simultaneous inducing uplift forces on the spillway slabs (Balmforth, 2020). This mechanism caused the collapse of a singular slab section and then progressed as more fill was removed, resulting in multiple other slabs collapsing into the void space left by the eroded fill material.

A major point noted in the report conducted by Balmforth (2020), that the dam had survived events with larger hydraulic loads. This reveals that the defects in the structure were the major causive factor in this particular collapse. Figure 2-23 illustrates the damaged section of the dam spillway.

Figure 2-23: Toddbrook dam spillway damage (Balmforth, 2020)

These case studies provide further evidence to corroborate the view shared across much of the literature that vulnerability of a dam to climate change is a combination of event loading intensity and dam structural adequacy and management (Hughes & Hunt 2012, Atkins 2013, Oroville Dam Spillway Incident Independent Forensic Team (IFT) 2018, Cole & Cashman, 2021).

2.7 Summary and Major Gaps

There exists a wealth of knowledge on the risk analysis of climate change effects on embankment dam worldwide, particularly in relation to new research. Some of the major points identified are:

- Embankment dams are more susceptible to climate change effects than concrete dam types, with homogeneous dams being the most vulnerable while other more intricate design such as CFRD dams being highly resistant to climate drivers (Zhong, et al., 2021).
- Climate change impacts are felt primarily in embankment dams due to erosion, either in the form of external erosion due to overtopping or internal erosion due to piping (Fluixa-Sanmartin, Altarejos-Garcia, et al. 2018, Kostecki and Banasiak 2021).
- For risk assessments to be relevant they must incorporate the variable nature of the climate and dam systems for the future (Fluixa-Sanmartin, Altarejos-Garcia, et al. 2018, Fluixa-Sanmartin, et al. 2019).
- Climate change impact is the summation of the event intensity and the management and monitoring systems utilized for the dam, as opposed to only the event (Hughes & Hunt 2012, Atkins 2013, Oroville Dam Spillway Incident Independent Forensic Team (IFT) 2018, Cole & Cashman, 2021).

Notwithstanding these and other important concepts, there still exist several major gaps that need to be addressed in future research:

- Scarcity of research data in some regions such as the Caribbean and other developing states, particularly in terms of specific climate projections relating to extreme events (The Climate Studies Group Mona UWI 2020, Cole and Cashman 2021).
- Scarcity of detailed information on the embankment dams in the Caribbean, revealed from the lack of information obtained during the desk study.
- Issue with the accuracy and availability of rainfall IDF curves for the Caribbean region (Lumbroso, et al., 2011).

- Issues with downscaling climate models: most techniques employed in this field reproduce mean of the climate signal, leading to underestimation of triggering precipitation in some cases (Fluixa-Sanmartin, Altarejos-Garcia, et al. 2018).
- Lack of information on drought effects – this may be the critical case in some regions as opposed to increased flood loading (Atkins 2013, Cole and Cashman 2021).
- Many response mechanisms are based on static assumptions, whereas climate change is dynamic (Fluixa-Sanmartin, Altarejos-Garcia, et al. 2018).

3 Methodology

3.1 Overview of section

This section of the dissertation provides a description and justification of the data analysis process that was applied in this research project. and includes justification of the methods selected and details about the type of data analysed, sources of data, procedure involved in the analysis and limitations experienced. The key purpose of this segment is to enable the reader to understand the logical processes behind the development of the ensuing conclusions and to demonstrate that best practice was followed to produce the results of the analysis. The methodology begins with a background of the type of data analysis selected, followed by the type and source of data, method steps and software utilized.

3.2 Type of data analysis

The type of analysis selected for this research was an embankment dam fragility analysis based on utilising the historical failure and incident information from embankment dam case histories. This analysis involved gathering several case studies of similar embankment dam structures that underwent the similar loading scenarios of varying intensities, in this case overtopping due to a high rainfall event. The outcome of dams experiencing this event is evaluated utilizing a binomial distribution, in that case either failure or non-failure. The failure vs. intensity is then plotted with the fragility curve being developed by utilizing a logistic regression, whereby the probability of a specific type of embankment dam failing by overtopping can be checked based on the intensity of the rainfall experienced during the storm.

Figure 3-1 shows a generic representation of the type of fragility curve developed after this type of analysis, with the y-axis showing the probability of failure and the x-axis showing the intensity measure; it must also be noted that the probability can never be higher than 1 or lower than 0 (Analytics Vidhya, 2020). This fragility analysis is also a simplified representation of the risk formulation, with the intensity measure representing the event probability (hazard), the embankment dam structure representing the failure probability (exposure) and the dam breach failure being the consequence.

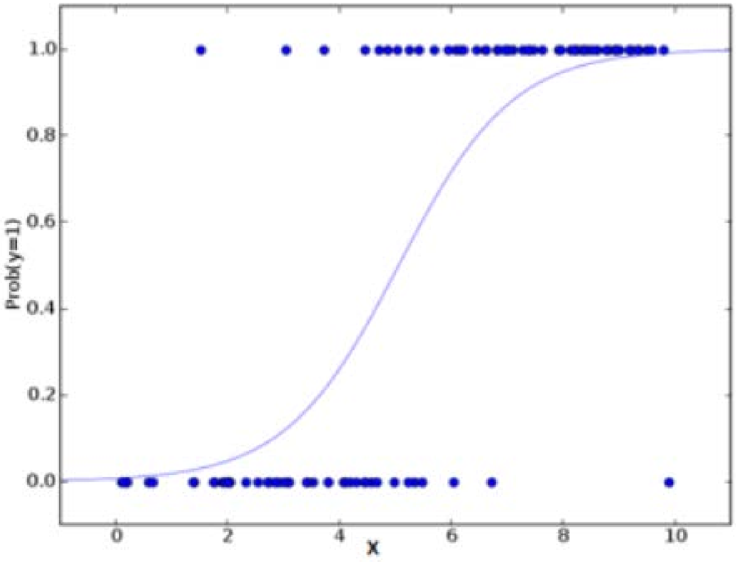


Figure 3-1: Generic fragility curve (Analytics Vidhya, 2020)

This type of analysis utilizes a correlation function to reveal the trend between the historical failures of a particular mode, erosion via overtopping for embankment dams, and event strength and duration, rainfall intensity during storms or flood events. The justification for this type of analysis is the fact that the causative relation between dam breaching events and erosion via overtopping is strongly established in the literature, with the primary cause of overtopping being due to rainfall intensity during storm events.

Given the focus on historical case studies, it was necessary to collect accurate information about the dam characteristics and event intensities. The proceeding section details this data collection and processing process.

3.3 Type and Sources of Data

The key data required includes (i) previous case study information about dam structural performance under the overtopping scenario (ii) rainfall data for the overtopping events (iii) information about Caribbean dams (iv) rainfall data and projections for Caribbean countries being investigated. Though a brief description of the primary and secondary sources is provided below, a full list of the information sources is provided in the reference section of the document.

3.3.1 Case Study Information

The case study information includes data about the dam characteristics, location, incident or failure mechanism, date of incident/failure, tributary information and other pertinent details relating to the dam and event. The chief data source utilized to gather this information was the Association of State Dame Safety Official (ASDSO) database (spreadsheet made available online via the https://damsafety.org/incidents). This source provided mainly information relating to the USA and was a highly comprehensive listing for most of the case studies. Nonetheless, further case study information was gathered, verified, and updated using several other sources that included other online data bases, research articles, newspaper reports, dam safety reports, state agency websites and technical reports. A full list of the information sources is provided in the reference section of the document.

It must be noted that there was a significant lack of information relating to the specific details of the embankment dam type such as the material properties of the fill and design consideration such as zoning. Therefore, the key similarity identified between the dams being that they were all earthen embankment structures.

3.3.2 Historical Weather Data

The historical weather data is specifically a collection of data on the rainfall accumulation and event duration relating to the dam incidents in the case studies. This information was collected based on the date provided for the dam incident occurrence and reports rain gauge information over the specified event period. Given most of the data points are in the USA, the key source of the data was the American National Weather Service via the government website (https://www.weather.gov/). This allowed the researcher to selected rain gauge stations with the closest proximity to the affected structures. The process of data selection via this website is illustrated in Figure 3-2

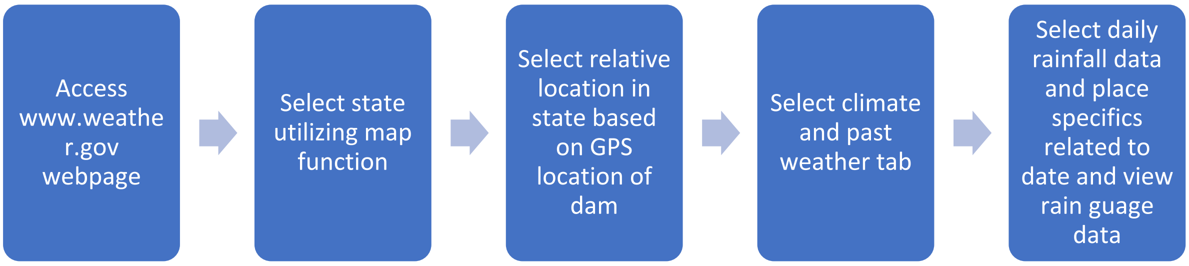


Figure 3-2: Steps required to view rainfall data via www.weather.gov

In cases where the weather information was unavailable on this website, due to the dated nature of the incident or location being outside of the USA, the researcher utilized information from newspaper articles, research articles and dam safety reports.

3.3.3 Caribbean dam data

The Caribbean dam database created for this study included data such as the name of the structure, location, dam characteristics, construction type, performance history and the current operational status. The chief data source utilized to gather this information was the Caribbean and Central American dam database produced by the Food and Agriculture Organization of the United Nations (FAO) AQUASTAT online webpage (https://www.fao.org/aquastat/en/databases/dams).

