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Incorporating Climate Change into the Safety of Dams Flood Risk Analysis Process

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6. AUTHOR(S)
Timothy J. Clarkin,
Jose A. Feliciano Cestero,
Daniel R. Levish,
David P. Keeney

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N/A

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Technical Service Center
Bureau of Reclamation
U.S. Department of the Interior
Denver Federal Center
P.O. Box 25007, Denver, CO 80225

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Denver Federal Center
PO Box 25007, Denver, CO 80225-0007

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14. ABSTRACT
As the Bureau of Reclamation (Reclamation) oversees hundreds of high hazard dams in the western United States, addressing flood risk is critical, particularly in the context of climate change, which is expected to alter hydrological patterns and potentially increase flood risks. This study aims to develop a comprehensive methodology for integrating climate change information into the Reclamation's Safety of Dams process for Flood Risk Analysis. A literature review identifies potential approaches for addressing climate change in flood hazard and downstream consequence analyses. The study proposes screening processes for use in the eight-year comprehensive review cycle and a three-step process for incorporating climate change into flood hazard analyses, featuring a decision-scaling approach. Further, it discusses key considerations for estimating downstream consequences amidst uncertainties in population and land use assumptions. The report concludes with proposals for future work to operationalize the screening process and use prototyping studies to improve and refine the flood hazard and downstream consequences approaches. Ultimately, this effort seeks to improve the long-term resilience and safety of dam infrastructure as climate conditions evolve.

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The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Cover Image – Link River Dam (Tim Clarkin/Bureau of Reclamation).

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Incorporating Climate Change into the Safety of Dams Flood Risk Analysis Process

Prepared by:

Bureau of Reclamation
Technical Service Center
Denver, Colorado

Additional Contributors, in alphabetical order:

Giorgia Fulcheri, Technical Service Center (TSC), Seismology and Geomorphology
Dom Galic, TSC, Risk Cadre
Subhrendu Gangopadhyay, TSC, Applied Hydrology 1
Kathleen Holman, TSC, Applied Hydrology 2
Maribeth Kniffin, TSC, Applied Hydrology 2
Marketa McGuire, TSC, Applied Hydrology 1
Jason Schneider, TSC, Risk Cadre
Amanda Stone, TSC, Applied Hydrology 2
Kevin Thielen, CGB Region, Resource Management
Kent Walker, Dam Safety Office

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Incorporating Climate Change into the Safety of Dams Flood Risk Analysis Process

TIMOTHY CLARKIN Digitally signed by TIMOTHY CLARKIN
Date: 2024.10.31 12:14:19 -06'00'

Prepared by: Timothy J. Clarkin, P.E.
Civil Engineer, Applied Hydrology 1, 86-68210

JOSE FELICIANO CESTERO Digitally signed by JOSE FELICIANO CESTERO
Date: 2024.11.01 07:05:30 -06'00'

Prepared by: José A. Feliciano Cestero, P.E.
Civil Engineer, Geographic Applications and Analysis, 86-68260

DANIEL LEVISH Digitally signed by DANIEL LEVISH
Date: 2024.11.01 07:18:02 -06'00'

Prepared by: Daniel R. Levish, Ph.D.
Geologist, Seismology and Geomorphology, 86-68330

DAVID KEENEY Digitally signed by DAVID KEENEY
Date: 2024.11.01 09:37:10 -06'00'

Prepared by: David P. Keeney, M.S.
Meteorologist, Applied Hydrology 1, 86-68210

JADE SODDELL Digitally signed by JADE SODDELL
Date: 2024.11.06 08:20:15 -07'00'

Peer reviewed by: Jade R. Soddell, Ph.D.
Manager, Applied Hydrology 1, 86-68210

Acronyms and Abbreviations

AFP	annualized failure probability
ALL	annualized life loss
CAS	corrective action study
CMIP	Coupled Model Intercomparison Project
CR	comprehensive review
DS	decision scaling
DSO	Dam Safety Office
DV	depth × velocity
EPA	Environmental Protection Agency
FAC	Project Planning and Facility Operations, Maintenance, and Rehabilitation
FD	final design
FHA	flood hazard analysis
GCM	general circulation model
GHCN	Global Historical Climatology Network
HUC	Hydrologic Unit Code
ICLUS	Integrated Climates and Land Use Scenarios
ICOLD	International Commission of Large Dams
IE	Issue Evaluation
NOAA	National Oceanic and Atmospheric Administration
PAR	population at risk
PDF	probability density function
PFM	potential failure mode
RCEM	Reclamation Consequence Estimating Methodology
RCPs	representative concentration pathways
Reclamation	Bureau of Reclamation
RIDM	Risk-Informed Decision-Making
SNOTEL	Snow Telemetry
SOD	Safety of Dams
SSPs	shared socioeconomic pathways

U.S.	United States
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
Water(SMART)	Sustain and Manage America's Resources for Tomorrow

Symbols

ºF	degrees Fahrenheit
±	plus or minus

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Figures

Executive Summary

As the owner of hundreds of high hazard dams in the Western United States (U.S.), the Bureau of Reclamation (Reclamation) considers flood risk in making decisions to ensure the safety of its dams. Climate change threatens to alter hydrology in basins across the U.S., potentially resulting in increases in flood risk. However, the quantitative impacts of climate change on probabilistic flood loadings have not been considered in Reclamation's risk assessments and decision-making up until now. The goal of this study was to develop a methodology for incorporating climate change information into the Reclamation Safety of Dams (SOD) process for Flood Risk Analysis. Incorporating climate change information would help make dam safety decisions more resilient to future changes, by allowing decisions to consider and address potential future changes to flood risk. This report summarizes the findings of a literature review, outlines initial conclusions for technical aspects of developing climate change informed, hydrologic hazard estimates and projected downstream consequences estimates, and provides recommendations for additional studies necessary for formalizing and finalizing methodologies. The methodologies developed and recommended by this report provide a framework to incorporate climate change information into the Reclamation SOD process for Flood Risk Analysis; however, they are not considered final and will continue to be refined through additional phases of study and prototyping analysis studies of dam sites.

The Safety of Dams (SOD) Process

The SOD process includes an 8-year recurring cycle of comprehensive reviews (CRs) for high hazard dams in Reclamation's portfolio, in which Reclamation reviews design and risk information for each dam. Types of risk include flood (often referred to as "hydrologic"), seismic, and various other static risk considerations. When flood hazard information is found to be deficient, flood risk is estimated to be near the visual guidelines. Alternatively, when the interpretation of flood risk could be affected by key uncertainty sources, the SOD process provides an avenue for justifying further study and a phased approach to resolving identified dam safety issues. Flood hazard analysis (FHA) and information on downstream consequences are used to develop the risk estimates that inform decision-making throughout this process. To date, neither flood hazard nor downstream consequences analyses have consistently considered projections of future conditions. Therefore, in basins substantially impacted by climate change, considering the potential future changes in flood hazards and population at risk could help support long-term decision-making.

Literature Review

Section 2 summarizes the literature review conducted as part of this study, highlighting the need for improved methodologies. After providing an overview of climate science and distinguishing between top-down approaches—which rely on model-driven scenario analyses—and bottom-up approaches—which assess vulnerabilities first—the review focused on the two main areas of study: FHA and downstream consequences. Current Federal (e.g., Bulletin 17C) and

Reclamation guidance for FHA does not address how to incorporate climate change information in these analyses, and there is not yet a consensus approach in the academic and dam safety communities. Section 2 ultimately recommends a bottom-up approach called "decision scaling" for use in FHA.

Emerging research has begun to address climate change effects on downstream consequences, yet similar to flood hazard analysis there remains a lack of consensus in methodologies to estimate downstream impacts and integrate land-use projections. At this stage, no single methodology for estimating downstream consequences was identified, and instead a set of additional tasks are proposed. Overall, this literature review underscores the need for a unified methodology to address climate change in both FHA and direct downstream consequences (i.e., loss of human life).

Comprehensive Review (CR) Screening Process

Section 3 focuses on the considerations of climate change in the CR process. The CR cycle is a key component in how Reclamation continually monitors, evaluates, and assesses risk for its dams. Currently, the flood hazard review includes some high-level analysis of projected monthly streamflows for the basin but is not used in updating loads or decision-making. Trends in climate change information are not considered in updated downstream consequences information during the CR. The CR process represents an opportune framework for conducting screening for climate change impacts. Both screening processes use a similar three step approach:

1. **Consider historical change:** study historical streamflow and meteorological records to understand ongoing change.

2. **Consider future change**: analyze projected changes to streamflow and meteorology to understand predicted change.

3. **Make recommendation:** meet with team to determine implications of Steps 1 and 2.

As each dam is evaluated every 8-years, these series of checks can be repeated to determine if further analysis is needed at each site.

Climate Change in Flood Hazard Analysis (FHA)

Section 4 presents a methodology for incorporating climate change information into FHA after a deficiency has been identified for a dam and an issue evaluation or it is determined that more detailed study is needed. The proposed methodology is based on a decision scaling approach and includes three steps:

1. **Identify vulnerabilities:** study the facility and basin to understand what drives flood risk and identify thresholds for decision-making.

2. **Hazard exploration:** use sensitivity analysis to understand what climate conditions would result in flood risk exceeding the decision-making threshold.

3. **Climate informed hazard estimation:** analyze climate projections to determine if the future is more or less likely to result in conditions that exceed the decision-making threshold.

While decision scaling is often used to analyze systems with multiple benefits and potential vulnerabilities, the recommended methodology focuses on flood hazards and flood risk at dams. Thus, the focus is on how climate change affects extreme flood events and in turn societal risk from dam failure.

Climate Change in Downstream Consequences

Section 5 focuses on a methodology for estimating downstream consequences, also when a deficiency has been identified. While a methodology was not identified for this aspect of the study, the section outlines key considerations in developing a methodology in the future. Discussion focuses on uncertainties in population projections, settlement patterns, and channel and floodplain roughness assumptions.

Proposal for Future Work

Section 6 concludes the report with a summary of what was accomplished and presentation of initial proposals for continued work to refine and develop the screening processes and methodologies for projected flood hazards and population at risk. **The methodologies developed and recommended by this report are not considered final and will continue to be refined through additional phases of study and prototyping studies.**

Future Work on Comprehensive Review Screening Process

As the datasets and tools necessary for conducting the proposed screening processes are not currently available, this section outlines a proposal for additional work needed for proper implementation. For future work on the CR screening process, this report proposes three main tasks:

- **Data collection:** collect historical data and climate change information for use in screening process.

- **Analysis:** develop a tool for implementing the statistical tests identified for the screening process.

- **Storage and Dissemination:** develop a database and web-based tool or repository where the collected data and analysis results can be stored and viewed by CR team members.

Future Work on Projected Flood Hazards and Downstream Consequences Analyses

While the efforts to incorporate climate change information into flood hazards and downstream consequences reached different levels of completion, both would benefit by further work to test and refine the proposed guidance. Prototyping studies are needed for both aspects, to better identify flood driving mechanisms, selection of appropriate climate change information (e.g., emissions scenarios and global climate models), and improve the methodology before broader application. For future work to improve the methodologies through prototyping analyses, this report proposes the following workflow:

- **Select prototyping sites**: Identify 3–5 dams across Reclamation's portfolio.
- **Conduct prototyping study**: Apply identified methodologies for one dam at a time.
- **Modify methodology**: Refine and improve methodologies based on findings of each prototyping study.

1.0 Introduction

1.1 Project Background

This report was prepared by the United States (U.S.) Bureau of Reclamation (Reclamation), Technical Service Center, and Dam Safety Office (DSO) as part of the Water Resources Planning Office's Sustain and Manage America's Resources for Tomorrow (WaterSMART) Program, Climate Change Case Study request for proposals. The goal of this study was to develop a methodology for incorporating climate change information into the Reclamation Safety of Dams (SOD) process for flood risk[1] analysis. As the owner of hundreds of high hazard dams in the Western U.S., Reclamation considers flood risk in making any decisions relevant to the condition and operations of its dams. These decisions range from structural modifications (e.g., replacing a spillway or outlet works) to operational changes (e.g., changing seasonal guide curves). Reclamation's SOD process requires probabilistic flood loadings information to evaluate the risk of hydrologic potential failure modes (PFMs). Climate change threatens to alter hydrology in basins across the U.S., potentially resulting in increases in flood risk. However, the quantitative impacts of climate change on probabilistic flood loadings have not been considered in risk assessments and decision-making, up until now. Incorporating climate change information would help make decisions more resilient, by allowing decisions to consider and account for future changes to flood risk. Thus, a methodology for addressing the effects of climate change in the SOD process is needed.

This study examines the risk-informed decision-making process and the challenge of incorporating climate change information and the associated uncertainties into that process. This report summarizes the findings of a literature review (section 2), outlines initial conclusions for technical aspects of incorporating climate change information into the SOD process (sections 3–5), and provides recommendations for additional studies necessary for formalizing and finalizing methodologies (section 6). This study provides guidance for determining when climate change information has the potential to impact the SOD process and how to incorporate that information in a scientifically informed manner.

1.2 Safety of Dams (SOD) Process and Climate Change

This section describes the SOD process and components pertinent to this report. This is a high-level summary and simplification of the process. For more detailed information, the reader is directed to the pertinent Reclamation Manuals, such as FAC[2] PO2, FAC 01-07, and FAC 06-01, which can be found on the Reclamation website[3]. While the SOD process considers multiple

[1] Within Reclamation's risk analysis framework this is referred to as "hydrologic risk." However, as hydrologic risk includes both extremes—floods and droughts—the term "flood risk" will be used throughout this report to clarify this study's focus on risk from floods.
[2] FAC is a three-letter alpha code for the subject area Project Planning and Facility Operations, Maintenance, and Rehabilitation
[3] https://www.usbr.gov/recman/index.html.

types of PFMs, including flood, seismic, and static PFMs, this study focuses on aspects related to flood PFMs only. The SOD process begins with eight-year recurring cycle of comprehensive reviews (CRs) for high hazard dams in Reclamation's portfolio. During the CR, existing flood hazard information for the dam is reviewed and evaluated to determine if it is appropriate for use in the current CR risk analysis. When flood hazard information is found to be deficient, flood risk is estimated to be near the visual guidelines, or interpretation of risk could be affected by a key uncertainty, a dam safety case may be built that there is increasing justification to better understand the risks via an issue evaluation (IE). If the IE leads to the conclusion that there is increasing justification to reduce the risk, a corrective action study (CAS) and final design (FD) will be conducted to evaluate structural and/or operational changes to the dam. In each phase (IE, CAS, and FD), a risk analysis is conducted to estimate the risk for the dam or risk during construction, in the case of FD. This process involves many engineers and scientists across many disciplines. Each of these components of the SOD process are shown in figure 1. The following sections describe the components in more detail and focus on how climate change information is (or is not) currently considered.