Multiple correspondences were also written to the governmental water agencies and authorities in the selected countries identified in the scope to help validate and improve on the data in this listing. However, data was only provided by the Dominica Water and Sewerage Company Limited (DOWASCO) for the island of island of Dominica. Though instructive, this information only contains information about intake structures, which is outside the scope of this research and implicitly confirms that the island of Dominica does not have any major embankment dam structures. To validate and improve the information in the spreadsheet provided by the FAO AQUASTAT database, the researcher utilized information from newspaper articles, research articles, and technical reports. Albeit the researcher was still unable to gather full information for some of the dam structures due to lack of data being available.

3.3.4 Caribbean climate data and projections)

The data utilised for this research contains rainfall intensity values based on the historical trends in the Caribbean and the projected values through the end of century. Given the rainfall data required for design can vary based on the specific design objectives set by different jurisdictions, a range of design return periods were selected for evaluation (covered in more depth under the proceeding data analysis section). This information was gathered from a few different sources as a unified source was not established by the researcher. The country specific data retrieved, and primary source is described below. This information was gathered for Antigua and Barbuda, Jamaica, and Trinidad and Tobago (the only Caribbean countries that fell under the scope of the assessment that had embankment dam assets):

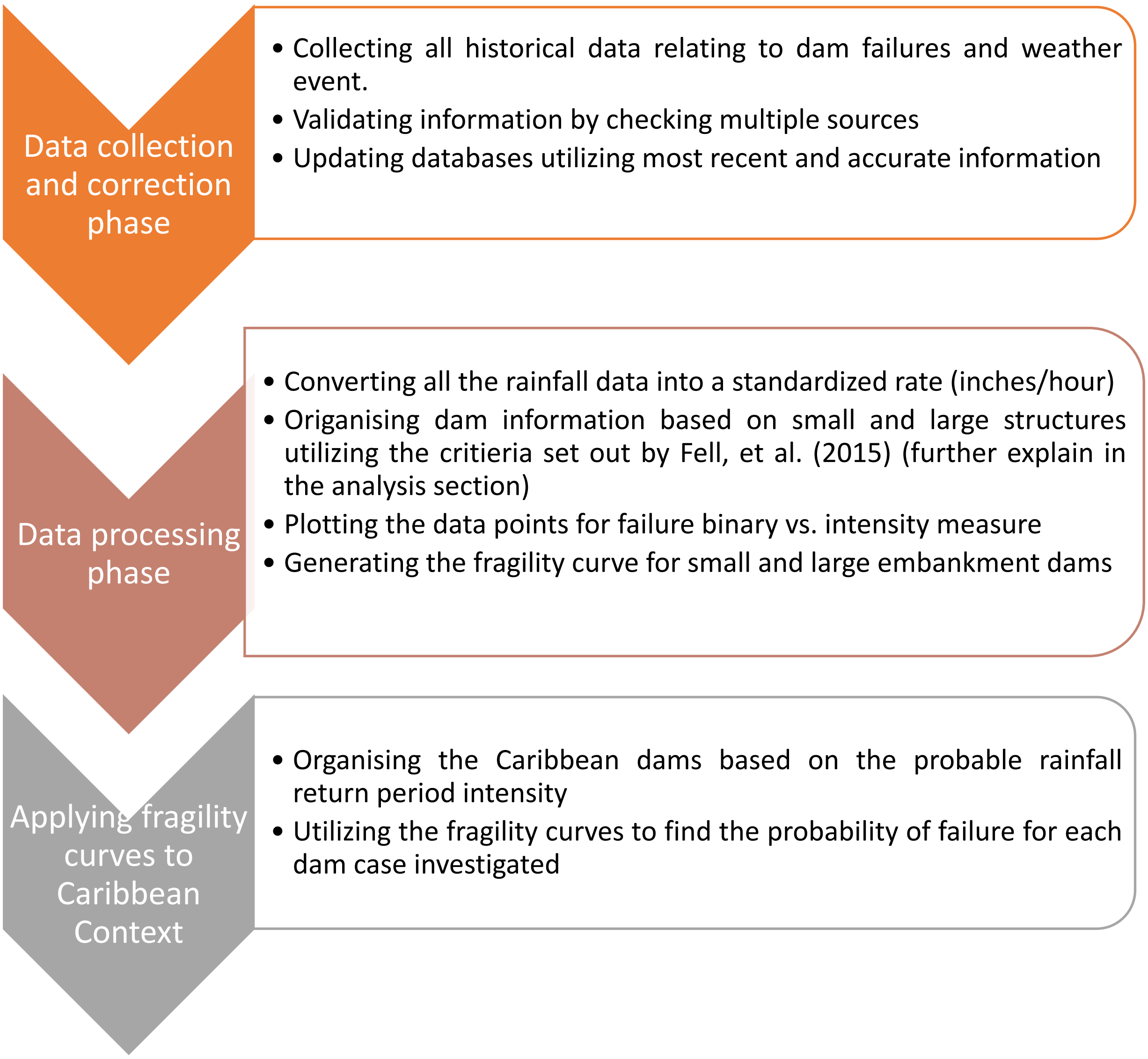
Antigua and Barbuda – Technical Assistance for Flood Management and Slope Stabilization Interventions in Antigua and Barbuda (Cashew Hill): Draft Technical Analysis and Design Report (Alpha Engineering & Design (2012) Ltd., 2016)

Jamaica – Spreadsheet with return period rainfall events for the Kingston and St. Andrew (KSA) rain gauge stations received directly from the Meteorological Service Division in Jamaica (Correspondence received from Ronal Moody) (Meteorological Service Division (Jamaica), 2022)

Trinidad and Tobago – Rainfall Curves for Trinidad (Lauriston Lewis Associates Ltd., n.d.)

3.4 Method Steps

This method steps followed to generate the results of the analysis is depicted in Figure 3-3 below:



Data collection and correction phase

- Collecting all historical data relating to dam failures and weather event.
- Validating information by checking multiple sources
- Updating databases utilizing most recent and accurate information

Data processing phase

- Converting all the rainfall data into a standardized rate (inches/hour)
- Origanising dam information based on small and large structures utilizing the critieria set out by Fell, et al. (2015) (further explain in the analysis section)
- Plotting the data points for failure binary vs. intensity measure
- Generating the fragility curve for small and large embankment dams

Applying fragility curves to Caribbean Context

- Organising the Caribbean dams based on the probable rainfall return period intensity
- Utilizing the fragility curves to find the probability of failure for each dam case investigated

Figure 3-3: Method steps adopted for analysis

3.5 Software Utilized

The software utilized to organise and process the data was Microsoft Excel and Python. Microsoft Excel – is a software program created by Microsoft that enables users to organise, edit, coordinate, and perform calculation (Techopedia, 2020). This software was used to sort all the data into tables under common heading and to do minor calculations such as generating the rainfall intensity rates.

Python – is a computer programming language that is utilized to generate a myriad of programs and automate calculation processes (Courser, 2022). This software was the major program used to generate the fragility curves based on the data tables organized in excel.

4 Data Analysis

4.1 Overview of section

This section provides a detailed description of the analysis and present sample data and calculations undertaken. This section has been presented in the same order of the analysis process: input data, data processing and output data. The majority of the data was taken from US sources and reported the values in imperial; therefore, the values are reported in imperial to maintain consistency reduce any conversion errors. Dates are also stated like the US format (Month/Day/Year).

4.2 Input Data

4.2.1 Historical Weather data

The historical weather information was sourced based on the date of the event and is reported in terms of depth of water accumulated (either in inches or millimetre). To get this into a standardized rate, the average duration of the storm or high rainfall event is incorporated. A sample calculation of this is shown below:

Rainfall rate = Total accumulated rainfall÷Total duration of storm

For example, in the case of Hurricane Irene, it is estimated that this storm caused approximately 6 inches of rain over a 24-hour period for the Cummings Pond Dam in the state of New Hampshire (New Hampshire Department of Environmental Services, 2021). This translates into a rainfall rate of 0.25 in/hr (calculation shown below).

Rainfall rate = 6 in ÷ 24 hr = 0.25 in/hr

A sample of this information tabularized is illustrated in Table 4-1 with this data point. The full data set has been included in Appendix A and Appendix B.

Table 4-1: Sample of historical rainfall information

Name of Event	Location	Date	Rainfall Accumulated (in.)	Time period (day)	Intensity (in./hr.)
Hurricane Irene	Cummings Pond Dam (New Hampshire)	28/08/2011	6	1 (24 hrs)	0.25

4.2.2 Case study embankment dam data

To develop the failure binary for the case study history, the cases were sorted based on embankment dams that experienced overtopping during the incident, with cases that experienced a breach failure being assigned 1 and cases that did not breach (non-failure) being assigned 0. Each of the cases histories was then matched with the corresponding rainfall intensity to establish the correlation analysis. A sample of this information for the Cummings Pond dam tabularized is illustrated in Table 4-2.

Table 4-2: Sample of case study information

Name of dam	Failure (Yes/No)	Failure Binary (1/0)	Intensity of Event (in/hr)	Dam height (ft)	Max Storage (ac-ft)
Cummings Pond Dam	No	0	0.25	10	1343

The data has grouped based on the designation of large and small dams to investigate the impact of size on the statistical distribution of failure probability. This size designation was based on the guidelines set out in the text Geotechnical Engineering of Dam (Fell, et al., 2015), which state that a large dam is classified as a dam with a height greater than 15m (≈49 ft) **or** any dam between 10 to 15m (≈32 to 49 ft) that meets one of the following:

- Crest length greater than 500 m (≈1640 ft)
- Reservoir capacity greater than 1 million m^3 (≈811 ac-ft)
- Designed for a minimum max. flood discharge of 2000 m^3/s (≈70630 ft^3/s)
- The design of the dam is peculiar.

This resulted in a sample size of fifty-one (51) small dam and fourteen (14) large dams (FEMA and other US state agencies have similar dam size designations). Given the extensive nature of the data set, it has been placed in Appendix C and Appendix D, with some additional information for referencing purposes.

4.2.3 Caribbean dam information

The key data required to establish a connection between the embankment dams from the case studies and the structures in the Caribbean is the size information and rainfall zone. Information relating to the performance history has also been added as this provides insight into the impact of past weather systems. A sample of this information for the Caroni-Arena dam in Trinidad and Tobago is illustrated in Table 4-3. The full list, which contains 7 cases across the Caribbean, has been placed in Appendix E.

Table 4-3: Sample of Caribbean dam information

Country	Name of Dam	Height (ft)	Max Storage (ac-ft)	Rainfall zone	Performance history
Trinidad and Tobago	Caroni-Arena Reservoir	134	0.25	5	-Issues related to drought experienced in the year 2020

A key observation gained from the references reviewed for the dams reveal that overtopping incidents were exceedingly rare for the dams covered in the study, with only the following two (2) cases being reported:

Jamaica – Rio Cabre Damhead – 1 overtopping failure

- In May 1991, heavy flood rains resulted in the collapse of the dam. Specifics relating to the amount of rainfall were not provided by the source (National Irrigation Commision Ltd., 2019).

Trinidad and Tobago – Navet Reservoir – 1 incidence of emergency spillway

- In 2020, heavy rains resulted in the emergency spillway being utilized for the first time in the structures history (Newsflare, 2020)

These incidents, though few, do illustrate the potential dangers faced by embankment structures if overtopping is allowed to occur.

As it relates to dry conditions and drought incidents, there have been significantly more cases reported across the region, including concrete dam and intake structures (Antigua

Observer 2020, Fletcher 2020, Cole & Cashman, 2021). However, notes on the structural impact of these events were not found in the literature review.

4.2.4 Caribbean rainfall data and climate projections

This section of the analysis reports the rainfall intensities based on varying return periods typically utilized for design of structures in the Caribbean. The reference documents, such as the rainfall intensity duration and frequency (IDF) curves, are added to Appendix F. All the intensities are based on a 24-hr duration, a typical assumption for storm duration, with an increase of 20% for the future projections for each case as specified in the guidance provided by The Climate Studies Group Mona UWI (2020).

To select the return periods for the Caribbean, a comparison of the values from the continental USA and the Caribbean was done to ensure that the values were within the same order of magnitude. This is necessary as intensity values that much higher than the ones utilized to develop the fragility curve would in points that fall above 100% probability of failure, meaning that the projected change in risk could not be assessed.

This assessment revealed that the rainfall intensities experienced in the Caribbean are significantly greater than those experienced in the Continental USA, apart from Trinidad and Tobago. An example of this utilizing Jamaica and New York reveals the following:

Jamaica: 1 in 100 rainfall intensity – 0.67 in/hr (Meteorological Service Division (Jamaica), 2022)

New York: 1 in 100 rainfall intensity – 0.26 in/hr (Northeast Regional Climate Centre (NRCC), 2022)

This demonstrates that the magnitude of a 1 in 100-year rainfall event in Jamaica is approximately 2.5 times that of the one in New York. A more comparative event in Jamaica is a 1 in 5-year return period, which has an intensity of 0.29 in/hr based on the values provided by the Meteorological Service Division in Jamaica (2022). Therefore, the values for the countries investigated are selected based on this comparison. It is also key to note that the projected rainfall specified by the Northeast Regional Climate Centre (NRCC), 2022, for New York for the year 2100 utilizing a high RCP of 8.5, returned a value of 0.30 in/hr, a 15% increase. This is in agreement with the findings of The Climate Studies Group Mona UWI

(2020). Table 4-4 reports the values of rainfall intensity for the base case (present-day) and projected (future-day) rainfall. Minor calculations are done to convert the metric values to imperial.

Table 4-4: Rainfall intensity values for selected Caribbean Islands

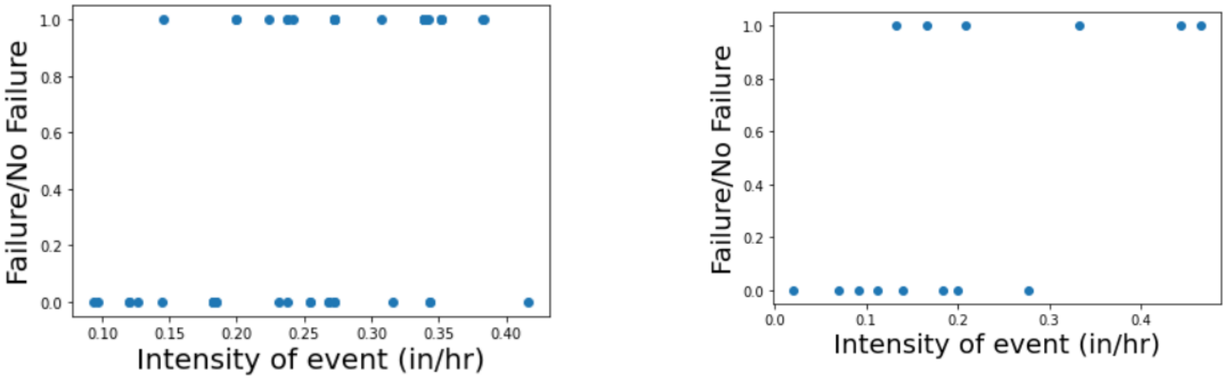
Country	Return period	Base (present day) Rainfall intensity (mm)	Rainfall intensity mm/hr	Rainfall intensity (In/hr)	Projected rainfall intensity (in/hr)
Antigua and Barbuda	1 in 20	190	7.92	0.31	0.37
Jamaica	1 in 5	178	7.40	0.29	0.35
Trinida and Tobago	1 in 100	150	6.25	0.25	0.30

As it relates to Trinidad and Tobago, there are some possible explanations for the lower rainfall intensities when compared to the other islands:

- Trinidad is considered to be south of the Hurricane belt in the Caribbean and is thus expected to experience less high rainfall events (The Climate Studies Group Mona UWI, 2020)
- The information utilized to generate these values is considerable dated in comparison to the information for the other islands (from 1940-1966), therefore it is likely that more accurate information is available. But this was not found in the public domain, and as such the information available was used in the analysis. Nonetheless, the process utilized can be extrapolated if updated data is present and the result replicated.

4.3 Data Processing

The data processing involved plotting the data from the case studies utilizing python and then generating the fragility curves by applying logistic regression to the information. Figure 4-1 shows the plotted data before the fragility curve is developed.



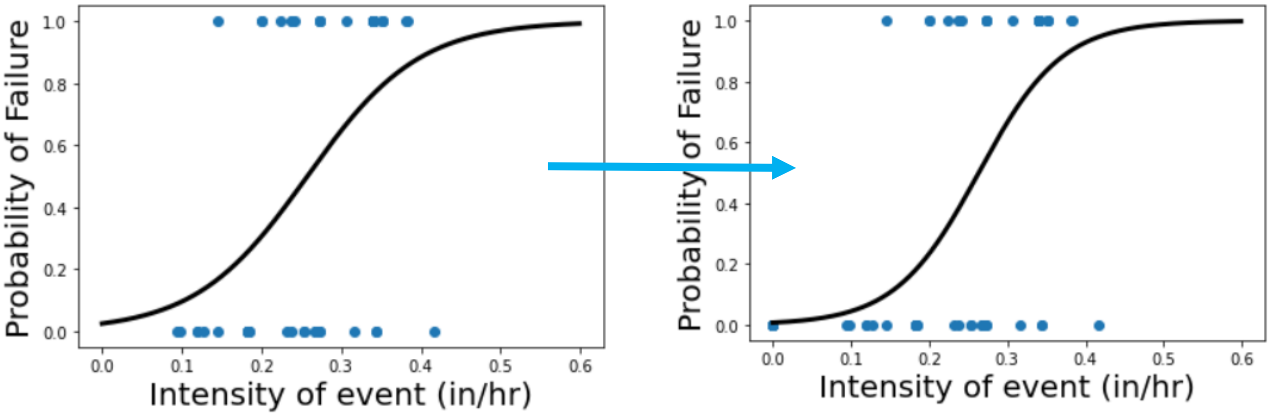
Plot of data for small dams		Plot of data for large dams	
Lowest intensity (in/hr)	0.094	**Lowest intensity (in/hr)**	0.021
Highest Intensity (in/hr)	0.416	**Highest Intensity (in/hr)**	0.465

Figure 4-1: Plot of data point for (a) small dams and (b) large dams

The fragility curve is then developed utilizing the logistic function or equation, where a linear set of values for ‘z’ existing in the range of (-∞, ∞) is mapped to the probability interval of (0,1) (Sharma, 2021). This function is typically represented as the following formula (Sharma, 2021):

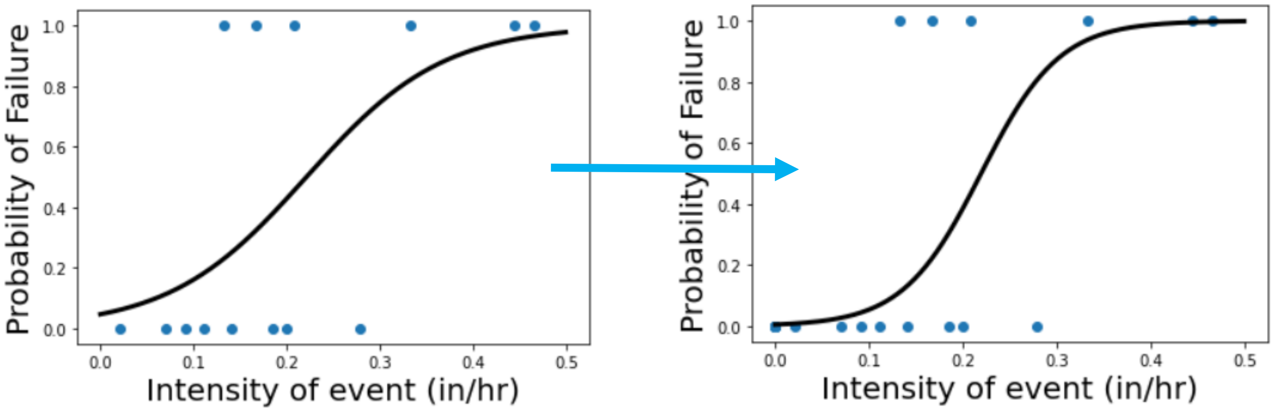
$$\sigma(z) = \frac{1}{1+e^{-z}}$$

Subsequent to developing this fragility curve, it was observed that at zero intensity (0 in/hr) the probability of failure was marginally higher than zero (see non padded charts in Figure 4-2 and Figure 4-3). Intuitively, this is evidently an error, as it is expected that the probability of failure for the design case would be zero (0) if the intensity measure is zero (0). Therefore, a statistical tool referred to as padding was applied to the data to correct this issue, in this case a matrix of zeroes or dummy values is added to the start of the data to adjust this error. This is a standard technique use to adjust data sets with data sets with similar range of values like this such as Near-field Acoustic Holography (NAH) and Fast Fourier Transform (FFT) for spatially varying earthquake motions (Scholte & Roozen 2003, Van Dinh & Basu 2012). Figure 4-2 and Figure 4-3 illustrates this conversion for the small dam and large dam data, respectively. To ensure the scales were the same the standard deviation and mean for the plot was maintained.