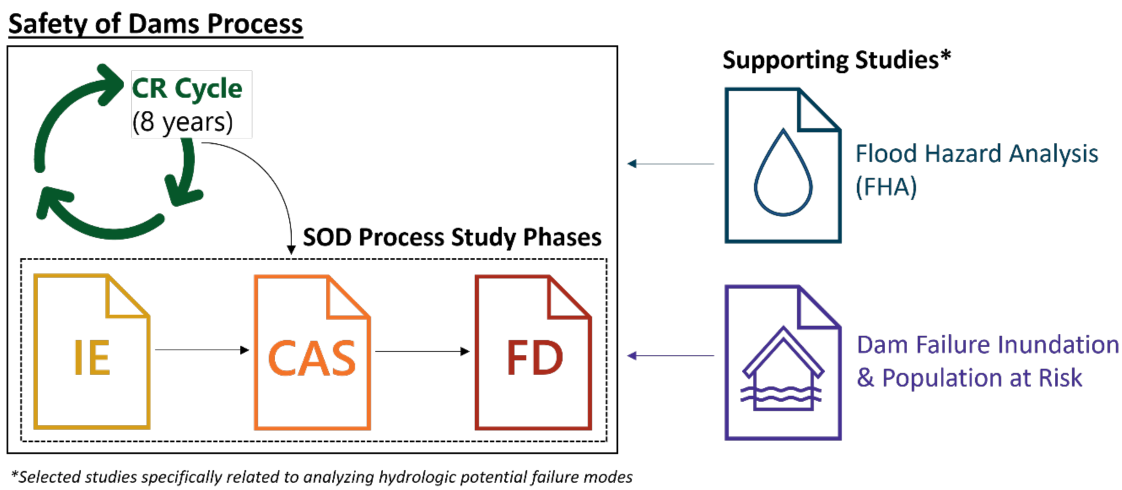


Figure 1.—Schematic of the Safety of Dams process—including comprehensive review, issue evaluation, corrective action study, and final design—and selected supporting studies specifically related to analyzing flood potential failure modes.

The CR conducted every eight years for high hazard dams in Reclamation's portfolio is a key component in how Reclamation continually monitors, evaluates, and updates risk estimates for its dams. Each year, CRs are completed for approximately 35–40 dams in Reclamation's portfolio. As described earlier, through the CR process, existing flood hazard information for the dam is reviewed and evaluated to determine if it is appropriate for use in the current CR risk analysis. Currently, the flood hazard review includes some high-level analysis of climate change information trends for the basin, focused on monthly streamflow statistics. However, this analysis considers only one aspect of climate change (resulting streamflow) and is not currently used in updating loads or decision-making. Similarly, while population at risk (PAR) estimates are updated as part of each CR, climate change information and population trends are not considered in completing these updates to downstream consequences information. The CR cycle represents an important opportunity for early detection of climate change impacts, as each dam can be reanalyzed and reevaluated every eight years. Section 3 presents some proposed screening processes for incorporating climate change information into the CR cycle.

When a dam safety issue is identified, additional phases of study are undertaken to better understand and mitigate risk. Risk estimates are used to inform decision-making throughout the SOD process. Risk is quantified in terms of the annualized failure probability (AFP) and the annualized life loss (ALL), the latter being a product of the AFP and estimated life loss (Reclamation 2022). Life loss is the primary measure used by Reclamation in estimating downstream consequences[4] in Risk-Informed Decision-Making (RIDM) (Reclamation 2022). To estimate AFP, flood loadings are developed through the combination of a flood hazard analysis (FHA) and reservoir routing analysis. To estimate downstream consequences, a dam failure inundation study and a PAR study are conducted. Thus, when considering flood PFMs, the two primary inputs to the risk analyses and decision-making process used within the SOD process are studies evaluating flood hazards and studies evaluating downstream consequences. Both of these types of underlying studies represent key opportunities to incorporate climate change information into the SOD process. Both are described in more detail in the following paragraphs.

1.2.1 Flood Hazard Analysis (FHA)

The FHA is a detailed study of available at-site and regional streamflow and precipitation, and paleoflood information for the basin. Current federal guidelines are published in Bulletin 17C (England et al. 2018), which outlines the data and methods used in flood flow frequency analysis. The FHAs often involve multiple lines of evidence, such as a statistical streamflow analysis, paleoflood information, and rainfall-runoff modeling, and result in estimates of the magnitudes and probabilities of rare floods. The resulting floods (or hydrographs) from the FHA are used in reservoir routing analysis to estimate if critical elevations are reached, operational capacity and duration of the spillway and/or outlet works flows, or if the dam is overtopped.

These hydrographs have associated probabilities (e.g., 100-year flood or 1 percent annual exceedance probability) and can be described in terms of multiple flood characteristics, which include peaks, volumes, durations, and seasonality. These flood characteristics are defined as follows (figure 2):

- **Peak:** the maximum flow ordinate in the hydrograph.

[4] Consequences herein refers to direct downstream consequences, i.e., loss of human life. While direct downstream consequences of a dam failure are the primary measure of consequences in the SOD process, indirect consequences (i.e., economic loses, environmental impacts, impacts to critical infrastructure, etc.) are beginning to be considered within Reclamation's RIDM as potential incidents instead of PFMs.

- **Volume:** the total area beneath the hydrograph, typically determined by summing the product of flow and time for each hydrograph ordinate.
- **Duration:** the total elapsed time for the hydrograph, typically determined as the period when flow exceeds baseflow.
- **Seasonality:** the month or season during which the flood occurs.

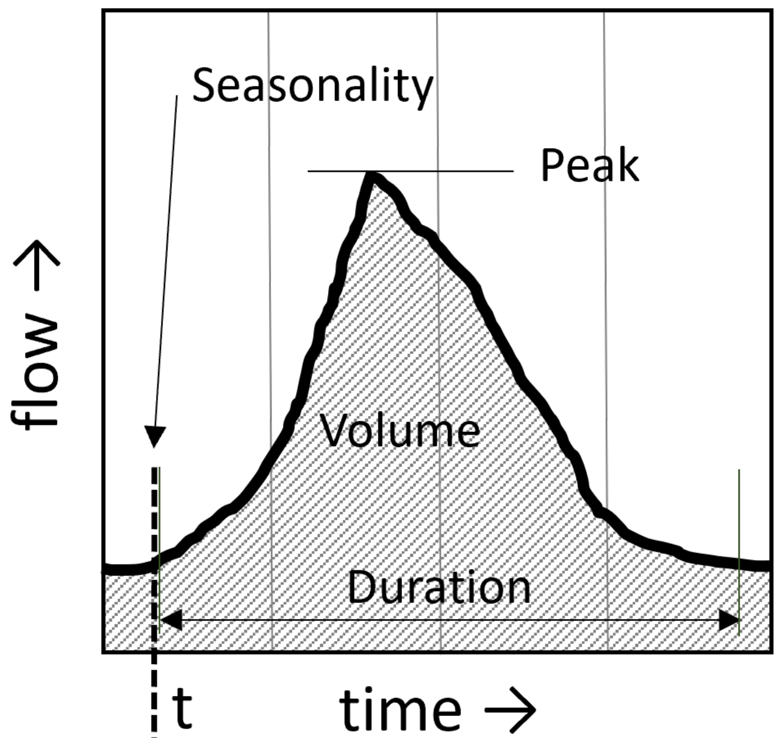


Figure 2.—Example schematic showing a hydrograph and highlighting the flood characteristics described in the text: peak is the maximum flow ordinate in the hydrograph; volume is the total area beneath the hydrograph; duration is the total elapsed time for the hydrograph; and seasonality is the month or season during which the flood occurs.

Depending on the dam, reservoir routing analysis may be more or less sensitive to some of these flood characteristics. For instance, a dam with a small storage capacity and large spillway capacity is likely intended to pass large floods and would be more sensitive to peak flows exceeding spillway capacity. Other dams may be more sensitive based on their ability to store large floods (volumes), sustain high releases (duration), or be adequately drawn down prior to a flood (seasonality). While related, each of these flood characteristics may have different dominant driving climate variables and be affected differently by climate change. Potential flood impacts may include but are not limited to changes in precipitation, storm characteristics, storm types, wildfire or other disturbance changes to watershed characteristics (such as vegetation and infiltration rates), snowpack dynamics, storm seasonality, and reservoir storage characteristics (Reclamation 2021b; Seneviratne et al. 2021).

The results of the reservoir routing analysis are used in a risk analysis along with other information to evaluate the probability of failure by a given PFM. Currently, one of the key assumptions of FHA is stationarity, thus climate change information (or even basin trends) is not considered. However, in basins impacted by climate change, this assumption of stationarity may result in misrepresentation of future (and even current) flood hazards. Incorporation of climate change information in the Reclamation SOD process is of great interest due to how climate change may alter the flood risk for Reclamation dams and appurtenant structures. Estimating the impact of climate change would help make decisions for these dams more resilient. Thus, a methodology for addressing the effects of climate change within FHA is needed. Section 2 presents a literature review and section 4 a proposed methodology for developing projected flood hazards using climate change information.

1.2.2 Downstream Consequences

Releases from a dam have the potential to generate adverse impacts on downstream areas. These impacts can be due to the operation of the hydraulic features of the dam (i.e., spillway, outlet works, etc.), due to the overtopping of the dam if the hydraulic features are not sufficient to handle a flood event, or with the eventual failure of the dam if conditions at the dam deteriorate in a way that intervention to avoid a failure is unsuccessful. These impacts are typically called downstream consequences or consequences. These terms are used interchangeably throughout this report.

Downstream consequences estimation requires data obtained from a dam failure inundation study and a PAR study (Reclamation 2019). For a flood PFM, a dam failure inundation study takes the results from the reservoir routings and applies them as initial conditions in a breach model of the dam (the dam is often assumed to fail either by overtopping or internal erosion) to calculate a breach hydrograph. This hydrograph is then routed downstream to calculate the maximum flood extent, maximum flood depth, flood wave travel times (wave front and peak), and the flood intensity[5]. Estimation of life loss resulting from flooding requires an understanding of the following factors (Reclamation and U.S. Army Corps of Engineers [USACE] 2019):

- Flood characteristics including maximum extent, depth, velocity, flood wave travel time;
- PAR in the flooded areas;
- warning and evacuation assumptions for that PAR, and
- estimation of fatality rates.

[5] flood intensity is defined as the product of maximum depth and maximum velocity ($depth \times velocity$) or DV

A PAR study uses the results from the inundation analysis to estimate the population located within the maximum flood extent. The results from these two studies are then used to estimate the downstream consequences using Reclamation Consequence Estimating Methodology (RCEM; Reclamation 2015b). The RCEM is an empirical method to estimate life loss due to dam failure and is based on estimates of documented fatalities due to historic dam failures. It correlates the fatality rates (life loss divided by the total population affected by the flood) to be applied to the PAR with the flood intensity and warning time (estimated using the flood wave travel time) experienced by the PAR. The result of this process is an estimate of life loss associated with a PFM to be used in estimating the ALL. Currently, neither climate change nor population growth are considered in dam failure inundation studies nor PAR studies. However, if projected flood hazard information is used in risk analysis, downstream consequences should also be used for a similar future period (e.g., 50 years). Section 5 presents potential options for projecting downstream consequences.

1.3 Study Overview

This project aimed to develop a methodology for incorporating climate change information into SOD flood risk analyses. Because of the complexity of the SOD process, the working group included a multidisciplinary team of Reclamation engineers and scientists. Working group team members from the Technical Service Center and DSO included representatives from Applied Hydrology, and Seismology and Geomorphology for flood hazards; Geographic Applications and Analysis for downstream consequences; and the Civil Engineering Services Division, Geotechnical Services Division, and DSO for reservoir routing and risk analysis.

The study approach consisted primarily of (1) a curated literature review and (2) discussions and work sessions. The literature review approach and findings are summarized in section 2. The work sessions that followed the literature review resulted in identification of methodologies for incorporating climate change information into the SOD process. These methodologies are documented in the later sections: section 3 describes the proposed methodologies for incorporating climate change information into the CR process; section 4 describes the proposed methodology for incorporating climate change information into FHA; and section 5 describes some initial insight into developing projected downstream consequences in light of climate change and population change. section 6 concludes the report with a discussion of what was accomplished and recommendations for continued work.

Figure 3 shows a modification of the schematic of the SOD process (see figure 1), which includes annotations showing which parts of the process are covered by which sections of this report.