(a) Non-padded fragility curve (b) Padded fragility curve

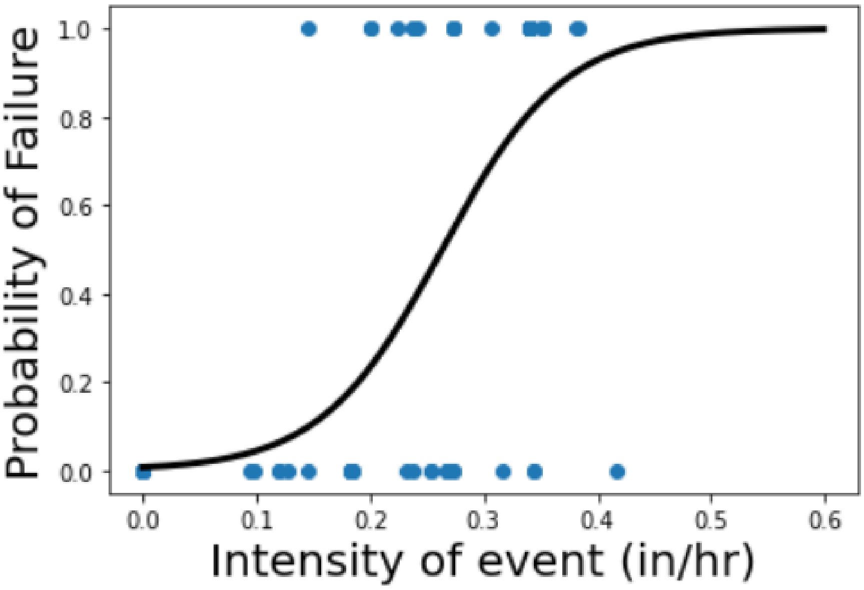
Figure 4-2: Comparison of (a) non-padded fragility curve vs. (b) padded fragility curve (small dams)



(a) Non-padded fragility curve (b) Padded fragility curve

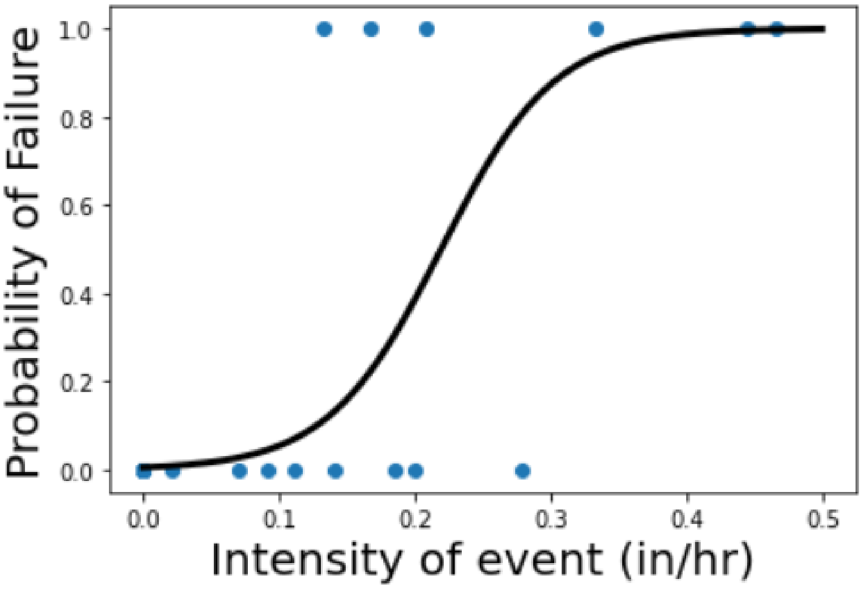
Figure 4-3: Comparison of (a) non-padded fragility curve vs. (b) padded fragility curve (large dams)

The final fragility curves for the small and large dams are shown in Figure 4-4 and Figure 4-5, respectively.



Mean	0.2995
Standard Deviation	0.1732
Intensity resulting in 100% probability of failure	0.55 in/hr

Figure 4-4: Final Fragility curve for small dams



Mean	0.2495
Standard Deviation	0.1443
Intensity resulting in 100% probability of failure	0.45 in/hr

Figure 4-5: Final Fragility curve for large dams

4.4 Output Data

The fragility curves generated from the analysis were then utilized to quantify the current and future probability of failure for dams within the region. This was done by mapping the intensity values of the rainfall events for the countries being covered. There were both large and small dams for Jamaica and Trinidad, with only a small dam in Antigua and Barbuda. Nonetheless, both fragility curves were applied for all countries, as this future construction could have either type of dam.

Table 4-5 presents the current and future probability of failure per country, while Figure 4-6 shows a sample of how the probability was extracted from the fragility curves utilizing Jamaica and the fragility curve for large dams. In Figure 4-6 the yellow line represents the current intensity and corresponding probability of failure, while the red line represents the projected intensity and corresponding probability failure.

Table 4-5: Current and future probability of breaching failure caused by overtopping events

Country	**Size of dam**	**Current Probability of Failure**	**Future Probability of Failure**	**Increase (%)**
Antigua and Barbuda (1 in 20-year return period)	Small	72%	89%	+17%
	Large	89%	98%	+10%
Jamaica (1 in 5-year return period)	Small	62%	83%	+21%
	Large	85%	96%	+11%
Trinida and Tobago (1 in 100-year return period)	Small	43%	67%	+24%
	Large	67%	87%	+20%

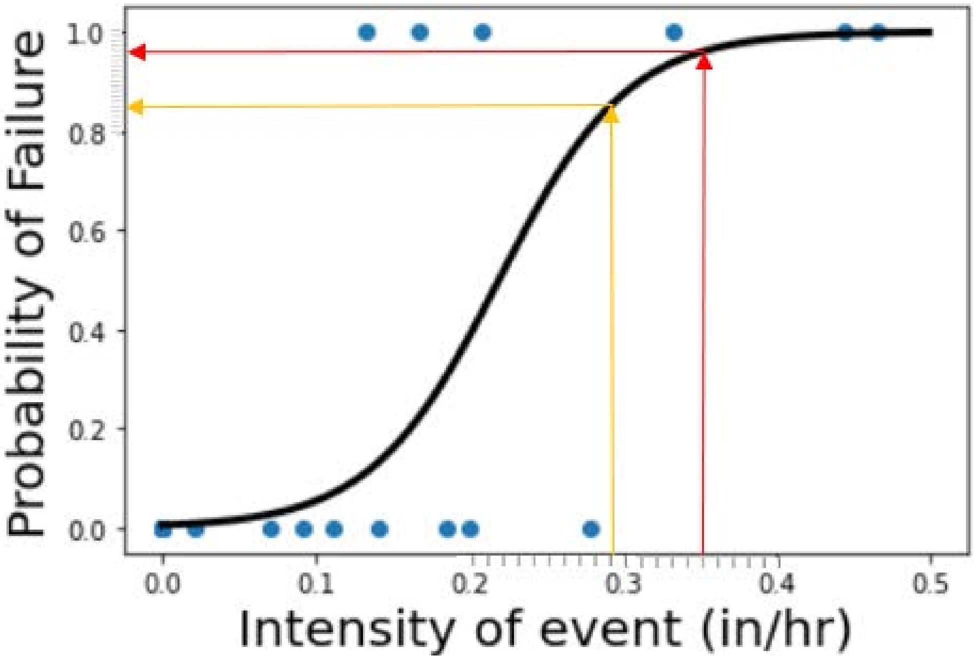


Figure 4-6: Fragility curve for large dams applied to case study in Jamaica

5 Discussion of Results

5.1 Overview of section

This section of the dissertation provides an interpretation of the analysis results, with critical discussions on the significance of the results and the potential impact and limitations of the information produced. It is meant to provide further context and provide the linkage between the objectives of the research, the work done during the research and the ensuing conclusion drawn. To provide a logical pathway for this the section has been divided into discussions on the fragility curves developed from the case study history, applying these curves to the Caribbean dam data set and limitation of the data.

5.2 Fragility analysis from case studies

The fragility curves developed from the analyses are illustrative of the connection between the intensity of a given rainfall event and probability of a breach occurring due to overtopping of dam. As mentioned in the methodology, this analysis is seen as a valid connection as external erosion is the key cause of failure during overtopping events, with the level of erosion being connected to the intensity of the rainfall event.

Sources within the literature, such as Atkins (2013) propose that this failure mechanism is precipitated by increased water velocity and pressure associated with increased rainfall and higher water depths. The analyses of the case study also reveal a trend whereby there was a general increase in probability of failure as the rainfall intensity of the events increased.

However, there were some outliers that exist in the data set that require additional explanation. The outliers in this case being dams that failed at relatively low intensity or the other extreme – embankment dams that survived high intensity events. An embedded assumption in the regression analysis is that all the dams possess similar characteristics and are well designed. Therefore, cases that reportedly had issues in construction or design were removed from the listing when the case studies were compiled. However, there still exist a possibility that some of the dams that were utilized had inherent problems, which could have led to their collapse under low intensity events. At the other end of spectrum, it is possible that the dams that passed at high intensities may have benefitted for emergency action plans or were constructed utilizing a more erosion resistant design.