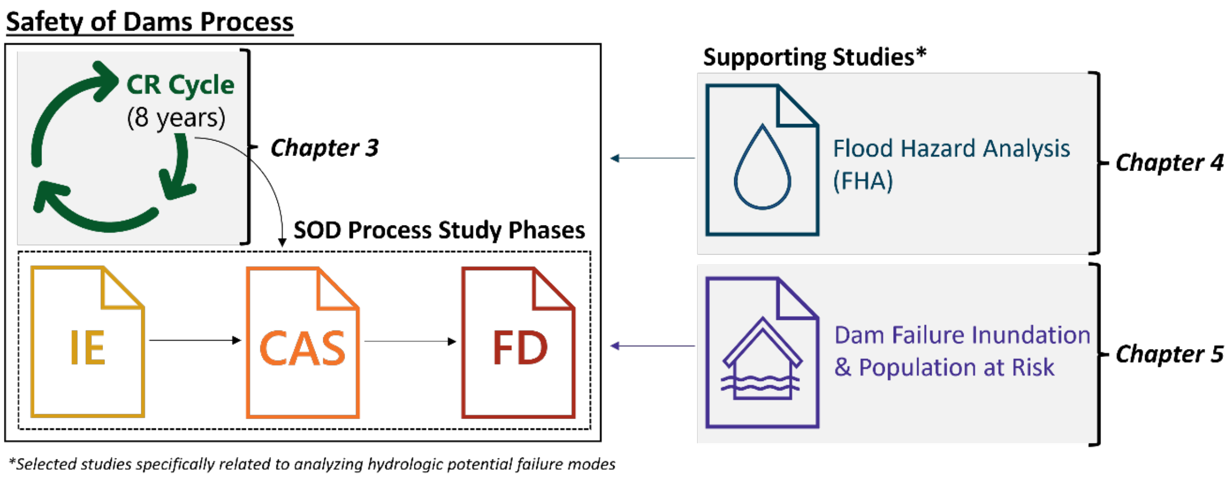


Figure 3.—Schematic of the Safety of Dams process—including comprehensive review, issue evaluation, corrective action study, and final design—and selected supporting studies specifically related to analyzing flood potential failure modes.[6]

2.0 Literature Review

2.1 Section Overview

The literature review focused on a curated list of literature, including references described in Bulletin 17C (England et al. 2019), current guidance by governmental agencies, and other references proposed by working group members. The literature review is believed to be representative of the state of the field, even if not exhaustive of all possible emerging methodologies and current literature. No key word search was used to select papers for review.

The breadth of research focused on climate science is extensive. While other papers have attempted to summarize the state of climate science (e.g., the U.S. Geological Survey [USGS] in Terando et al. 2020), this report provides only a brief context on climate science in section 2.2, before describing the literature reviewed regarding flood hazards in section 2.3, and downstream consequences in section 2.4.

2.2 Climate Science

Climate variability has been a topic of research for hundreds of years; however, over the last century two major changes have occurred. First, observations of multiple natural variables (e.g., sea level, precipitation, temperature, etc.) have increasingly suggested a shift in the Earth's

[6] Annotations have been included showing which parts of the process are covered by which sections of this report.

climate, from what for some time was thought to be "stationary" to recognition of the "non-stationary" reality of Earth's climate (Milly et al. 2008). Second, climate science has been propelled by the proliferation of data, increasingly sophisticated models, and an exponential growth in computing power on which the complex models run. In particular, general circulation models (GCMs),[7] are physics-based, numerical representations of Earth's climate processes that apply conservation of mass, momentum, and energy to coupled oceanic and atmospheric systems. The Coupled Model Intercomparison Project (CMIP) is an international modeling effort that aims to better understand past, present, and future climate changes through coordinated experiments and intercomparison efforts.

One important feature of GCM simulations is the ability to represent different possible futures of greenhouse gas concentrations in the atmosphere as "scenarios." Two primary categories of scenarios are representative concentration pathways (RCPs) and the more recent shared socioeconomic pathways (SSPs). The RCPs were a feature of the CMIP Phase 5 effort and represented different futures based on global greenhouse gas emissions and the resulting relative concentration of greenhouse gasses in the atmosphere when compared to the pre-industrial era. In contrast, SSPs are a more recent approach and represent different futures based on global socioeconomic development (and resulting greenhouse gas emissions) and have interdependence with the RCPs—they are not mapped to one another directly. The most frequently used RCPs are RCP2.6, RCP4.5, RCP6.0, and RCP8.5 (Terando et al. 2020), representing a scenarios in which the atmosphere's radiative forcing in 2100 is 2.6, 4.5, 6.0, and 8.5 Watts per square meter higher than pre-industrial levels, respectively. Because future global development decisions are unknown, each of these scenarios is considered to have equal probability. The SSPs describe plausible alternatives in trends in the evolution of society and ecosystems over a century timescale in the absence of climate change or climate policies (O'Neill et al. 2014). The SSPs are named 1 through 5 and represent different combinations of climate mitigation/adaptation strategies; high mitigation/adaptation (SSP1, best case scenario); no mitigation (SSP5, worst-case scenario).

While the GCM simulations published through the CMIP framework form the basis for international and national climate assessments, such as the Intergovernmental Panel on Climate Change Sixth Assessment Report (IPCC 2023) or the U.S. Global Change Research Program Fifth National Climate Assessment (USGCRP 2023), limitations remain in the applicability of GCM output in particular areas of research related to water management. These limitations include (1) the relatively coarse spatial scale of the models requiring downscaling or other means to convert model output to meaningful watershed scales (Mearns et al. 2014), and (2) biases in representation of extreme precipitation resulting in propagated bias in modeled hydrologic processes (Mehran et al. 2014; Abdelmoaty et al. 2021). Because of these limitations, practitioners and researchers have taken many different approaches to downscaling GCM output to different spatial and temporal scales for informing decision-making, sometimes introducing additional discrepancies, uncertainty, and error (Vano et al. 2020). Because orographic impacts

[7] While GCM can also sometimes stand for "global climate model", this report uses "general circulation models." The meaning of the two terms is equivalent.

often affect Reclamation basins, reliable methods are needed for downscaling GCM output to inform basin-scale hydrology and meteorology. This is important, since it is likely that changes in extreme precipitation diverge from changes in the mean (Tabari 2020).

2.3 Flood Hazards

Current guidance for FHAs is published in "Guidelines for Determining Flood Flow Frequency—Bulletin 17C" (England et al. 2019) and various Reclamation documents and manuals (Reclamation 1989, 2006, 2013, 2023). The methods outlined in these documents do not address how to incorporate climate change information and instead assume stationarity. Federal guidance has not reached consensus for how to quantitatively consider climate change information in estimating flood hazards (England et al. 2019). The following paragraphs discuss some of the approaches encountered as part of the literature review. In conducting literature review, references recommended by Bulletin 17C were considered in addition to others identified by team members. Literature reviewed ranged from flood frequency within the context of non-stationarity to broad frameworks for climate change analysis and decision-making.

Many have tried to address the question "whither water management?" posed by Milly et al. (2008). For example, some have explored the mathematical implications of non-stationarity and climate change information in flood frequency estimates (Stedinger and Griffis 2011; Salas and Obeysekera 2014; Salas et al. 2018) or sought to address the large uncertainties introduced through extrapolation and modeling (Serinaldi and Kilsby 2014; Meresa et al. 2020). Meanwhile, other research has focused on understanding the anomalous or episodic conditions associated with extreme floods (Hirschboeck 1987; Jain and Lall 2001; Liu et al. 2020), and long-term climate variability through use of longer sighted paleoclimate information (Redmond et al. 2002; Harvey et al. 2011; Rodysill et al. 2018).

While these studies have been on the more academic and theoretical side, governmental and non-governmental organizations have been releasing frameworks for climate change and decision-making. The dominant approach is typically categorized as "top-down" and consists of a model driven approach that uses traditional scenario analyses to determine the range of future conditions to inform decision-making (Brown et al. 2012). In contrast, "bottom-up" approaches generally focus on vulnerability assessment first, establishing decision thresholds prior to selecting scenarios and projecting future conditions (Marchau et al. 2019). Examples of both approaches can be seen in the literature published in the last decade.

In Reclamation, commonly used approaches for analyzing climate change can be categorized as top-down. For instance, when incorporating climate change information into Basin Studies (part of the WaterSMART[8] program; Reclamation 2014) and the SECURE[9] Water Act Report to Congress (Reclamation 2021), the general approach has been to use a GCM projection

[8] SMART stands for Sustain and Manage America's Resources for Tomorrow
[9] SECURE is typically capitalized, but is not an acronym.

membership diagram and select GCMs representative of various future climate designations (e.g., warm-wet, central tendency, etc.) and use the modeled output in decision-making. However, these studies and methods do not directly address flood risk. While various frameworks for climate change have been published (Brekke et al. 2009; Raff et al. 2009), these frameworks have not been widely implemented because of the large uncertainties in the projections and unknown roadmap for incorporating into Dam Safety processes. Thus, the need for developing a methodology which incorporates climate change information into Reclamation's FHA remains.

The USACE recently published guidance for conducting in-depth analysis for projected hydrology and meteorology (USACE 2023). While this guidance initially appears similar to a bottom-up approach—beginning with identification of system vulnerabilities and related climate variables—the guidance overall appears to resemble a top-down approach. The approach includes a modeling chain, working its way through emissions scenarios, GCMs, downscaling, hydrologic modeling, that is then integrated into USACE's existing planning and decision-making framework. In Canada, Ouranos (a non-profit organization funded by the province of Quebec in Canada) recently released a report featuring the results of three working groups focused on climate change and dam safety (Ouranos 2021). Working group 1 developed an approach resulting in the largest design flood, working group 2 chose an array of approaches that consider "as many uncertainties as possible", and working group 3 focused on how to use the information from working groups 1 and 2 in a decision-making framework, largely based on the framework published by International Commission of Large Dams (ICOLD) (ICOLD 2016). For another example of a top-down approach, in Australia the Australian Rainfall and Runoff (ARR) guidance presents a framework for determining if climate change information should be incorporated into design flood estimation (Ball et al. 2019). Ultimately, the ARR guidance presents a top-down approach that uses pre-processed projections of future trends in precipitation-frequency and is recommended for use in studies with long enough planning horizons and residual risk (Bates et al. 2019). While not an exhaustive list, each of these approaches (USACE, Ouranos, and AAR) use more traditional, top-down techniques.

Other organizations have been developing and publishing guidance with more bottom-up aspects. For example, guidance published by ICOLD (2016) presented a general system-wide, collaborative approach, and listed multiple options for analyzing climate change impacts, ranging from "what-if" sensitivity type analyses to a modeling chain approach similar to the USACE approach described above. The United Nations Educational, Scientific and Cultural Organization (UNESCO 2018) and International Hydropower Association (IHA 2019), both published guidance representing "bottom-up", system risk driven frameworks. In the academic sphere, the term 'decision-making under deep uncertainty' is quickly emerging, with an array of vulnerability and decision-driven approaches (Brown et al. 2012; Ray and Brown 2015; Marchau et al. 2019). For example, the concept of decision scaling (DS) presented in Brown et al. (2012) is described as replacing the question "what will the future climate be?" with the question "is the climate that favors action A more or less likely than the climate that favors action B?" This, and other 'decision-making under deep uncertainty' approaches, shift the decision-making process to a more collaborative process focused on system vulnerabilities. Again, while not an exhaustive list of publications, each of these frameworks and studies feature, or include, bottom-up techniques.

Meanwhile, in the dam safety community, emerging research explores the adverse effects of climate change connected to dam safety issues, such as extended drawdown (Olsen and Malama 2021), quantification of risk (Broit 2023), stress on water resources (Chavan and Sharma 2023), and changing probable maximum floods (Hughes et al. 2023; King and Micovic 2023). For a more specific example, Fluixá-SanMartín et al. (2018) focused on developing a risk analysis framework for translating from climate change scenarios all the way to economic and social consequences of dam failure. The framework included representation of gate performance statistics, PFMs, and an array of societal risks associated with dam failure. The framework was later applied in a case study on a dam in Spain (Fluixá-SanMartín et al. 2019). In Sweden, Energiforsk, a government funded research institute focused on energy, released a detailed literature review of climate change methodologies and presented an initial impact chain type of analysis for climate change and dam safety (Energisforsk 2023). Earlier references can also be considered in this category of dam safety, such as those from ARR (2019), Ouranos (2021), USACE (2023), and Energiforsk (2023). Another interesting perspective is the “climate-informed” methods presented by Brown et al. (2019), where GCM modeling of larger atmospheric circulation variables are considered instead of more direct variables (e.g., temperature and precipitation) for use in predicting extreme precipitation and streamflow in the basin of interest.

2.4 Downstream Consequences

Not many studies have been found in literature that look into specific methodologies to estimate the effect of climate change on downstream consequences. Fluixá-SanMartín et al. (2018) named surface roughness and water viscosity changes related to increased sediment load in the system as two variables that can be used to study the effects of climate change in the downstream routing of a dam break flood wave as part of their risk analysis framework. For accounting for population change in the PAR, the authors suggest a few approaches, from a simple extrapolation of past growth of the studied PAR into the future to more complex analysis at the local level that tries to spatially distribute future PAR (e.g., Calderón and Silva 2021). Fluixá-SanMartín et. al. (2019) used a previously established relationship between maximum reservoir pool level and peak breach flow but offered no details about how this relationship was calculated or reference to any study that performed this analysis. Furthermore, the future consequences were estimated by applying a simple national projection of population growth that does not consider the change in population due to climate change. The authors do not provide specific details about loss of life estimation but reference the 2012 Spanish Committee on Large Dams Technical Guidelines on Dam Safety (SPANCOLD 2012) which suggests DSO-99-06 (called the Graham Method) (Reclamation 1999) as one of its preferred consequences estimating methods.

The Environmental Protection Agency (EPA) published national land use changes estimates for the U.S. as part of the Integrated Climates and Land Use Scenarios (ICLUS) project (EPA 2017).

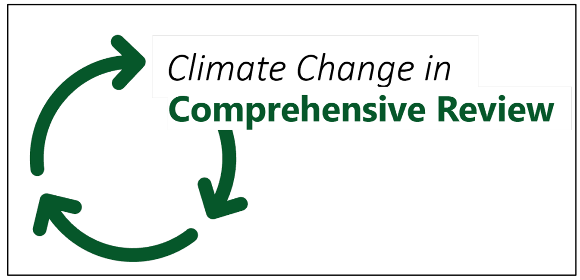
The data set provides land use time series by the decade from 2000 to 2100 based on two SSP/RCP (SSP2/RCP4.5 and SSP5/RCP8.5) combinations and two different climate models (FIO-ESM and HadGEM2). The ICLUS uses statistical relationships between population density, road capacity and land use classes to allocate new land uses in the projected dataset. The parametrization of the land use change model was based on land use changes between 2000–2010. The spatial allocation of projected land use uses a population growth model to calculate the demand for the new land uses and allocates it based on a theory that the best land use prevails (EPA 2017). The dataset provides land use projections classified in 19 distinct categories that are consistent with the standard land cover descriptions of the national land cover database. The advantage of this classification is that tables correlating values of Manning's n to national land cover database land use types are readily available in literature.