5.3 Use of fragility curve for Caribbean dams

The comparative values of the large and small fragilities when applied to the Caribbean region reveal that the smaller dams in the region have a lower probability of failure for current events when compared to larger dams in the region. However, these smaller dam structures are more susceptible to the effects of climate change, with the average increase in failure probability for large dams being equal to 13.6 % (10% - Antigua and Barbuda, 11% - Jamaica, 20% -Trinidad and Tobago), with the increase projected for small dams being 20.6% (17% - Antigua and Barbuda, 21% - Jamaica, 24% -Trinidad and Tobago).

It is also statistically significant that Trinidad and Tobago will see the largest increase in dam failure probability for both cases, despite having the lowest intensities. This shows that, according to the fragility curves, areas that have historically had lower intensities are more susceptible to increased probabilities of failure. Albeit, with countries like Jamaica and Antigua having much higher values of rainfall intensities than the continental USA, the chances of dam failure under overtopping is very high, with events like a 1 in 100 for Jamaica (0.67 in/hr) surpassing the 100% failure probability limits for both graphs (0.45 in/hr for large dam fragility curve and 0.55 in/hr for small dam fragility curve)

It is key to note that overtopping is a necessary condition for a breaching failure to occur. As referred to previously under the analysis section, reports of overtopping incidences in the Caribbean are very low, which offers an explanation as to why more breaching failures do not occur despite the high rainfall intensities experienced in the region. A physical explanation for this could be the drought issues that are experience within the region, thereby resulting in low initial reservoir levels when storms occur.

5.4 Limitations

Some of the limiting factors on the data is:

- Lack of accurate damage data in some instances. The case studies did not have the specific breach information for all cases, with some sources listing possible secondary and tertiary triggering events in addition to the primary cause (external erosion caused by overtopping).
- The conditions of the dam prior to event are unknown in the majority cases. Factors such as the dam water and sedimentation levels are important contributors to

breach failure. Additional information on factors like these would improve the accuracy of the fragility curves significantly.

- Lack of specifics on the type of construction, such as soil type and zoning characteristics. These specifics would also improve the sensitivity of the fragility curve as the level of erodibility could be used as another factor to measure.
- Lack of information on maintenance history

6 Conclusion

The research conducted revealed that climate change will likely impact embankment dam structures in the Caribbean under the piping case due to increased drought effects and under the overtopping case due to increased rainfall intensity during extreme storm and hurricane event. Due to the timescales involve in the embankment breach studies and the information available in the reference literature, only the overtopping case was quantified.

The study returned two fragility curves for the probability of failure due to overtopping: one for large embankment dams and the other for small embankment dams. As the Caribbean Islands covered in the study have different return-periods per event, a comparable event was utilized for each system i.e., similar rainfall intensities but different return period per country. The corresponding increase in risk for the Caribbean dams under climate change impacts for the specific countries is stated below:

- Antigua and Barbuda – for a rainfall intensity of 0.31 in/hr, there is an increased risk of + 17% for small dams and +10% for large dams
- Jamaica – for a rainfall intensity of 0.29 in/hr, there is an increased risk of + 21% for small dams and +11% for large dams
- Trinidad and Tobago - for a rainfall intensity of 0.25 in/hr, there is an increased risk of +24% for small dams and +20% for large dams.

7 Scope for future research

It is recommended that future research on the topic focus on the existing gaps in the literature review and improve upon the data availability in the Caribbean. Some of the specific areas include:

- Applying this regression analysis to other damage states, particularly drought conditions
- Further studies to quantify the impact of droughts on dam failure
- Incorporation of cascading effects into quantitative dam risk analyses
- Incorporation of physical experiments and finite element analysis (FEA) to provide additional tools to quantify dam risk

It is key to note that the timescales involved in these future studies would require significantly more time compared to the analysis utilized for this study

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9 Appendices

Appendix A: Weather Information for small dams

No.	**Dam Name**	**Location**	**Latitude**	**Longitude**	**Named Hydrologic Event**	**Date of Incident**	**Rainfall Accumulated (in)**	**Time Period (days)**	**Intensity of event (in/hr)**	**Station name**
1	ARMADILLO DRIVE LAKE DAM	TX	30.7896	-95.5282	Harvey	08/29/2017	19.99	2	0.416	HUNTSVILLE
2	ARRAN LAKES DAM	NC	35.029	-78.981	Matthew	10/08/2016	8.13	1	0.339	FAYETTEVILLE (PWC)
3	BARTLETT POND DAM	NY	44.1	-73.5117	Irene	08/28/2011	3.04	1	0.127	TUPPER LAKE SUNMOUNT
4	BAXLEY 501 POND DAM	SC	34.1114	-79.3352	Hurricane Florence	09/16/2018	7	2	0.146	MYRTLE BEACH
5	BELVEDERE LAKE DAM	NY	42.745	-74.7603	Irene	08/28/2011	2.89	1	0.120	GLOVERSVILLE 7NW PECK LAKE
6	BENNETTS BRIDGE RD. DAM	NC	35.0773	-77.9099	Matthew	10/08/2016	8.45	1	0.352	KINSTON 7 SE
7	CHATHAM LAKE DAM	SC	34.6732	-79.9104	Hurricane Florence	09/16/2018	6.55	1	0.273	DARLINGTON
8	COVINGTON MILLPOND DAM	SC	34.6077	-79.6314	Hurricane Florence	09/16/2018	6.55	1	0.273	DARLINGTON
9	CRAWFORD	SC	34.6639	-80.2922	Hurricane	09/16/2018	6.55	1	0.273	DARLINGTON

No.	Dam Name	Location	Latitude	Longitude	Named Hydrologic Event	Date of Incident	Rainfall Accumulated (in)	Time Period (days)	Intensity of event (in/hr)	Station name
	POND DAM				Florence					
10	CUMMINS POND DAM	NH	43.7777	-72.0155	Irene	08/28/2011	3.49	1	0.145	LEBANON MUNICIPAL AP
11	DEVONWOOD LOWER DAM	NC	35.075	-78.995	Matthew	10/08/2016	8.13	1	0.339	FAYETTEVILLE (PWC)
12	DOUBLE A LAKE 1 DAM	TX	30.6965	-94.7329	Harvey	08/29/2017	11.4	2	0.238	WOODVILLE
13	DURHAMS LAKE DAM	NC	35.281	-78.057	Matthew	10/08/2016	4.8	1	0.200	SMITHFIELD
14	GUY LAKE DAM	NC	35.488	-78.71	Matthew	10/08/2016	5.8	1	0.242	CARTHAGE WATER TREATMENT PLANT
15	H.F. LEE POWER STATION COOLING LAKE DAM	NC	35.381	-78.085	Matthew	10/08/2016	9.17	1	0.382	MOUNT OLIVE 6SE
16	HOUSE-AUTRY DAM	NC	35.1869	-78.3762	Matthew	10/08/2016	4.8	1	0.200	SMITHFIELD
17	INDIAN KILL RESERVOIR DAM	NY	41.2367	-74.2083	Irene	08/28/2011	4.39	1	0.183	WEST POINT

No.	Dam Name	Location	Latitude	Longitude	Named Hydrologic Event	Date of Incident	Rainfall Accumulated (in)	Time Period (days)	Intensity of event (in/hr)	Station name
18	LAKE HARTUNG DAM	NJ	41.0416	-74.5339	Irene	08/27/2011	7.58	1	0.316	OAK RIDGE RESERVOIR
19	LAKE NEEPAULIN DAM	NJ	41.2145	-74.6257	Irene	08/27/2011	6.44	1	0.268	SUSSEX 1 NW
20	LAKE PLACIDA	PA	40.1531	-76.5894	TS Lee	09/07/2011	2.32	1	0.097	LANDISVILLE 2 NW
21	LAKE POCO DAM	PA	40.5434	-75.0803	Ivan	09/17/2004	5.55	1	0.231	BUCKSVILLE
22	LAUREL LAKE DAM	NC	35.011	-78.489	Matthew	10/08/2016	8.13	1	0.339	FAYETTEVILLE (PWC)
23	LILY POND DAM	NY	41.2822	-74.2461	Irene	08/28/2011	4.39	1	0.183	WEST POINT
24	LINDY'S LAKE DAM	NJ	41.0745	-74.3707	Irene	08/28/2011	6.1	1	0.254	WANAQUE RAYMOND DAM
25	LOCH LOMMOND	NC	35.07	-78.998	Matthew	10/08/2016	8.13	1	0.339	FAYETTEVILLE (PWC)
26	LONG VALLEY FARM LAKE DAM	NC	35.213	-78.976	Matthew	10/08/2016	5.72	1	0.238	DUNN 4 NW
27	LOWER	NY	41.3538	-73.9774	Irene	08/28/2011	4.39	1	0.183	WEST POINT

No.	Dam Name	Location	Latitude	Longitude	Named Hydrologic Event	Date of Incident	Rainfall Accumulated (in)	Time Period (days)	Intensity of event (in/hr)	Station name
	CRAGSTON LAKE DAM									
28	MAXWELL MILL POND	NC	35.07	-77.7878	Matthew	10/08/2016	8.45	1	0.352	KINSTON 7 SE
29	MCCOLL POND DAM	SC	34.4948	-79.4096	Hurricane Florence	09/16/2018	6.55	1	0.273	DARLINGTON
30	MIRROR LAKE DAM	NC	35.0544	-78.9222	Matthew	10/08/2016	8.13	1	0.339	FAYETTEVILLE (PWC)
31	MONROE RECREATION LAKE DAM	NY	41.3242	-74.1869	Irene	08/28/2011	4.39	1	0.183	WEST POINT
32	MORRIS MILL POND (SOUTH DIVISION STREET)	MD	38.326	-75.6024	Hurricane Michael	10/11/2018	6.56	1	0.273	SALISBURY-WICOMICO REGIONAL AIRPORT
33	MOUNTAINDALE RECREATION LAKE DAM	NY	41.6969	-74.5181	Irene	08/28/2011	8.21	1	0.342	MOHONK LAKE
34	MT. VERNON ESTATES	NC	34.853	-78.876	Matthew	10/08/2016	8.13	1	0.339	FAYETTEVILLE (PWC)

No.	Dam Name	Location	Latitude	Longitude	Named Hydrologic Event	Date of Incident	Rainfall Accumulated (in)	Time Period (days)	Intensity of event (in/hr)	Station name
35	PENFIELD POND DAM	NY	43.9219	-73.5356	Irene	08/28/2011	2.88	1	0.120	ESSEX JUNCTION 1 N
36	RAYCONDA UPPER DAM	NC	35.0267	-79.0222	Matthew	10/08/2016	8.13	1	0.339	FAYETTEVILLE (PWC)
37	RED HOOK MILLS DAM	NY	42.0106	-73.8728	Irene	08/28/2011	12.87	2	0.268	EAST JEWETT
38	RHODES LAKE DAM	NC	35.2258	-78.6528	Matthew	10/08/2016	5.72	1	0.238	DUNN 4 NW
39	RICHLAND CREEK WS SCS SITE 107A DAM	TX	31.8655	-96.7147	Unnamed	06/10/2010	4.43	1	0.185	NAVARRO MILLS DAM
40	RICHLAND CREEK WS SCS SITE 15 DAM	TX	31.8507	-96.5642	Unnamed	06/10/2010	2.25	1	0.094	CORSICANA CAMPBELL FIELD
41	RICHLAND CREEK WS SCS SITE 16 DAM	TX	31.7883	-96.6242	Unnamed	06/10/2010	4.43	1	0.185	NAVARRO MILLS DAM
42	SCNONAME 14015	SC	33.7333	-80.0917	Matthew	10/08/2016	5.38	1	0.224	SUMTER
43	SHADOW	NJ	40.3528	-74.085	Irene	08/28/2011	8.23	1	0.343	FREEHOLD-MARLBORO

No.	Dam Name	Location	Latitude	Longitude	Named Hydrologic Event	Date of Incident	Rainfall Accumulated (in)	Time Period (days)	Intensity of event (in/hr)	Station name
	LAKE DAM									
44	SHANTY DRIVE DAM	NJ	-	-	Irene	08/28/2011	8.23	1	0.343	FREEHOLD-MARLBORO
45	SILVER LAKE	NC	35.802	-77.949	Matthew	10/08/2016	9.22	1	0.384	WILSON 3 SW
46	SKY VIEW POND DAM	NY	41.3133	-74.1653	Irene	08/28/2011	4.39	1	0.183	WEST POINT
47	SMITH LAKE DAM	NC	34.863	-78.73	Matthew	10/08/2016	8.13	1	0.339	FAYETTEVILLE (PWC)
48	SPRING LAKE DAM	SC	34.4582	-79.8616	Hurricane Florence	09/16/2018	6.55	1	0.273	DARLINGTON
49	SULLIVAN	PA	41.4767	-76.3767	TS Lee	09/07/2011	7.36	1	0.307	DUSHORE
50	TULL MILLPOND DAM	NC	35.155	-77.734	Matthew	10/08/2016	8.45	1	0.352	KINSTON 7 SE
51	UPPER WARWICK DAM	NY	41.2289	-74.3608	Irene	08/28/2011	6.1	1	0.254	WANAQUE RAYMOND DAM

No.	Dam Name	Location	Latitude	Longitude	Named Hydrologic Event	Date of incident	Rainfall Accumulated (in)	Time Period (day)	Intensity of event (in/hr)	Station name
1	ALBRITTON LAKE DAM	USA - MS	30.9806	-89.6881	Unnamed	03/11/2016	4.8	1	0.200	HATTIESBURG 5SW
2	BRISEIS	AUSTRALIA	-41.1749	147.8173	Unnamed	04/04/1929	11.16	1	0.465	-
3	LAKE EANES DAM	USA - TX	31.8528	-98.6182	Unnamed	06/01/1988	6.67	1	0.278	Comanche - June 1988
4	MARTINS CREEK (PA-467)	USA - PA	41.7647	-75.7467	TS Lee	09/08/2011	3.36	1	0.140	Station: SUSQUEHANNA
5	MCCARTY LAKE DAM	USA - TX	33.885	-80.4617	Unnamed	08/04/1978	2.68	1	0.112	Search Breckenridge
6	MOUNTAIN CREEK WS SCS SITE 10	USA - TX	32.498	-97.0421	Unnamed	05/27/2015	1.67	1	0.070	Joe pool station used

	DAM								
7	NOPPIKOSKI	SWEDEN	-	-	Unnamed	09/07/1985	3.2	1	0.133	-
8	POWELL LAKE DAM	USA - TX	32.2093	-101.269	Unnamed	02/23/2000	0.5	1	0.021	Breckenridge Coop
9	RICHLAND CREEK WS SCS SITE 31 DAM	USA - TX	31.8705	-96.5676	Unnamed	06/10/2010	4.42	1	0.184	-
10	SCHAEFFERS	USA - AR	-	-	Unnamed	06/05/1921	10	2	0.208	Average across days
11	SPEEDWELL FORGE	USA - PA	40.2039	-76.3075	Unnamed	10/29/2012	2.21	1	0.092	Lancaster airport
12	SWIFT DAM	USA - MT	48.1627	-112.872	Unnamed	06/10/1964	7.99	1	0.333	-
13	TOUS	SPAIN	39.1371	-0.6525	Unnamed	10/20/1982	4	1	0.167	-
14	TWO MEDICINE DAM	USA - MT	-	-	Unnamed	06/10/1964	10.66	1	0.444	-

Appendix C: Case study for small dams

Case No.	**Dam Name**	**Location**			**Failure (Yes/No)**	**Failure Binary**	**Named Hydrologic Event**	**Date of Incident**	**Intensity of event (in/hr)**	**Dam Height (ft)**	**Max Storage (ac-ft)**	**Year constructed**
		State	Latitude	Longitude								
1	ARMADILLO DRIVE LAKE DAM	TX	30.7896	-95.5282	No	0	Harvey	08/29/2017	0.416	13	47	1800
2	ARRAN LAKES DAM	NC	35.029	-78.981	Yes	1	Matthew	08/29/2017	0.339	21	144	1958
3	BARTLETT POND DAM	NY	44.1	-73.5117	No	0	Irene	08/28/2011	0.127	14	1447	1918
4	BAXLEY 501 POND DAM	SC	34.1114	-79.3352	Yes	1	Hurricane Florence	09/16/2018	0.146	7	259	1953
5	BELVEDERE LAKE DAM	NY	42.745	-74.7603	No	0	Irene	08/28/2011	0.12	20	210	1900
6	BENNETTS BRIDGE RD. DAM	NC	35.0773	-77.9099	Yes	1	Matthew	10/08/2016	0.352	5	-	-
7	CHATHAM LAKE DAM	SC	34.6732	-79.9104	No	0	Hurricane Florence	09/16/2018	0.273	17	53	1978
8	COVINGTON MILLPOND DAM	SC	34.6077	-79.6314	Yes	1	Hurricane Florence	09/16/2018	0.273	11	400	1900
9	CRAWFORD POND DAM	SC	34.6639	-80.2922	Yes	1	Hurricane Florence	09/16/2018	0.273	16	71	1960
10	CUMMINS POND DAM	NH	43.7777	-72.0155	No	0	Irene	10/08/2016	0.145	10	1343	1880

11	DEVONWOOD LOWER DAM	NC	35.075	-78.995	Yes	1	Matthew	08/29/2017	0.339	25	175	-
12	DOUBLE A LAKE 1 DAM	TX	30.6965	-94.7329	No	0	Harvey	08/29/2017	0.238	15	164	1942
13	DURHAMS LAKE DAM	NC	35.281	-78.057	Yes	1	Matthew	10/08/2016	0.200	12	112	1929
14	GUY LAKE DAM	NC	35.488	-78.71	Yes	1	Matthew	10/08/2016	0.242	14	72	1950
15	H.F. LEE POWER STATION COOLING LAKE DAM	NC	35.381	-78.085	Yes	1	Matthew	10/08/2016	0.382	17	5446	1955
16	HOUSE-AUTRY DAM	NC	35.1869	-78.3762	Yes	1	Matthew	10/08/2016	0.200	9	308	1850
17	INDIAN KILL RESERVOIR DAM	NY	41.2367	-74.2083	No	0	Irene	08/28/2011	0.183	23	728	1958
18	LAKE HARTUNG DAM	NJ	41.0416	-74.5339	No	0	Irene	08/27/2011	0.316	10	-	-
19	LAKE NEEPAULIN DAM	NJ	41.2145	-74.6257	No	0	Irene	08/27/2011	0.268	22	143	1927
20	LAKE PLACIDA	PA	40.1531	-76.5894	No	0	TS Lee	09/07/2011	0.097	6	18	1910
21	LAKE POCO DAM	PA	40.5434	-75.0803	No	0	Ivan	09/17/2004	0.231	13	-	-
22	LAUREL LAKE DAM	NC	35.011	-78.489	Yes	1	Matthew	10/08/2016	0.339	12	50	-