In addition to land use changes to 2100, the dataset provided by ICLUS includes population growth estimates based on two SSPs (SSP2 and SSP5). The demographic model takes into consideration Internal Revenue Service county-to-county migration from 1991–2000 to parametrize the population model; it also considers transportation networks (roads and mass transit) to predict migration and adds a dynamic climate as an amenity[10] parameter to quantify the effects of climate change into migration patterns. A sensitivity analysis of the demographic model to specific dynamic climate variables (i.e., humidity-adjusted January/July temperature and summer/winter precipitation) showed that regional migration patterns changed when these variables were included in the model versus when the model was run assuming a non-changing climate. The study also found that these differences were small compared to the differences between SSP/RCP combination scenarios. In conclusion, assumptions about fertility and migration rates had a larger effect in the overall migration patterns than the changes in regional climate due to changes in the amenities parameter assigned to specific climate variables.

[10] Climate amenity is defined in the ICLUS report as: Climate variables in association with their perceived value and putative influence on migration decisions. For example, the climate variables selected to represent climate amenities in ICLUS v2 are average monthly humidity-adjusted temperature and average seasonal precipitation for both summer and winter.

3.0 Climate Change in Comprehensive Review (CR)

3.1 Section Overview



As described in section 1.2, the SOD process includes an eight-year recurring CR cycle for high hazard-potential dams in Reclamation's portfolio. The CR cycle is a key component in how Reclamation continually monitors, evaluates, and updates risk estimates for its high-hazard dams. Similarly, the CR cycle represents an opportune framework for conducting screening for climate change impacts. As each dam is evaluated, a series of climate change screening tests could be implemented to determine if further analysis is needed at the site. As part of the CR cycle, these tests would be updated every eight-years, allowing for the screening analysis to be updated with the latest observed data and climate change information each time. This section of the report presents two proposed screening processes for use in the CR process for Reclamation's dams and include a proposal for additional work needed to implement these screening processes.

First, a flood hazard climate change screening process is presented in section 3.2. Following a DSO pilot study in 2015 (Reclamation 2015a), each CR includes a supplemental climate change analysis section, which features a summary of the projected monthly streamflow changes (Reclamation 2021a). In the current form, the supplemental climate change analysis provides the basis for qualitative discussion on climate change impacts on flood hazards but lacks the level of detail to provide quantitative insight into climate change impacts on flood hazards. This report recommends expanding the supplemental climate change analysis with trend and changepoint analysis on observed and projected timeseries of streamflow and meteorological data. Section 3.2 outlines the proposed flood hazard screening process and provides additional information on what is needed for implementation.

Second, a downstream consequences climate change screening process is presented in Section 3.3. While most CRs now include an update to PAR estimates, these estimates do not consider future population growth and resulting potential changes in downstream consequences. In areas with large growth (or decline) these estimates could play a critical role in future assessments of risk and help in building the case for (or against) the need for additional study. This report recommends incorporating a screening level analysis of population growth trends and projections in updating PAR during the CR. Section 3.3 outlines the proposed PAR screening process and provides additional information on what is needed for implementation.

Later in this report, Section 6.2 presents a description and list of tasks recommended for implementing these screening processes.

3.2 Flood Hazard Screening

This process aims to answer the question: are there projected and observed increases in flood hazards, and do they potentially impact facility risk? In order to provide a more comprehensive answer to this question, a few key factors should be considered:

- **Analyzing observed data** for the dam to determine if trends can be detected;
- **Incorporating climate change information** and findings published in other studies for the basin or region developed by Reclamation (or other entities) that provide insight into the pertinent flood mechanisms for the dam; and
- **Providing clear information and guidance** for use by CR team members in determining if additional analysis of climate change projections is warranted as part of a SOD recommendation for the dam.

The proposed flood hazard screening process is broken into the three steps outlined in the following subsections. The results of these analyses would be documented in the Supplemental Climate Change section of the Flood Hazard section in the CR.

3.2.1 Step 1: Consider Historical Climate

This step aims to answer the question: "is there a substantial increasing trend in the observed flood characteristic(s) and flood driver(s) for this dam?" **Any statistically significant trend of 2 percent per year or greater or statistically significant change point resulting in a 20 percent or greater change in mean will be considered substantial.** This step focuses on analyzing observed data to see if projected changes can already be detected. To do this, first, representative data must be collected. The following datasets will be needed:

- **Reservoir information: S**easonal guide curves (optional), area capacity information, and reservoir capacity allocation charts informed by the most recent reservoir area capacity information should be collected. These can typically be found in standing operating procedures or water control manuals, depending on the dam. Reservoir characteristics include outlet, spillway, flood control, surcharge, and safe downstream capacities, the operational flood season based on flood guide curves, and an understanding of whether the dam is designed to pass or store floods.
- **Inflow:** daily inflow data can be compiled from a combination of gaged records prior to the dam's construction, gaged records immediately upstream of the dam after construction (representing at least 85 percent of the drainage area), and/or calculated

inflows[11] for the dam. In addition, paleoflood non-exceedance information from the Paleoflood section of the Flood Hazard section of the CR should be recorded.

- **Outflow and storage (optional):** outflow and storage data can be compiled from a gage at the dam and/or internal operations data (e.g., Hydromet). If this information is unavailable, no further effort should be made to collect or estimate it as part of this screening process.
- **Meteorology:** daily precipitation, air temperature, and snow water equivalent (or snow depth) are the variables of interest. For basins less than 500 square miles, a single point observation site can be used (e.g., Global Historical Climatology Network [GHCN], Snow Telemetry [SNOTEL], etc.). For basins equal or greater than 500 square miles, spatial estimates (e.g., nClimGrid or GridMet) should be used in addition to observations from multiple sites.

If a minimum of **30 years**[12] of at-site records cannot be compiled or observations are of poor quality, multiple nearby sites should be used as a regional proxy. Once these datasets have been collected, flood characteristics (see section 1.2.1) can be analyzed.

There is a broad body of research on the topic of flood driving mechanisms that can be leveraged for this identification process (e.g., Berghuijs et al. 2016; Holman 2018; Schlef et al. 2019; Shen and Chui 2023). Potential drivers that could be considered include rainfall, rain-on-snow, and snowmelt runoff, although more detailed descriptions exist (e.g., North American Monsoon or Tropical Cyclones). Pertinent published findings should be included based on the understanding of flood driving mechanisms for the basin. Determining flood characteristics should also include data analysis using both average and event or water year basis:

- **Average:** Average flood characteristics can be described through **monthly** box-and-whisker plots containing all of the collected datasets: inflow, outflow, storage, precipitation, air temperature, and snow. The comparison of these monthly statistics should help reveal the primary flood season and possible drivers (e.g., if runoff peaks during snowmelt, it is likely snowmelt contributes to floods).
- **Event or water year:** A minimum of three of the largest floods should be analyzed. To identify these events, analysis should consider the historically largest annual inflow volume, seasonal inflow volume, maximum daily inflow (or peak), and maximum reservoir storage. For each of the selected events, the **daily** timeseries of inflow, outflow, storage, precipitation, air temperature, and snow timeseries should be plotted, as

[11] Because calculated inflows are computed using surface elevation and area capacity information from bathymetric surveys, there is the potential for abrupt changes in inflow estimates when area capacity information is updated. Dates when area capacity information has been updated should be noted and special care given in computing trends and changepoints when using calculated inflow datasets.
[12] Thirty years is commonly used "rule of thumb" minimum samples size in statistics and is often used in representing climate normals.

described above, for the entire water year. Analysis should then focus on the weeks or months leading up to the flood to understand more specifically what contributed to the floods. Antecedent and concurrent air temperature, precipitation, and changes to snowpack may lend insight into what contributed to the floods. In some cases, more events may need to be analyzed, because of the presence of multiple flood mechanisms.

The results of these average and event analyses, combined with review of reservoir information, should help identify what flood characteristic(s) contribute to risk at the dam (e.g., peaks, volumes, antecedent pool elevations, etc.). Ultimately, these efforts should help understand: the flood season (e.g., April–May–June), flood driver (e.g., rainfall), flood hydrograph duration (e.g., seven-days), and if antecedent reservoir storage plays a role (e.g., floods can occur outside of the operational flood season).

With the flood characteristics in mind, the datasets listed above (i.e., daily inflow, outflow and storage, and meteorology) can then be analyzed for changepoints and trends. Special attention should be given to the flood season and flood driving mechanisms in this analysis. Analysis of changepoints and trends should be conducted using non-parametric methods recommended in Bulletin 17C but cited from Helsel et al. (2020). Bulletin 17C recommends using a Theil trendline and used the Mann-Kendall test to calculate the Kendall Tau (τ) p-value to measure significance of trends, and the Mann-Whitney (or Wilcoxon rank-sum) and Kolmogorov-Smirnov tests for changepoints. Other statistical tests can be added as the screening process is tested and revised, including methods for considering quantile trends. In all cases, while statistical significance can be determined with a p-value equal or less than 0.05. If antecedent pool elevations contribute to the risk, it is important to also consider identifying shifts in seasonality (e.g., Villarini 2015; Beyene *pending*). Additionally, understanding if the basin has been impacted by recent wildfires could be useful in understanding changepoints and trends in a basin. Paleoflood non-exceedance information should be plotted along with inflow timeseries to show the relative magnitude.

Table 1 outlines each of the datasets, metrics, and comparisons to be made. Note that in multiple cases "comparison thresholds" are defined. These thresholds are intended to help focus the trend analysis more directly on the effect on reservoir operations (e.g., flood control space) and basin stationarity (e.g., National Oceanic and Atmospheric Administration [NOAA] Atlas 14 precipitation frequency). In some cases, the proposed thresholds presented may need to be adjusted to better represent meaningful changes. For example, if a reservoir has a small outlet works and frequently operates using the spillway, the outlet works may not be a reasonable threshold for comparison.

Table 1.—Recommended historical timeseries statistical analyses and tests

Dataset	Metric	Comparison threshold	Timeseries to test for changepoints and trends
Inflow	Peak (max mean daily) Inflow	Lesser of outlet works capacity and safe downstream capacity	1. Annual maximum series 2. Annual maximum series 10-year rolling distribution mean and SD 3. Partial duration series frequency and magnitude of exceeding threshold in any given year
Inflow	Event inflow volume (duration depends on mechanism)	Flood control space or surcharge	1. Annual maximum volume series 2. Annual maximum volume series 10-year rolling distribution mean and SD 3. Partial duration volume series frequency and magnitude of exceeding threshold in any given year
Inflow	Seasonality	Guide curve "flood season"	1. Annual maximum series date 2. Annual maximum volume series start, end, and centroid date
Outflow	Peak (max mean daily) Outflow	Safe downstream capacity	1. Partial duration series frequency and magnitude of exceeding threshold in any given year
Met.	Precip. Ann. Max	NOAA Atlas 14[13] 10 and 25-year depth	1. Annual maximum series 2. Annual maximum series date 3. Partial duration series frequency and magnitude of exceeding threshold in any given year
Met.	Precip. Ann. Total	None	1. Annual total series
Met.	Annual Air Temp	None	1. Annual mean series 2. Annual maximum series 3. Annual minimum series
Met.	Annual Max. Snow	None	1. Annual maximum series 2. Annual maximum series date 3. Annual ablation series date (first day snow is all melted) 4. Annual ablation duration series date (time between maximum and ablation)

[13] NOAA Atlas 15 may not be an applicable replacement, if distribution parameters are not published.

While expert knowledge is needed in determining whether trends and changepoints (even statistically significant ones) represent a "substantial" increase in the context of flood risk, as stated earlier any statistically significant trend of 2 percent per year or greater or statistically significant change point resulting in a 20 percent or greater change in mean will be considered substantial**.** These percentages may be revisited after the screening process has been tested. Regardless of whether increases are deemed substantial or not, this information is compiled and used to inform Steps 2 and 3.

3.2.2 Step 2: Consider Future Climate

This step aims to answer the question: "is there a substantial **increase** in the projected magnitude of runoff and flood driver(s) for this dam?" If timeseries analysis is conducted, the same definition of significance listed above should be used. However, if comparisons are only made between statistical averages of the historical period and future periods, **a substantial increase will be defined as any statistically significant increase in runoff, precipitation, or snowpack of 20 percent or greater, or statistically significant increase in maximum or minimum air temperatures of 2 degrees Fahrenheit (ºF).** This step, as in the current CR process, focuses on considering projections of future climate to understand how future flood regimes may differ from current conditions. However, while the current process focuses only on monthly streamflow (or "runoff"), the proposed process will include projections of future precipitation, air temperature, and snowpack. If available, information from the ongoing climate change and extreme precipitation study by Lybarger et al. (*pending*)[14] should be incorporated into the standard climate change information used in this step.

First, downscaled projections of runoff, precipitation, air temperature, and snowpack should be collected. This collection will likely leverage information already collected and downscaled as part of the SECURE report (Reclamation 2010), using current best estimates of downscaled climate change information. In each case, multiple emission scenarios (e.g., RCPs or SSPs) should be considered. Estimates representing median projected conditions can be used for decision-making and high (e.g., RCP 8.5/SSP 5) and low (e.g., RCP 4.5/SSP 2) can be used to bound the range of potential future changes. The historical simulations from these downscaled estimates should be compared to the seasonal patterns identified in Step 1. If there is poor agreement in seasonality and/or magnitude for the historical simulations when compared to observed records, this may indicate limitations in the downscaling and runoff simulation methods used. In these cases, the projections should be used with caution.