23	LILY POND DAM	NY	41.2822	-74.2461	No	0	Irene	08/28/2011	0.183	10	17.9	1949
24	LINDY'S LAKE DAM	NJ	41.0745	-74.3707	No	0	Irene	08/28/2011	0.254	23	69	1930
25	LOCH LOMMOND	NC	35.07	-78.998	Yes	1	Matthew	10/08/2016	0.339	21	109	-
26	LONG VALLEY FARM LAKE DAM	NC	35.213	-78.976	Yes	1	Matthew	10/08/2016	0.238	18	672	-
27	LOWER CRAGSTON LAKE DAM	NY	41.3538	-73.9774	No	0	Irene	08/28/2011	0.183	10	46	1897
28	MAXWELL MILL POND	NC	35.07	-77.7878	Yes	1	Matthew	10/08/2016	0.352	14	130	-
29	MCCOLL POND DAM	SC	34.4948	-79.4096	Yes	1	Hurricane Florence	09/16/2018	0.273	14	72	1969
30	MIRROR LAKE DAM	NC	35.0544	-78.9222	Yes	1	Matthew	10/08/2016	0.339	12	24	1958
31	MONROE RECREATION LAKE DAM	NY	41.3242	-74.1869	No	0	Irene	08/28/2011	0.183	14	68	1936
32	MORRIS MILL POND (SOUTH DIVISION STREET)	MD	38.326	-75.6024	No	0	Hurricane Michael	10/01/2018	0.273	12	191	1941
33	MOUNTAINDALE RECREATION LAKE DAM	NY	41.6969	-74.5181	Yes	1	Irene	08/28/2011	0.342	16	66	1973
34	MT.VERNON ESTATES	NC	34.853	-78.876	Yes	1	Matthew	10/08/2016	0.339	14	4056	-

35	PENFIELD POND DAM	NY	43.9219	-73.5356	No	0	Irene	08/28/2011	0.120	14	1100	1980
36	RAYCONDA UPPER DAM	NC	35.0267	-79.0222	Yes	1	Matthew	10/08/2016	0.339	19	20	-
37	RED HOOK MILLS DAM	NY	42.0106	-73.8728	No	0	Irene	08/28/2011	0.268	26	104	1899
38	RHODES LAKE DAM	NC	35.2258	-78.6528	Yes	1	Matthew	10/08/2016	0.238	15	2304	1770
39	RICHLAND CREEK WS SCS SITE 107A DAM	TX	31.8655	-96.7147	No	0	Unnamed	06/10/2010	0.185	31	886	1970
40	RICHLAND CREEK WS SCS SITE 15 DAM	TX	31.8507	-96.5642	No	0	Unnamed	06/10/2010	0.094	30	1764	1963
41	RICHLAND CREEK WS SCS SITE 16 DAM	TX	31.7883	-96.6242	No	0	Unnamed	06/10/2010	0.185	31	796	1962
42	SCNONAME 14015	SC	33.7333	-80.0917	Yes	1	Matthew	10/08/2016	0.224	9	144	1955
43	SHADOW LAKE DAM	NJ	40.3528	-74.085	No	0	Irene	08/28/2011	0.343	16	-	1931
44	SHANTY DRIVE DAM	NJ	-	-	No	0	Irene	08/28/2011	0.343	9	-	-
45	SILVER LAKE	NC	35.802	-77.949	Yes	1	Matthew	10/08/2016	0.384	13	538	1785
46	SKY VIEW POND DAM	NY	41.3133	-74.1653	No	0	Irene	08/28/2011	0.183	24	25	1952

47	SMITH LAKE DAM	NC	38.1893	-90.7567	Yes	1	Matthew	10/08/2016	0.339	10	242	-
48	SPRING LAKE DAM	SC	34.4582	-79.8616	Yes	1	Hurricane Florence	09/16/2018	0.273	16	145	-
49	SULLIVAN	PA	41.4767	-76.3767	Yes	1	TS Lee	09/07/2011	0.307	11	123	1948
50	TULL MILLPOND DAM	NC	35.155	-77.734	Yes	1	Matthew	10/08/2016	0.352	8	518	1875
51	UPPER WARWICK DAM	NY	41.2289	-74.3608	No	0	Irene	08/28/2011	0.254	40	80	1912

Appendix D: Case study for large dams

Case No.	**Dam Name**	**Location**			**Incident Type (Yes/No)**	**Failure Binary**	**Named Hydrologic Event**	**Date of Incident**	**Intensity of event (in/hr)**	**Dam Height (ft)**	**Max Storage (ac-ft)**	**Year constructed**
		Country/ State	Latitude	Longitude								
1	ALBRITTON LAKE DAM	USA - MS	30.9806	-89.6881	No	0	Unnamed	03/11/2016	0.200	33	1369	1995
2	BRISEIS	AUSTRALIA	-41.1749	147.8173	Yes	1	Unnamed	04/04/1929	0.465	75.5	2756	1928
3	LAKE EANES DAM	USA - TX	31.8528	-98.6182	No	0	Unnamed	06/01/1988	0.278	35	2215	1926
4	MARTINS CREEK (PA-467)	USA - PA	41.7647	-75.7467	No	0	TS Lee	09/08/2011	0.140	52	180	1967
5	MCCARTY LAKE DAM	USA - TX	33.885	-80.4617	No	0	Unnamed	08/04/1978	0.112	50	6696	1942
6	MOUNTAIN CREEK WS SCS SITE 10 DAM	USA - TX	32.498	-97.0421	No	0	Unnamed	05/27/2015	0.070	43	6457	1956
7	NOPPIKOSKI	SWEDEN	-	-	Yes	1	Unnamed	09/07/1985	0.133	62	567	1966
8	POWELL LAKE DAM	USA - TX	32.2093	-101.269	No	0	Unnamed	02/23/2000	0.021	35	2988	1939
9	RICHLAND CREEK WS SCS SITE 31 DAM	USA - TX	31.8705	-96.5676	No	0	Unnamed	06/10/2010	0.184	35	5838	1963
10	SCHAEFFERS	USA - AR	-	-	Yes	1	Unnamed	06/05/1921	0.208	90	3190	1910
11	SPEEDWELL FORGE	USA - PA	40.2039	-76.3075	No	0	Unnamed	10/29/2012	0.092	35	2372	1966
12	SWIFT DAM	USA - MT	48.1627	-112.872	Yes	1	Unnamed	06/10/1964	0.333	157	31000	1914

13	TOUS	SPAIN	39.1371	-0.6525	Yes	1	Unnamed	10/20/1982	0.167	230	42967	1977
14	TWO MEDICINE DAM	USA - MT	-	-	Yes	1	Unnamed	06/10/1964	0.444	37	16000	1913

Appendix E: Caribbean embankment dam data base

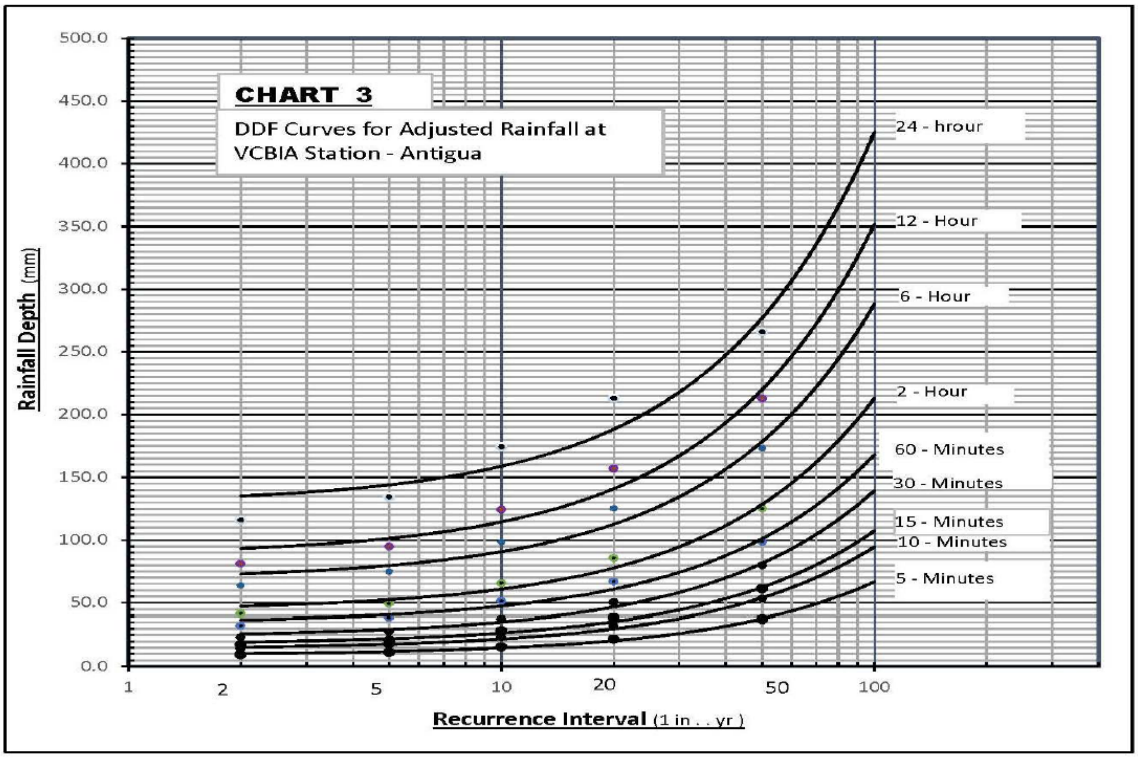
Country	Name of Asset	Dam Height (ft)	Reservoir Capacity (ac-ft)	Geolocation		Construction Type	Completion	Main Use	Comments Performance History	Rainfall Zone
				Latitude	Longitude					
Antigua and Barbuda	Potworks Dam	11.5	3688.75	17.062	-61.76	Earthen	1970	Water Utility	- Primarily affected by drought conditions. Currently reported as bring completely dry, with the area being overgrown with vegetation. - No reports of Overtopping	5
Jamaica	Mona Reservoir	35.0	2979.37	18.006	-76.76	Earth Embankment	1959	Water Utility	- Leakage problems at the beginning (from 1946 to 1958); bottom of dam lined with clay to address this - Experienced droughts throughout the years, significant droughts in recent years - High levels of siltation and turbidity	3
	Rio Cobre Damhead	-	-	18.045	-76.98	Embankment (Specifics unknown)	1876	Irrigation, industrial and water utility	- Heavy Flood rains on May 1991 resulted in the collapse of the Dam (Specific failure mechanism not mentioned) - Reconstructed in May 1995 (Recognized by ICE as project of year)	
Trinidad	Caroni-	134.0	37779.27	10.533	-61.23	Earth-filled	-	Water	- Issues related to droughts (2020)	5

Country	Name of Asset	Dam Height (ft)	Reservoir Capacity (ac-ft)	Geolocation Latitude	Geolocation Longitude	Construction Type	Completion	Main Use	Comments Performance History	Rainfall Zone
and Tobago	Arena Reservoir					Embankment + Concrete Weir		Utility		
	Hillsborough Reservoir (Tobago)	-	826.93	11.229	-60.67	Earth-filled Embankment	1952		- Issues relating to siltation throughout lifetime of dam	
	Navet Reservoir	-	15484	10.404	-61.25	Unknown (Likely a combination)	1962		- Overtopped in 2020 due to large rainfall event, spillway utilized for first time in structures history.	

Jamaica (Rainfall intensity table – Mona dam values used for analysis)

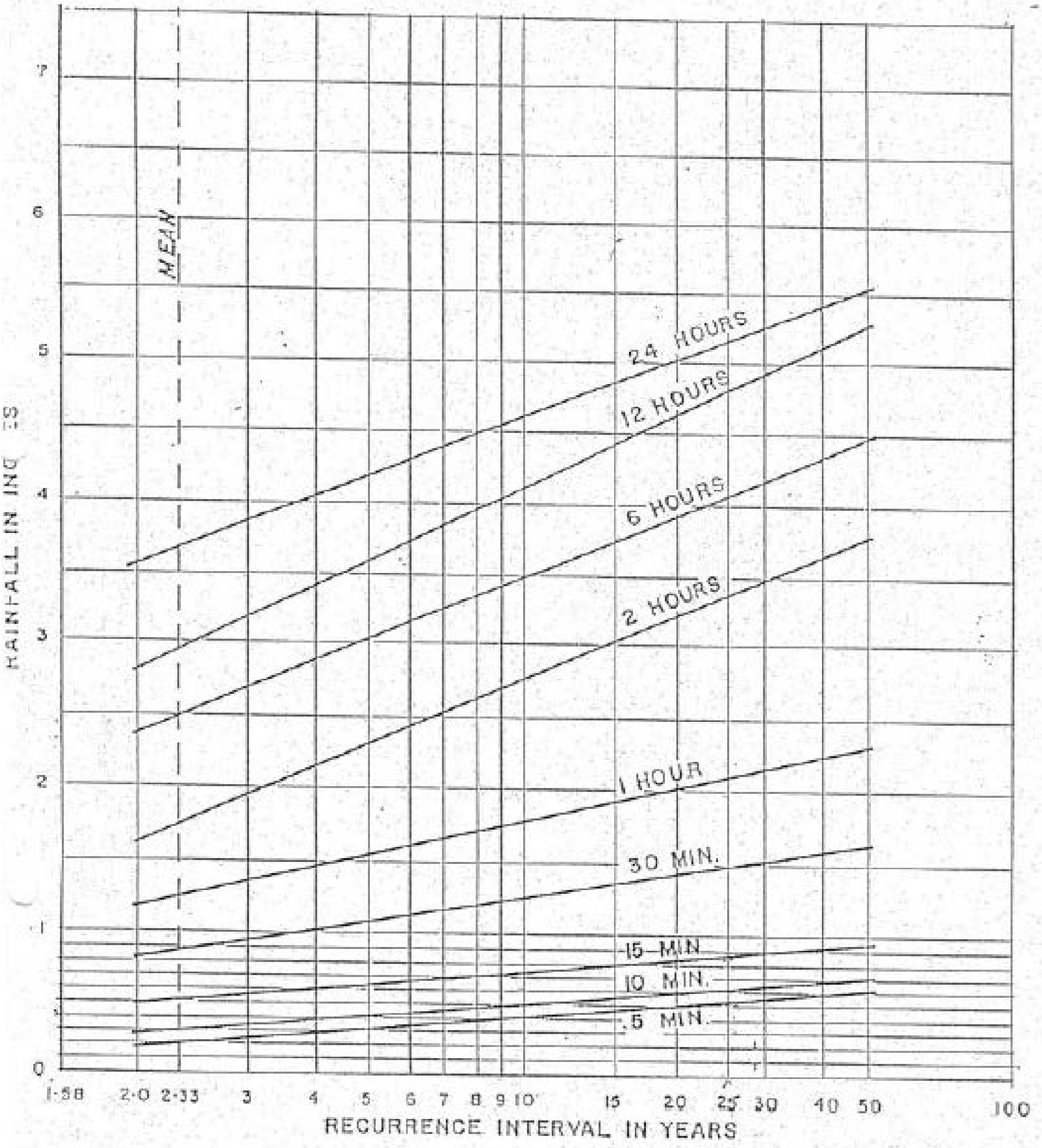
PARISH/STATION	**RETURN PERIODS**					
KINGSTON & ST. ANDREW	**T2**	**T5**	**T10**	**T25**	**T50**	**T100**
BRANDON HILL	185.8	239.1	274.7	318.3	349.5	379.5
CAVALIERS FP	180.9	266.0	346.3	468.7	571.6	682.3
CONSTANT SPRING FP	130.0	168.0	230.0	292.0	336.0	384.0
DALLAS	131.0	245.0	321.0	417.0	466.0	559.0
HARDWAR GAP	190.0	255.0	318.0	397.0	456.0	515.0
HERMITAGE	162.0	227.0	291.0	372.0	432.0	491.0
HOPE FP	121.0	189.0	255.0	338.0	323.7	369.2
IRISH TOWN	159.0	212.0	261.0	324.0	370.0	416.0
LANGLEY	200.0	291.0	359.9	451.2	520.2	589.3
LAWRENCE TAVERN	138.9	208.8	269.9	358.3	430.0	505.0
MAVIS BANK	169.2	242.0	313.0	400.0	465.0	529.0
MONA RESERVOIR	161.7	177.5	242.0	300.0	359.0	408.0
NEWCASTLE	154.7	200.5	231.8	270.8	298.9	326.1
NORBROOK	139.3	184.8	217.1	257.9	287.8	317.0
PALISADOES	166.0	251.2	305.1	368.8	413.2	455.2
ROSE HILL	118.9	208.3	305.2	466.6	611.6	774.9
SEA VIEW FP	181.0	270.0	354.0	459.0	537.0	615.0
STONY HILL	155.0	233.0	308.0	401.0	471.0	540.0
				370.0		

Antigua (Rainfall IDF Curve utilized for the analysis)



Trinidad and Tobago (Rainfall Intensity Curve utilized for assessment)

STATION NAME . . . *HOLLIS RESERVOIR*
STATION No. . . . . . *2·3*
PERIOD . . . . *1940–1966 (27 YEARS)*



Rainfall–Duration Frequency Curves
at Hollis Reservoir

2/2

9.1 Python Code

Appendix G Python Code (Small Dams – Nonpadded)

```
#Import the required libraries
import os
import numpy as np
import pandas as pd
import statsmodels.api as sm
import matplotlib.pyplot as plt
#Change working directory

project_path = '/content/drive/MyDrive/Dam Project/Fragility Analysis'
os.chdir(project_path)
input_path = os.path.join(project_path, 'Input Files')
output_path = os.path.join(project_path, 'Output Files')
print(os.getcwd())
#Load the data

df_data = pd.read_csv(input_path+'/Data_OT_Small.csv')

#Plotting data points

x1 =df_data['Intensity of event (in/hr) (real data)']
y =df_data['Failure Binary']

#Plotting functions
plt.scatter(x1,y,color='C0')
plt.xlabel('Intensity of event (in/hr)',fontsize=20)
plt.ylabel('Failure/No Failure',fontsize=20)
plt.show()


#Plotting logistic function to create fragility curve

x = sm.add_constant(x1)

reg_log = sm.Logit(y,x)
results_log = reg_log.fit()

def f(x,b0,b1):
return np.array(np.exp(b0+x*b1) / (1 + np.exp(b0+x*b1)))
x_pred = np.arange(0,15,0.001)

f_sorted = np.sort(f(x_pred,results_log.params[0],results_log.params[1]
))
x_sorted = np.sort(np.array(x_pred))

plt.scatter(x1,y,color='C0')
plt.xlabel('IM', fontsize = 20)
plt.ylabel('Probability of Failure', fontsize = 20)
plt.plot(x_sorted,f_sorted,color='Black', linewidth=3)
```

Appendix H Python Code (Small Dams – padded)

```python
#Import the required libraries
import os
import numpy as np
import pandas as pd
import statsmodels.api as sm
import matplotlib.pyplot as plt
#Change working directory

project_path = '/content/drive/MyDrive/Dam Project/Fragility Analysis'
os.chdir(project_path)
input_path = os.path.join(project_path, 'Input Files')
output_path = os.path.join(project_path, 'Output Files')
print(os.getcwd())
#Load the data

df_data = pd.read_csv(input_path+'/Data_OT_Small.csv')

#padding data

df_mod = df_data[['Intensity of event (in/hr) (real data)','Failure Binary']].copy()

zero_mat = np.zeros((1000,df_mod.shape[1]))
df_zero = pd.DataFrame(data=zero_mat, columns=df_mod.columns)
df_mod2 = pd.concat([df_zero, df_mod],axis=0)
x1 =df_mod2['Intensity of event (in/hr) (real data)']
y =df_mod2['Failure Binary']
#Plotting functions
plt.scatter(x1,y,color='C0')
plt.xlabel('Intensity of event (in/hr)',fontsize=20)
plt.ylabel('Failure/No Failure',fontsize=20)
plt.show()
#Plotting logistic function to create fragility curve

x = sm.add_constant(x1)
reg_log = sm.Logit(y,x)
results_log = reg_log.fit()

def f(x,b0,b1):
    return np.array(np.exp(b0+x*b1) / (1 + np.exp(b0+x*b1)))
x_pred = np.arange(0,15,0.001)
f_sorted = np.sort(f(x_pred,results_log.params[0],results_log.params[1]))
x_sorted = np.sort(np.array(x_pred))
plt.scatter(x1,y,color='C0')
plt.xlabel('IM', fontsize = 20)
plt.ylabel('Probability of Failure', fontsize = 20)
plt.plot(x_sorted,f_sorted,color='Black', linewidth=3)
```