Next, if possible and appropriate, the same timeseries trend analyses defined in table 1 should be applied to near-term (e.g., 2025–2049) projections. If timeseries are not available or practicable, instead monthly statistics from near-term projections *can* be compared to historical simulations. Because it is unlikely that direct comparison will be possible between climate change projection information and historical data from Step 1, it is assumed the comparison will be made between the GCM projections and their respective "historical period"—currently 1981–2010. Even with this internal comparison between different periods of simulated climate information, there may be disagreement. Analysis discussion should focus on the flood driving mechanism identified in Step 1. For example, if rainfall is the primary mechanism for floods at a certain dam, the analysis discussion should focus on future precipitation frequency (e.g., the ongoing extreme precipitation study by Lybarger et al. *pending*). Or if rain-on-snow is of primary concern, the analysis discussion would focus on air temperature and snowpack projections and the potential for rain-on-snow situations due to climate change (e.g., Musselman et al. 2018). Table 2 outlines each of the comparisons that should be made.

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[14] This effort undertaken by National Center for Atmospheric Research and Reclamation seeks to evaluate downstream effects of future climate extremes through dynamical downscaling of extreme precipitation events. This study will be used to develop a west-wide screening tools to identify infrastructure that may be vulnerable to the climate projections in those regions.

Table 2.—Recommended projected climate change information comparisons

Dataset	Comparisons to make
Runoff	1. Percent change in maximum monthly runoff volume 2. Percent change in annual runoff volume 3. Change in runoff seasonality (earlier or later, etc.)
Precip.	1. Percent change in maximum monthly precipitation depth 2. Percent change in annual total precipitation depth 3. Change in precipitation seasonality (earlier or later, etc.) 4. Change in precipitation frequency distribution (if available: Lybarger et al. *pending*)
Temp.	1. Percent change in hottest month 2. Percent change in coldest month 3. Change in melt seasonality (earlier or later)
Snow	1. Percent change in maximum monthly snowpack 2. Change in melt seasonality (earlier or later)

Again, while expert knowledge is needed in determining whether projected trends and changepoints (even statistically significant ones) represent a "substantial" increase in the context of flood risk, as stated earlier any statistically significant increase in runoff, precipitation, or snowpack of 20 percent or greater or statistically significant increase in maximum or minimum air temperatures of 2 ºF will be considered substantial. These thresholds may be revisited after the screening process has been tested. Regardless of whether increases are deemed substantial or not, this information is compiled and used to inform Step 3.

3.2.3 Step 3: Make Recommendation

The third and final step aims to answer the question: do projected and observed increases potentially impact facility risk? This step focuses on providing clear information for use by CR team members in determining if additional analysis of climate change projections is warranted as part of a SOD recommendation for the dam. While informed by data collected as part of the flood hazard screening process, the discussion and decisions process should be led by the CR's Senior Engineer. The PFMs (including highly unlikely PFMs) should be discussed given the observed changes in flood characteristics (Step 1) and climate projections (Step 2). Where appropriate, routing sensitivity analysis may even be considered, to understand how magnitude changes in flows could impact routing results.

If Step 1 and 2 find that projected and observed increases in flood magnitudes and driving mechanisms are substantial and potentially impact facility risk, the CR team should consider recommending further analysis of projected flood hazards (as described in section 4) as a stand-alone study or as part of any SOD recommendations generated from the CR. If not, then no further analysis is needed at this time. This analysis and recommendation should be documented in the Flood Hazards section of the CR.

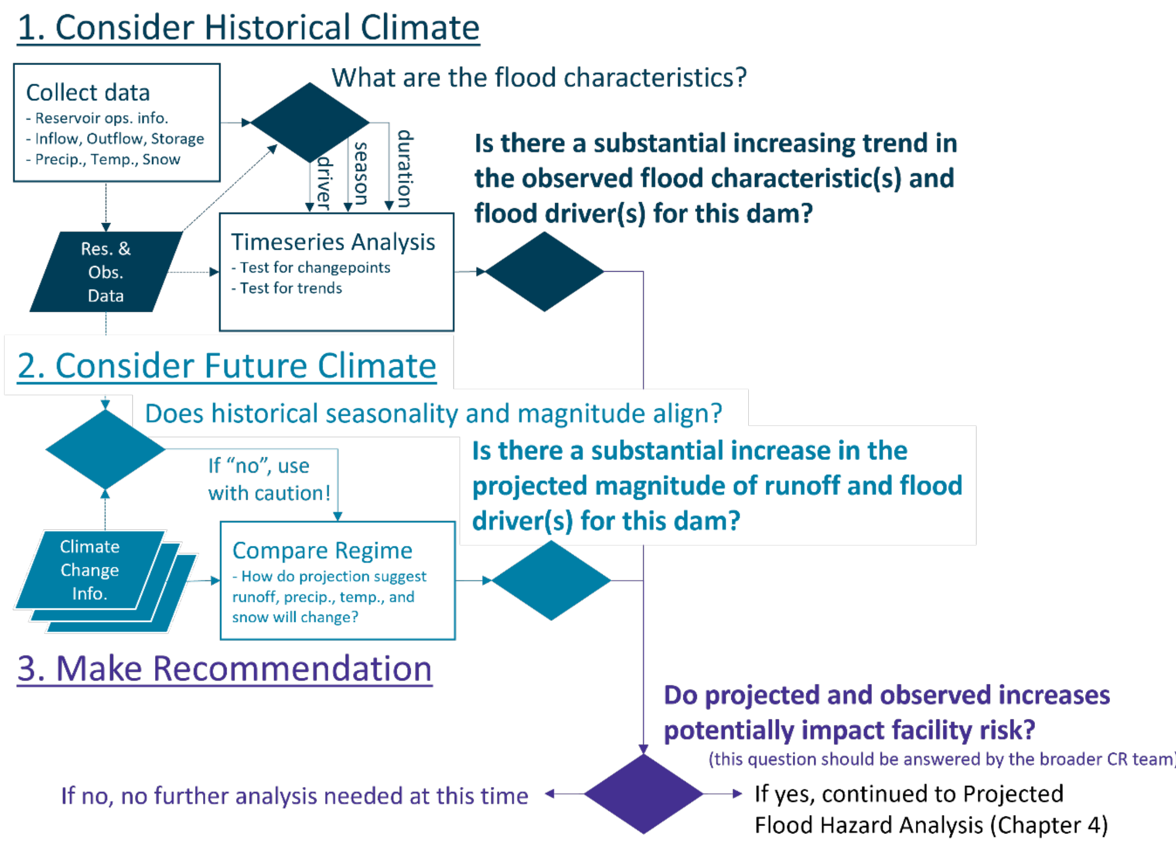


Figure 4.—Flow chart for flood hazard analysis screening process.

3.3 Downstream Consequences Screening

To provide a more predictive analysis of downstream consequences during the CR process, a few key factors should be considered. These factors are parallel to those identified for the flood hazard screening process:

- **Analyzing observed population trends** for the population centers that would be affected by a failure of the dam to determine if population is currently increasing or decreasing, to understand if projected changes are already occurring;
- **Incorporating published projections** of population change for the population centers (or region) that would be affected by the failure of the dam to provide insight into expected trends in population growth; and
- **Provide clear information and guidance** for use by CR team members in determining if additional analysis of population projections (e.g. as part of a SOD recommendation) may be warranted.

The proposed PAR screening process is broken into the three steps outlined in the following subsections. The results of these analyses would be documented in the Consequences section in the CR.

3.3.1 Step 1: Consider Historical Population

This step aims to answer the question: "is there a substantial trend in observed population change in communities potentially affected by a dam failure?" **Here substantial is any statistically significant trend greater than 2 percent per year or increase of 20 percent or more from the last PAR study (typically the previous CR)**. This step uses the U.S. Census dataset (or city or county estimates, if available) to consider the population change experienced in recent years (or at least between federal censuses). At this level of analysis, acceptable datasets include city, county, or even regional population data. No additional analysis of land use change or spatial representation of settlement patterns should be pursued. The focus is on analyzing the observed population change.

Ultimately, if there is a substantial trend in observed population change in communities potentially affected by a dam failure, the CR process continues to Step 2. If not, then no further analysis is needed at this time.

3.3.2 Step 2: Consider Future Population

This step aims to answer the question:" is there a substantial projected population change in communities potentially affected by dam failure?" **Here substantial is also any statistically significant trend greater than 2 percent per year or projected population increase of 20 percent for short-term projections.** This step, building on the current CR process to update PAR estimates, considers population projections for the population centers or region that would be affected by failure of the dam to provide insight into expected trends in population growth. Sources for these projections may include estimates published by the U.S. Census Bureau (Census Bureau 2023) or EPA (EPA 2017) or other non-governmental or academic sources (e.g., Hauer 2019). While all of these sources have considered different scenarios or even tried to link population growth to SSP and RCPs, here median estimates are recommended for decision-making and more extreme estimates (e.g., high and low) for representing the bounds of uncertainty. As in step 1, city, county, or even regional information on observed population change are acceptable for use in this analysis. No additional analysis of land use change or settlement patterns is needed.

Ultimately, if this step finds there is a substantial projected population change in communities potentially affected by dam failure, the CR screening process continues to Step 3. If not, then no further analysis is needed at this time.

3.3.3 Step 3: Make Recommendation

The third and final step aims to answer the question: "do projected and observed population change potentially impact facility risk?" This step focuses on providing clear information for use by CR team members in determining if additional analysis of PAR projections is warranted. While informed by information collected as part of the PAR screening process, the discussions and decision process should be led by the CR's senior engineer. Together with the risk analysis team, PFMs (including highly unlikely PFMs) should be discussed given the projected observed population change (Step 1) and population change (Step 2).

Ultimately, if Steps 1 and 2 find that projected and observed population change potentially impact facility risk, the CR team should consider recommending additional analysis of projected downstream consequences (as described in section 5) as a stand-alone study or as part of any ongoing SOD studies (e.g., IE, CAS, FD, etc.). If not, then no further analysis is needed at this time. This analysis and recommendation should be documented in the Consequences section of the CR.

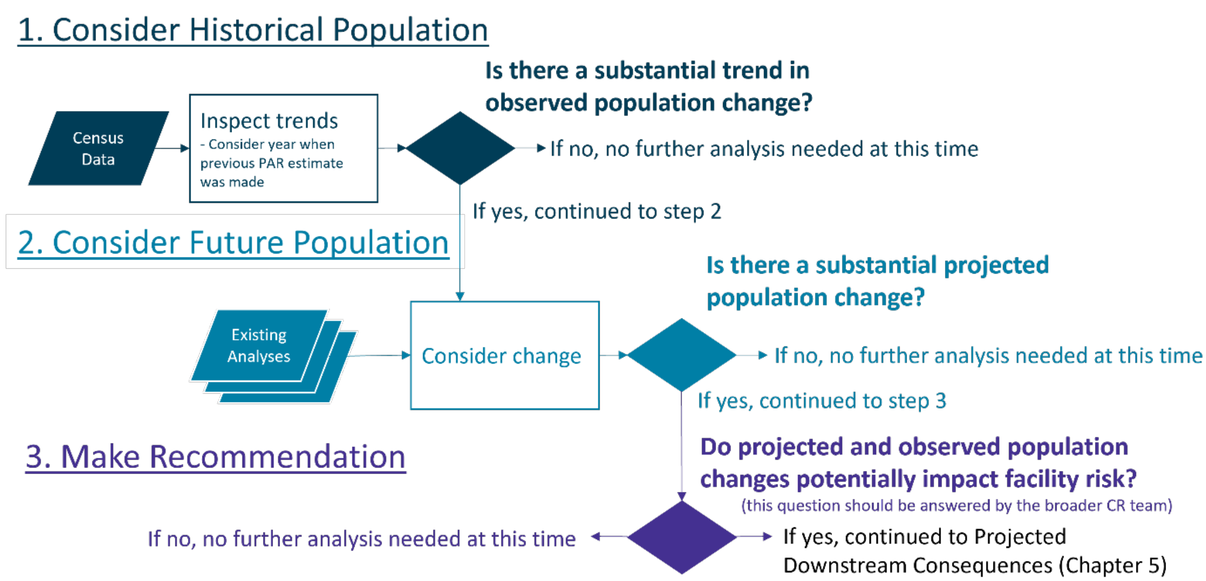


Figure 5.—Flow chart for downstream consequences screening process.

4.0 Climate Change in Flood Hazard Analysis (FHA)

4.1 Section Overview

As described in section 1.2.1, an FHA is a detailed study of available at-site and regional streamflow and precipitation information for a basin, and results in estimates of the magnitudes and probabilities of floods for that basin. This section addresses how to incorporate climate change information into the FHA process. This will be referred to as a "projected flood hazard analysis" or projected FHA. Section 2.3, earlier in the report, presented the findings of literature review and built the case for using a decision scaling approach in proposing a methodology. Section 4.2 provides some additional background on FHA, while section 4.3 proposes a methodology for conducting projected FHA. Later in the report, section 6.3 presents a proposal for a prototype study to continue refining this methodology.

4.2 Background

As described earlier, the standard assumption in FHA is stationarity (England et al. 2019). The FHA often includes multiple analysis approaches, including statistical streamflow analysis, paleoflood information, and rainfall-runoff modeling. Each of these analyses may require different methods for incorporating climate change information. For example, statistical streamflow analysis using observed flood peaks would need to incorporate either a time varying component to the distribution (e.g., Stedinger and Griffis 2011; Salas and Obeysekera 2014) or be more directly related to climate conditions (e.g., Brown et al. 2019), which vary with time. In contrast, paleoflood information may be used without adjustment, assuming even ongoing climate change falls within climate variability experienced since the Holocene epoch (Redmond et al. 2002); however, such an assumption may not be valid. Finally, for rainfall-runoff type approaches, climate-informed (Brown et al. 2019), dynamical downscaling (Lybarger et al. *pending*), or weather generator type approaches may be of use.

4.3 Proposed Methodology

As the working group reviewed the literature and considered different methodologies described in section 2.3, two frameworks garnered the most interest: the decision scaling approach (Brown et al. 2012) and the risk analysis approach (Fluixá-SanMartín et al. 2018). The decision scaling approach is sometimes described as a hybrid between top-down and bottom-up (Marchau et al.

2019), and generally features three main phases: (1) identification of climate hazards, (2) risk discovery, and (3) climate-informed risk estimation (Brown et al. 2012). The risk analysis approach represents a more traditional top-down approach, using climate projections to inform flood hazards and propagating those through a risk analysis process to arrive at failure probabilities and associated downstream consequences. While initially the risk analysis approach seemed applicable to Reclamation's SOD and RIDM processes, as the working group discussions continued, decision scaling emerged as the more favored option. There are a few primary reasons this was the conclusion:

1. The decision scaling approach is **focused on system vulnerabilities**. In the SOD process, risk analyses focus on analyzing the AFP and ALL associated with a set of PFMs (i.e., potential vulnerabilities) for the dam. Decision scaling allows the dam's vulnerabilities to be used in determining how to best analyze projected flood hazards, resulting in more applicable (and hopefully more credible) results.

2. The decision scaling approach is **collaborative**. Risk analyses are a collaborative effort, requiring a multidisciplinary team. Within the decision scaling framework, opportunities are provided for team input and feedback as the analysis is developed and progresses through the stages from identification of climate hazards to climate-informed risk estimation.

3. The decision scaling approach is **philosophically congruent with Reclamation's public protection guidelines**. Reclamation (2022) deemphasizes the visual guidelines as a binary decision-making threshold, instead focusing on the need for building the dam safety case for any recommended action. Decision scaling can easily be focused to provide the types of information needed for such case building, allowing for climate change analysis to focus on flood hydrology and risk assessment teams to focus on interpreting that information for the purposes of supporting a dam safety decision.

The proposed methodology for projected FHA takes the steps involved in decision scaling (Brown et al. 2012) and focuses it on flood hazards and flood risk for dams. The focus is on how climate change affects extreme flood events and in turn societal risk from dam failure, and indirectly on how climate change affects other benefits (e.g., water supply, hydropower, etc.). The proposed decision scaling methodology, projected flood hazards analysis, is broken into three main phases, containing six total steps:

1. **Identify Hazards**

    1.1. **Explore flood hazards** and link to climate variables.
    1.2. **Create system model** and vulnerability domain.

2. **Hazard Exploration**

    2.1. **Explore flood hazards** by perturbing the vulnerability domain using system model and stochastic modeling framework.

    2.2. **Define decision threshold** for increasing justification for action.

3. **Climate Informed Hazard Estimation**

    3.1. **Select and analyze ensemble of GCM** runs that represent climate variables of interest and calculate probability density function (PDF) for the likely future climate state.

    3.2. **Build case for decision** using PDF and decision threshold.

The projected FHA phase and steps are outlined in the flow chart in figure 6. Each of these phases and steps are described in more detail in the following paragraphs. This methodology is expected to be used within an FHA study being conducted as part of an ongoing IE, CAS, or FD level SOD study.

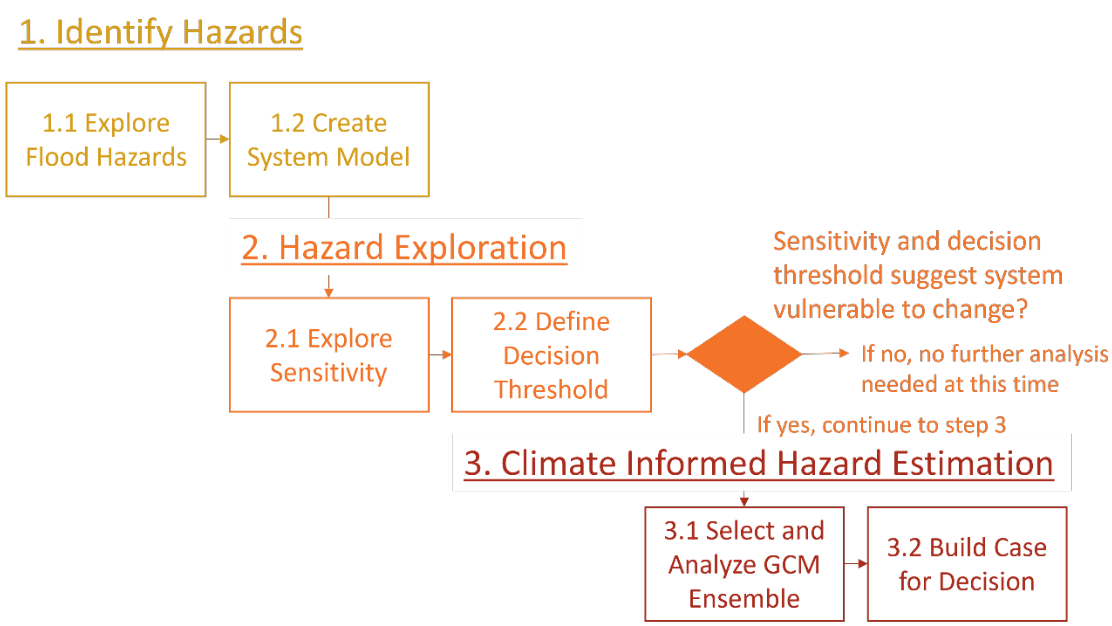


Figure 6.—Flow chart for projected flood hazards process.

4.3.1 Phase 1: Identify Hazards

4.3.1.1 *Step 1.1: Explore Flood Hazards*

The study team should first attempt to understand what has historically driven the flood risk for the dam, with a special focus on flood characteristics (e.g., peaks, volumes, and seasonality and typical starting elevation prior to flood inflows). This will build upon the work completed as part of the flood hazard screening already conducted for the dam (see Section 3.2). The dam's PFM are a good indicator of what flood characteristics drive flood risk. For example, internal erosion is typically driven by larger volume floods resulting in prolonged periods with the reservoir at higher pool elevations, while overtopping is typically driven by large peak floods that overwhelm outlet and spillway capacities and result in dam overtopping.

A thorough review of record high-pool events and other operational or dam safety incidents that have occurred in the past should be conducted. This will expand on the analysis conducted as part of Step 1 of the Flood Hazard Screening Process (Section 3.2). And, in some cases, diagnostic routing analyses (e.g., routings that independently test sensitivity to increasing peaks, volumes, or starting elevation) could be used to understand which flood characteristics drive flood hazards. The dam's authorized purposes and standing operating procedures can also provide insight into what drives flood risk, particularly through what seasons have flood control guide curves. Whether or not a dam has flood control space or downstream channel restrictions can lend insight into whether the dam is designed to pass flows (and is therefore more sensitive to peak flows exceeding spillway capacity) or store inflow volumes (and is therefore more sensitive to flood volumes exceeding flood control space).

For each flood characteristic, performance thresholds of interest should be identified. These may be specific flow rates or inflow volumes corresponding to dam capacities or annual exceedance probabilities of interest. For example, the flow capacity of a dam's spillway may be of particular interest in relation to peak flow magnitudes or the total storage capacity in relation to inflow volume magnitudes. **Ultimately, this step should result in one key flood characteristic being identified along with a performance threshold of interest.**

4.3.1.2 *Step 1.2: Create System Model*

Once the flood characteristic is identified, the next step is to understand what climate variables drive that characteristic. The climate variables explored should be among those explicitly modeled by or readily calculated from GCM output. For example, Brown et al. (2012) use basin mean annual temperature and mean annual precipitation as their climate variables and Franham et al. (2018) and Schlef at al. (2018) use a "climate-informed" approach—using large-scale atmospheric circulation indices to predict regional extreme precipitation and streamflow, respectively. The climate variables selected should have a physically understood connection to the flood characteristic (e.g., increase precipitation results in increased runoff) or statistically significant correlation and causation to the flood characteristic (e.g., positive anomalous sea surface temperatures are correlated to increased flood magnitudes in this basin). In both cases, published research should be used to justify the relationship. **This should result in identification of two or more climate variables connected to the flood characteristic.**

Once a set of climate variables have been identified, explored, and selected, the selected climate variables should be used in developing a system model and vulnerability domain. System models are typically described as climate response functions, which represent an efficient pipeline of multiple models that allow climate information to be translated to the performance indicator of interest. These could leverage time-varying or climate dependent distribution parameters, dynamical downscaling models, or weather generator techniques. Regardless of the specific modeling approach used, this system response model would link the climate variables identified in Step 1.2 to the flood characteristics identified in Step 1.1. This is similar to the climate informed approach described in Brown et al. (2019). These models may be statistical in nature, but typically include hydrologic components and should clearly incorporate each climate variable as a predictors (among other climate variables that should be held constant) and the flood characteristics as the variables being predicted. The system model should be calibrated using observed data and shown to reasonable reproduced observed basin hydrology for use in estimating flood frequency information, related to the flood characteristic of interest. **At this point, the vulnerability domain consists of the selected climate variables.**

Figure 7 shows a schematic of an example vulnerability domain defined by "precipitation" and "temperature" relative to present, from lower (-) to higher (+). This vulnerability domain is used in the following sections to provide an example of how the process progresses; however, note that exact variables (e.g., mean annual precipitation, annual maximum precipitation, etc.) are intentionally not defined for this conceptual example.

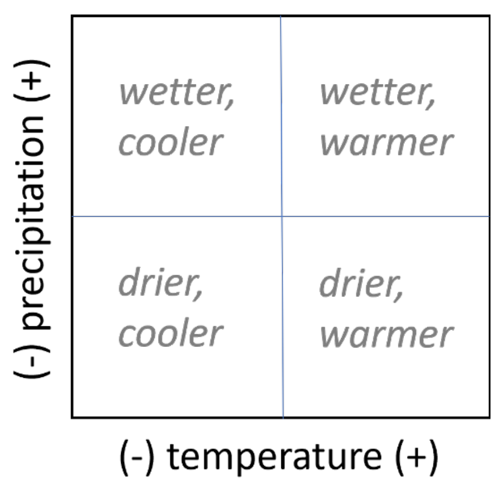


Figure 7.—Example schematic of a vulnerability domain defined by precipitation (vertical axis) and temperature (horizontal axis).

4.3.2 Phase 2: Hazard Exploration

4.3.2.1 *Step 2.1: Explore Sensitivity*

Hazard exploration is conducted by perturbing the climate variables and using the system model to understand how the flood characteristic (and thereby flood risk) responds. Ranges for testing should be based on understanding projected changes to the climate variables selected based on climate change information from multiple GCMs. This analysis will build on the range of changes considered as part of the flood hazard screening already conducted for the dam (see Section 3.2) or even GCM projection membership diagrams from any previously published studies for the basin. Keep in mind that too narrow of a range may make the sensitivity analysis useless for stress testing the dam and comparing to GCM output. **As a result, this study suggests considering the full range of projected values in the sensitivity analysis. If that range does not appear robust, analysis can consider a buffer around the published projected values (e.g., ±20 percent)**. The resulting output should represent at least annual maximum series frequency information for the flood characteristics of interest, but additional modeling and consideration of partial duration series frequency information may be of use where multi-events or antecedent conditions are of concern. **The result of this process will be sensitivity of the flood characteristics mapped directly to changes in the climate variables in the vulnerability domain.**

Figure 8 shows a schematic of the example vulnerability domain with sensitivity of a flood characteristic shown. Each of the symbols represents a relative change in the flood characteristic, either increasing (+) or decreasing (-), with larger size symbols denoting a larger sensitivity or change caused by the combined change of the climate variables.

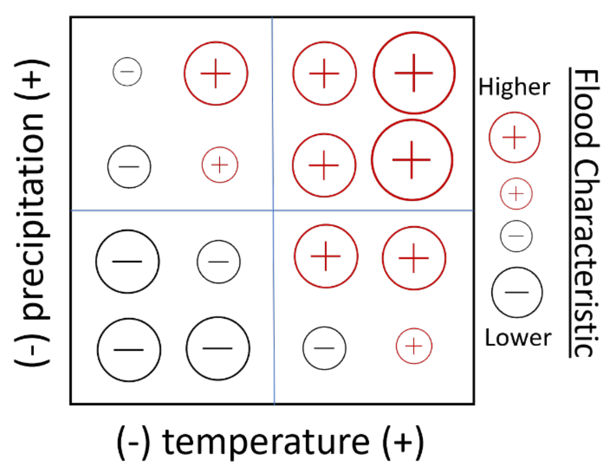


Figure 8.—Example schematic of a vulnerability domain with sensitivity of a flood characteristic shown as circle symbols, where larger symbols denote a larger sensitivity or change caused by the combined change of the climate variables.

4.3.2.2 *Step 1.2: Define Decision Threshold*

The study team should be reconvened to determine their threshold for increasing flood hazard. The earlier identified performance thresholds may be useful during this step. The primary focus should be on flood characteristics in reference to the dam's vulnerabilities determined in Step 1.1. **Ultimately, a threshold (e.g., X percent increase in flood volumes with certain probability) should be defined, above which there is increasing justification for action as a result of increasing flood hazard.** *Note that this threshold should* **not** *be a direct representation of the visual guidelines, but instead represent the team's understanding of when levels of increased flood hazards require action.*

Figure 9 shows a schematic of the example vulnerability domain with sensitivity of a flood characteristic shown and decision threshold superimposed on top. The shaded area (lower left) represents the region for decreasing justification for action, while the unshaded area (upper right) represents the region for increasing justification for action. For some dams, which have been overdesigned, this sensitivity analysis might suggest the dam in insensitive to the range of changes considered. If that is the case, a case may be built that further analysis (Phase 3) may be unnecessary at this time.

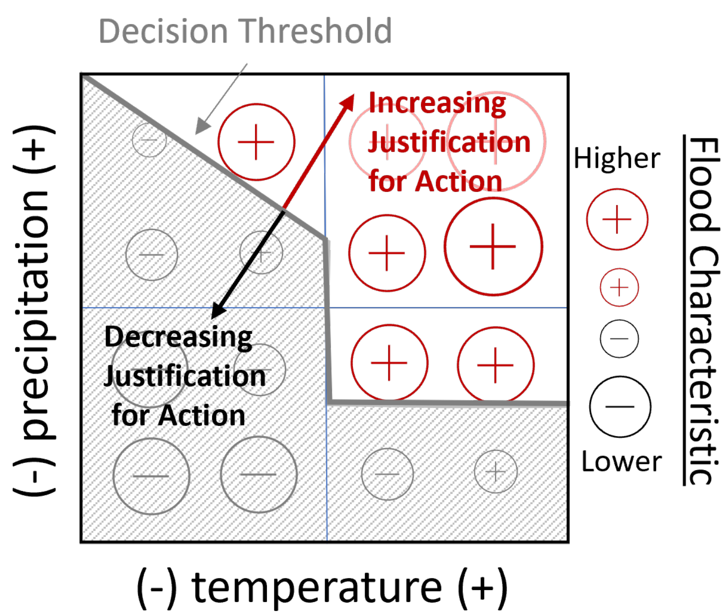


Figure 9.—Example schematic of a vulnerability domain with sensitivity of a flood characteristic shown as circle symbols and decision threshold shown as a grey line.[15]

[15] The shaded area (lower left) represents the region for decreasing justification for action, while the unshaded area (upper right) represents the region for increasing justification for action.

4.3.3 Phase 3: Climate Informed Hazard Estimation

4.3.3.1 *Step 3.1: Select and Analyze GCM Ensemble*

The GCMs that perform well[16] representing the variables of interest during the historical period should be selected, along with a range of emissions scenarios. From each of these climate projections, the climate variables should be extracted for the period of interest—typically about 50-years for dam modifications. The results from many climate projections can then be used to create a PDF that can be overlain on the vulnerability domain (Jones 2000). **The result will be a PDF or heat map of climate projections of the climate variables.**

Figure 10 shows a schematic of the example vulnerability domain with decision threshold and PDF (heat map) showing the probabilities for future conditions based on GCM output.

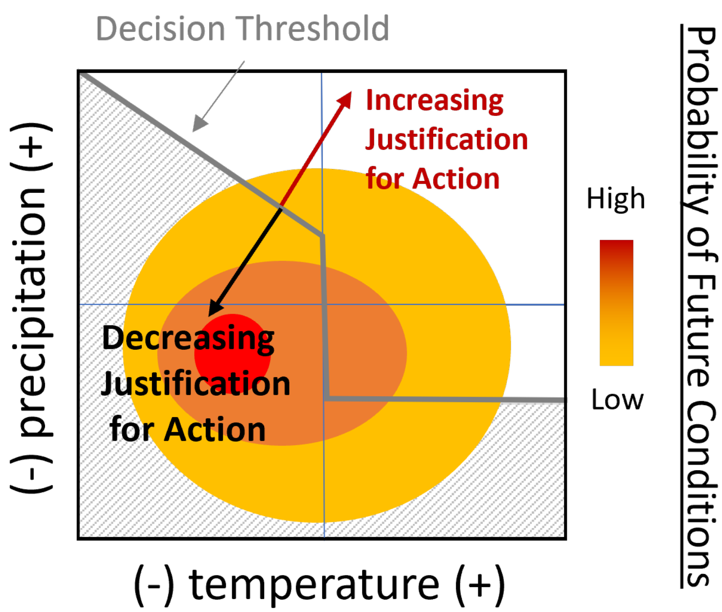


Figure 10.—Example schematic of a vulnerability domain with decision threshold and probability density function (heat map) showing the probabilities for future conditions based on GCM output.

[16] Methods for assessing GCM performance have not yet been identified as part of this methodology; however, it is likely performance will be measured using standard goodness-of-fit metrics (e.g., root mean square error, Nash-Sutcliffe efficiency, etc.) to compare the historical period of the GCM model simulations to observed data.

4.3.3.2 *Step 3.2: Build Case for Decision*

In the final step, the study team should use the PDF plotted against the decision threshold to help build the case for a decision. This process should include members of the risk team and involve discussing the various PFMs for the dam (including highly unlikely PFMs) and other considerations, such as direct downstream consequences (i.e., loss of life). And indirect consequences (e.g., loss of other benefits). This may result in the conclusion of increasing justification to take action to prepare for increasing flood hazard resulting from climate change. The decision should be well-grounded in the projected flood characteristic's effect on the dam's performance and flood risk.

5.0 Climate Change in Downstream Consequences

5.1 Section Overview

As described in section 1.2.2, downstream consequences estimation requires data obtained from two studies: a dam failure inundation study and a PAR study. For flood PFM, a dam failure inundation study takes the results from the reservoir routings and applies them as initial conditions in a breach model of the dam and then uses the breach hydrograph to calculate the maximum flood extent, maximum flood depth, flood wave travel times, and the flood intensity downstream of the dam. The PAR study uses the results from the inundation analysis to estimate the population located within the maximum flood extent. The result of this process is an estimate of life loss associated with a PFM to be used in estimating the ALL. Section 2.4, earlier in the report, presented a review of current approaches and datasets that can be used to incorporate climate change information into downstream consequences estimation. Section 5.2 provides some additional background information on the methods and concepts involved in estimating downstream concepts, and section 5.3 presents the next steps needed to develop a methodology for conducting projected downstream consequences analysis. Later in the report, section 6.3 presents a prototype study proposal to continue refining this methodology.

5.2 Background

Reclamation performs downstream consequences analysis to quantify the potential impacts of downstream releases. Downstream consequences from a dam release can be divided into two categories: direct or indirect consequences. Direct consequences are quantified through life loss estimates associated with flood hazard. Indirect consequences can be quantified through estimates of flood damages to infrastructure, socio-economic networks, flooded land value, etc. Reclamation directly considers life loss as downstream consequences in the RIDM process.

Estimation of life loss resulting from flooding requires an understanding of the following factors (Reclamation and USACE 2019):

- Flood characteristics including maximum extent, depth, velocity, flood wave travel time (arrival and maximum time).
- PAR in the flooded areas.

- Warning and evacuation assumptions for that PAR,
- Estimation of fatality rates.

The flood characteristics are obtained by performing a dam failure inundation study in accordance with FAC 01-01 Appendix E, Inundation Map Requirements (Reclamation 2017), while the methodology used to estimate PAR is summarized in Reclamation (2019). The results from these two analyses are then used to estimate downstream consequences using RCEM (Reclamation 2015b)

A dam inundation study can be divided into two separate analyses, (1) the estimation of the discharge from the dam, either through normal operations, mis-operation, or failure of the dam and (2) the downstream routing of this discharge.

The breach hydrograph is mainly a function of the dam type (e.g., concrete or embankment), dam geometry and materials, reservoir volume at the time of failure, and structural response of the dam to the applied loading (seismic event, hydrologic overtopping, elevated internal erosion risk due to first-filling condition in previously untested reservoir levels, etc.).

Downstream routing is then performed to map the maximum flood extent and calculate the flood intensity. Downstream flow attenuation is mostly a function of channel slope and resistance to flow. Surface roughness is parametrized into flood models by means of the Manning's n, which in theory is a measure of the flow resistance of the floodplain (Chow 1959), but in practice is used as a modeling calibration parameter (when data is available) to capture most of the complex interactions between the moving flow and the surface it is interacting with (e.g., energy losses due to vegetation, turbulence, floating debris or sediment, floodplain/channel blockage, etc.) (Trieste and Jarrett 1987). There is plenty of literature available to aid in the selection of Manning's n values for typical frequency flood events (e.g., Barnes 1967; Chow 1959). Dam break discharges can be several orders of magnitude larger than naturally occurring floods (estimated breach discharge for large dams can be on the order of hundreds of thousands to millions of cubic feet per second).

If the calibration of dam breach flood models is not feasible, a sensitivity analysis is used to understand the uncertainties introduced by these numerical input parameters in the downstream flooding. Reclamation has typically assigned a uniform value of Manning's n to flood models as a conservative approach to estimate this uncertain parameter. In recent years, with the more widespread use of two-dimensional hydraulic models and better geographic information system tools, guidance to correlate Manning's n to land cover categories has been developed and has become standard practice in floodplain hydraulic modeling applications. These values are typically presented as a range based on standard definitions of land use and the user is expected to use these as starting values and modify them through calibration to fit an actual flood event. Bornschein (2018) performed a sensitivity analysis on the effects of the terrain data and Manning's n on the downstream routing of a dam breach hydrograph. It was found the selection of Manning's n has a small effect on the maximum inundation extent but heavily influenced the flood wave travel time, i.e., leading edge and time to maximum. These two values are of great importance in estimating downstream consequences as they are used to inform the warning assumptions used to estimate consequences in RCEM.

A PAR study then takes the maximum flood extent, classified by DV (depth times velocity, or flood intensity) to estimate the population within the flood zone. The simplest level of analysis requires intersection of U.S. Census block level data with the inundation zone assuming that the population is uniformly distributed within the census block. This method is acceptable in dense urban areas where census blocks sizes are small (approximately the size of a city block), and the assumption of the population being uniformly distributed inside the block is a valid one. In rural areas (characteristic of most of Reclamation's inventory), census blocks are irregular in size, sparsely populated, and can be several hundred squared miles in area, thus this assumption does not apply as the population could be far away from the inundation zone and not affected at all by the flood. In this case, a PAR analysis requires use of additional data sources to redistribute the population within the census block and accurately count the population that is subjected to the flood. This is done via publicly available address data points, georeferenced parcel maps, building footprint databases, aerial imagery photo interpretation, and ultimately via site visits. The product of a PAR study is a summary of the affected population categorized by the flood intensity (characterized by DV) experienced where they are located.

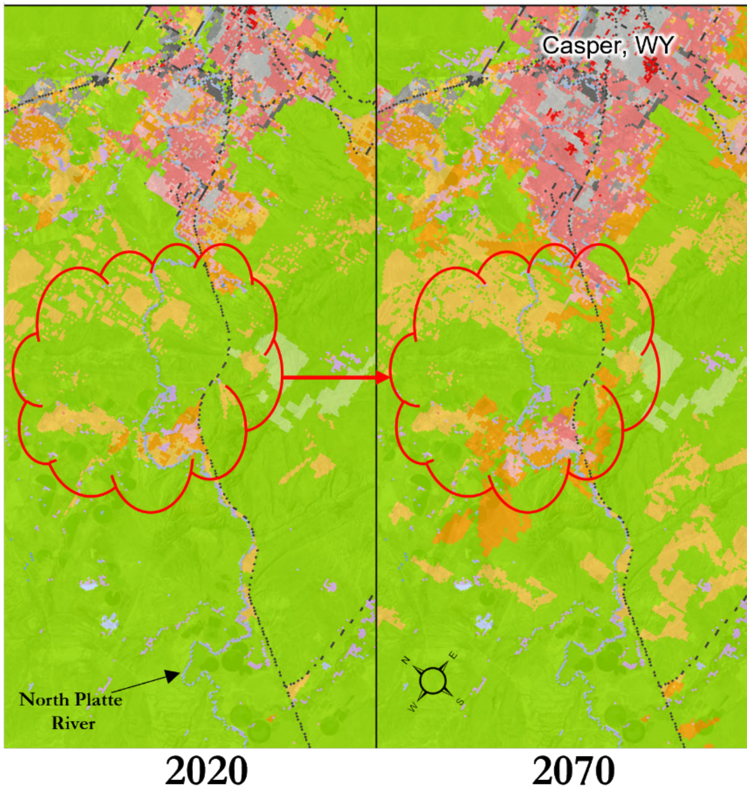
5.3 Proposed Methodology

No clear guidance or methodology to incorporate climate change information into downstream consequence estimation has been found in the literature. Fluixá-SanMartín et al (2018) provided a potential approach to look at the effects of climate change in the flood routing of releases from dams (operational or failure) by means of studying the effect of land use changes (i.e., changes in modeling roughness coefficient) on the flood wave routing. These effects were not considered in the subsequent application of their proposed framework to incorporate climate change information into the dam safety risk analysis process (Fluixá-SanMartín et al 2019). Understanding these effects would be a first step in developing a methodology that incorporates climate change information into the consequences estimation process. The ICLUS land use dataset can be useful in determining these effects.

Manning's n is an input parameter that is typically calibrated for hydraulic models but is impractical to calibrate in most dam breach routing models due to the large magnitude of the modeled flood; observational data rarely exists for a flood of similar magnitude in the studied river reach. Since Manning's n is a calibration parameter, typical values are found in the literature as a range. Without taking into consideration climate change, the selection of Manning's n will have an effect on flood wave timing potentially affecting the warning time assumptions used to estimate consequences if these effects are substantial, so this is one of the inherent uncertainties associated with a dam breach inundation analysis. It is possible that the difference in flood wave timing produced by climate change (through changes in land use) would be similar to the change in flood wave timing produced by the selection of a different value of

Manning's n. A sensitivity analysis like this has not been found in the literature and needs to be completed before the question of how climate change affects the consequences estimation process can be answered. It is expected this will have a similar level of effort to an inundation study.

The second part of assessing the effect of climate change in the downstream consequences is understanding how the population within the dam breach flood extent will change in the future. The two ICLUS datasets could be applied to current PAR estimation methodology to project future PAR. The simplest approach would be to use the population growth rates and apply them to current PAR estimates to project future consequences per SSP/RCP combination. This estimate would not consider where this future PAR is located and assumes that the growth is uniformly distributed across the current location of PAR. This assumption can be valid in dense urban areas but would not be in rural and less densely populated areas, a good portion of Reclamation dams are located in sparsely populated areas. Another, more detailed, approach could be to use the ICLUS land use dataset to determine where the future population could be located. Figure 11 presents a comparison of this dataset near Casper, Wyoming between 2020 and 2070; the figure highlights areas that are currently classified as grazing land and how the dataset projects those lands being developed into exurban and suburban type development with higher population density. This area is located downstream of several Reclamation dams. Future PAR counts in this area could be underestimated if only the simple approach is applied, whereas new areas of potential PAR are present in the 2070 projection that are not inhabited or only sparsely populated at the present time. This could be a good opportunity for applying machine learning to help understand and predict land use change.



Code	Class Name
0	Natural water
1	Reservoirs, canals
2	Wetlands
3	Recreation, conservation
4	Timber
5	Grazing
6	Pasture
7	Cropland
8	Mining, barren land
9	Parks, golf courses
10	Exurban, low density
11	Exurban, high density
12	Suburban
13	Urban, low density
14	Urban, high density
15	Commercial
16	Industrial
17	Institutional
18	Transportation

Figure 11.—Example of projected land use change between 2020 and 2070 near Casper, Wyoming from ICLUS SSP2/RCP4.5/HadGEM2 combination.

6.0 Discussion and Prototype Study Proposal

6.1 Discussion

The goal of this study was to propose a methodology for incorporating climate change information into the Reclamation SOD process for flood risk analysis. This effort included a focused literature review, including review of climate science and methods for incorporating climate change information into flood hazards and downstream consequences (section 2). Following the literature review, a series of methodologies are proposed. Section 3 presents proposed screening processes for considering climate change information within the CR process. Sections 4 and 5 focus on incorporating climate change information into the SOD process that occurs after a deficiency has been identified for a dam, typically through the CR process. Section 4 focuses on FHA, presenting a decision scaling approach. While decision scaling is often used to analyze systems with multiple benefits and potential vulnerabilities, this study's recommended methodology focuses on flood hazards and flood risk at dams. Thus, the focus is on how climate change affects extreme flood events and in turn societal risk from dam failure.

Section 5 focuses on incorporating climate change information in estimating downstream consequences, to be considered alongside the projected flood hazard results. As both pieces of information are used in risk analysis, it is important to have estimates of both for a similar time horizon (e.g., 50 years). Ultimately, a best approach was not identified and instead a set of additional tasks needed to define a methodology were proposed.

Figure 12 shows a schematic that combines simplified versions of the flood hazard screening and projected FHA flowcharts and places them in the context of the SOD process and this report's sections. A similar schematic for downstream consequences is not shown, because a methodology was not developed.

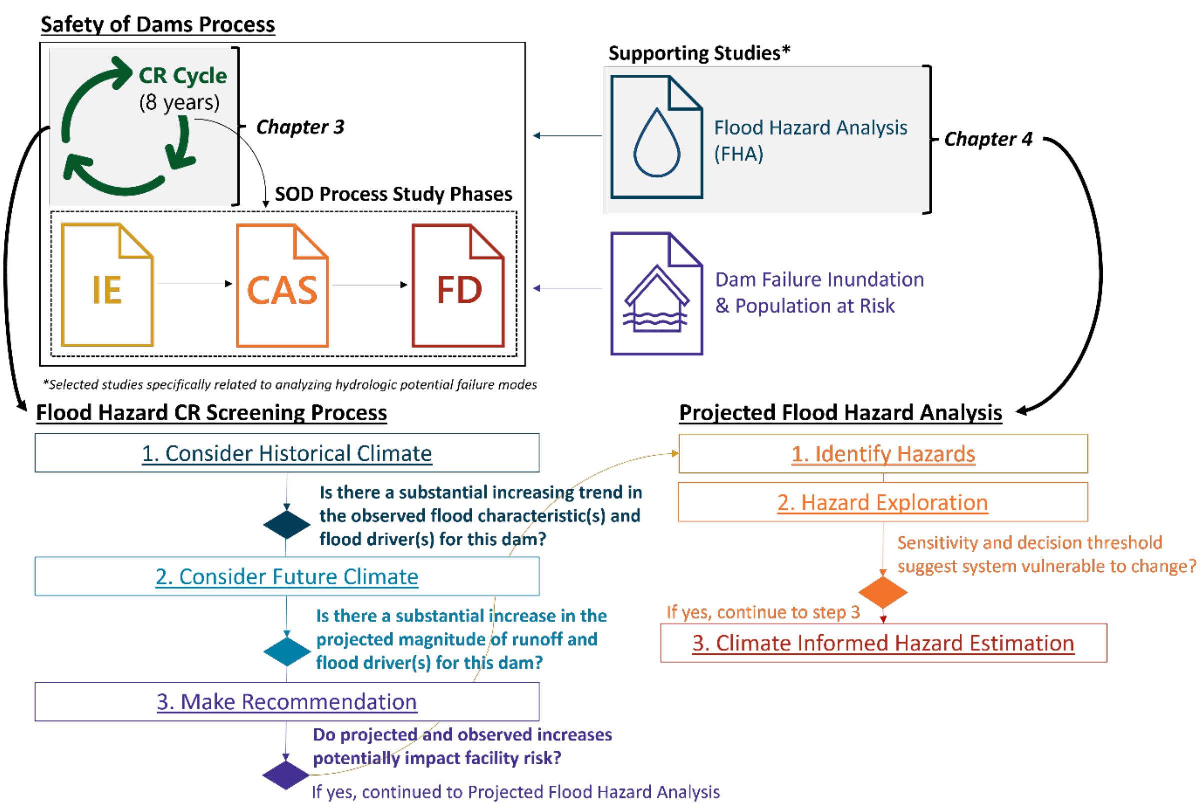


Figure 12.—Schematic combining simplified versions of the flood hazard screening (section 3.2) and projected flood hazard analysis (section 4.3) flowcharts and placing them in the context of the SOD process and this report's sections.

Because the methodologies recommended by this report are not considered final, they will continue to be refine through additional phases of study and prototyping studies. While this study proposed methodologies for some aspects of incorporating climate change information into the SOD process for flood risk analysis, further study is needed to develop a methodology for downstream consequences and to make the methodologies operational. The following sections present initial proposals for further work on the screening processes (section 6.2) and projected flood hazards and downstream consequences (section 6.3).

6.2 Screening Process Implementation Proposal

Additional work is recommended to implement the screening processes presented in section 3 efficiently and comprehensively. The following paragraphs outline some of the key considerations in this proposal, and table 3 lists some of the potential tasks that would be included.

Why: Further work is needed to compile the datasets and develop the tools for applying these screening processes in a consistent and efficient manner during the CR cycle.

Who: A multi-disciplinary working group of hydrologic engineers, civil/geotechnical engineers (risk cadre), geologists (paleo hydrogeologists), meteorologists/atmospheric scientists, data scientists, economists, and dam safety personnel.

Where: During implementation, the method should be tested on at least the list of potential prototyping sites listed in table 4, and at most all basins including Reclamation projects. In the future, this this analysis could be expanded to include basins throughout the U.S.

When: This study should take place over the next 1–2 years, allowing for completion of ongoing work (e.g., Beyene *pending*; Lybarger et al. *pending*).

Funding: Funding for this proposal will be pursued through multiple avenues and is not necessarily intended or expected to rely on WaterSMART funding.

What: Work is comprised of three main efforts: data collection, analysis, and storage and dissemination. Data collection emphasizes developing code modules to aid in collecting reservoir operations information, historical observations (population and hydroclimate), and projection information (population and hydroclimate) from published studies and existing model runs, as described in sections 3.2 and 3.3. **Part of this effort should also result in a list of trusted sources and datasets.** Analysis includes developing a tool for implementing the flowcharts presented in figure 4 and figure 5 and the timeseries analyses described in table 1 and table 2. The storage and dissemination work focuses on developing a database and web-based tool to host the code and a database (likely structured query language, or "SQL", based) where the collected data and analysis results can be stored, viewed, and updated by CR team members. Because this database will include reservoir operations information and PAR, it is likely it will be considered controlled unclassified information and need to be maintained behind Reclamation's network firewall. The Water Resource and Planning Office or DSO could be good hosts for this database. This development could be pursued in coordination with other efforts to develop guidance and tools within Reclamation (e.g., SECURE). Table 3 outlines the proposed tasks in more detail.

Table 3.—Recommended tasks for implementing proposed flood hazard screening process

Task	Sub task	Description	Potential options
1 - Data Collection	1.1 – Observed Hydroclimate Module	Develop code for collection, processing, and organization of observed hydrology information (e.g., daily streamflow, reservoir volume, precipitation, temperature, snowpack, etc.)	The program or tool could be developed in R, Python, or other programming languages for accessing data from USGS, Hydromet, SNOTEL, state water resources, GHCN, RISE, gridMET or CPC gridded
	1.2 – Climate Projections Module	Develop code for collection, processing, and organization of climate projection information (e.g., change in precipitation, temperature, seasonality, etc.)	The program or tool could be developed in R, Python, or other programming languages to access available information produced by the SECURE Report, completed basin studies, and statistically and dynamically downscaled climate projection data, available analysis by other studies (e.g., Lybarger et al. *pending*)
	1.3 – Population Observations Module	Develop code for collection, processing, and organization of observed population information (e.g., official U.S. censuses or other recorded population data)	The program or tool could be developed in R, Python, or other programming languages to access U.S. Census Bureau, state, county, or city records of population
	1.4 – Population projections Module	Develop code for collection, processing, and organization of population projection information (e.g., spatially distributed estimates of future population based on multiple RCPs and SSPs, as available)	The program or tool could be developed in R, Python, or other programming languages to access available information published by the U.S. Census Bureau, U.S. EPA, and other governmental and non-governmental organizations.
2 - Analysis	2.1 – Flood Mechanism Analysis	Completion of summary of flood mechanisms and associated climate variables (or indices) for basins included in this proposal.	Discussion and analysis by hydrology and meteorology team members and expanded literature review to identify flood mechanisms for Reclamation dams. Relationships between identified mechanisms should be physically explainable mechanisms and supported by findings in peer-reviewed publications.

Task	Sub task	Description	Potential options
	2.2 – Population Projection Analysis	Completion of survey of population projection datasets and relationships with climate scenarios for basins included in this proposal.	Discussion and analysis with scientific and policy communities and expanded literature review to identify appropriate population projection datasets for use in screening process.
	2.3 – CR Screening Application	Development of code for applying the flood hazard and downstream consequences screening processes. **2.3a – FHA Screening Analysis Module** Development of a module for application of the flood hazard screening process, including: - generating projected streamflow plots; - selecting applicable climate change projections depending on user selected flood mechanisms; - selecting appropriate dataset depending on user selected flood characteristics; and - conducting statistical tests on data **2.3b – Consequences Analysis Module** Development of a module for application of the PAR screening process, including: - selecting applicable projections of population based on a user supplied area of interest; - selecting applicable observations of population based on a user supplied area of interest; and - conducting statistical tests on data.	The program or tool could be developed in R, Python, or other programming languages and packaged into an executable or web-based app for easy deployment. The Consequences Analysis Module could be included in Tessel's inundation analysis module for easy access by CR team members

Task	Sub task	Description	Potential options
3 – Storage and Dissemination	3.1 – Storage and Update	Developing a long-term data management plan for developing the database schema, storage of database, and hosting of the analysis tool (if a web-based tool). Also, a plan for periodic updates as new information becomes available.	This would require support by Information Technology and partner offices to create dedicated server space (and data storage redundancy) where the CR team has access.
	3.2 – Dissemination	Developing a web-based tool for accessing and interacting with the collected data and analysis tool	This tool could be developed in R, Python, or other programming languages and would be permanently deployed on a Reclamation server. This task should be listed in a risk register, as there is high uncertainty (and risk) around the needed resources for this task.

6.3 Prototype Study Proposal

Additional work is recommended to refine and implement the proposed methodology for projected FHA (section 4) and develop a methodology for projected downstream consequences (section 5). **This study recommends conducting "prototyping" studies in series, such that each prototyping study is used to test and improve the methodologies before conducting the next study.** In this way, through a series of prototyping studies, the methodology will be refined and prepared for more general adoption within the SOD process. Each prototype study should include a similar working group of technical and decision-making personnel, with the addition of regional personnel associated with prototype study sites selected. Table 4 presents a list of potential prototype sites compiled in consultation with DSO, and the regional and area offices.

After conducting screening analysis on the list presented in table 4, 3–5 dams across Reclamation's portfolio should be selected for prototyping studies. These prototyping studies should include developing both projected FHA and downstream consequences data and should be conducted in a series approach, to allow for continually refining the guidance and methodology with each subsequent prototype site. The dams should be located across different regions, where different mechanisms drive flood risk and different climate change impacts are expected. Also, when possible, the dams should have different floodplain characteristics to help determine the appropriateness of various PAR projection methods depending on PAR type (urban/rural). This diversity will help ensure the prototype studies provides a more complete picture of how to implement these methodologies, while helping to identify a broader list of flood mechanisms, characteristics, and risk considerations. The following paragraphs define some of the key considerations in this proposal, and table 5 lists some of the potential tasks that would be included.

Why: Further work is needed to fully operationalize the proposed methodologies. Prototyping studies provide a good opportunity to test and improve the methodologies.

Who: A multi-disciplinary working group of hydrologic engineers, civil/geotechnical engineers (risk cadre and others), geologists (paleo hydrogeologists), meteorologists/atmospheric scientists, economists, and dam safety personnel.

Where: At 3–5 dams in Reclamation's portfolio that would be recommended for projected FHA based on the screening process in section 3.2 (e.g., have substantial projected climate change impacts to basin hydrology, have already experienced detected changes to basin hydrology, and for which there may be a dam safety case for better understanding how changes in basin hydrology impact risk). This initial screening will rely on available information described in section 3.2. These dams should be in different Reclamation regions and also in different climate regions (e.g., desert southwest vs. temperate Pacific Northwest, etc.). These dams should have diverse flood driving mechanisms (e.g., snowmelt driven flood volumes, atmospheric river driven flood peaks, etc.) and flood characteristics (e.g., peaks, volumes, seasonality, etc.). This will help to identify nuanced vulnerabilities at facilities (may not be driven entirely by PFMs). Finally, in the interest of resource limitations and improving techniques, these prototypes could be conducted in a series approach, beginning with the highest priority dam and continually refining the guidance and methodology with each subsequent prototype study. Table 4 presents a list of potential prototype sites.

When: It is likely each prototyping study will take multiple years to complete. These studies may be completed in series, or at least with enough latency to allow earlier prototyping studies to improve the methodology for later prototyping studies (i.e., a second prototyping study could begin Phase 1 as the first prototyping study moves to Phase 2). If needs arise for climate change analysis as a result of SOD recommendations, it is possible dams not listed in table 4 could take the place of identified prototyping sites and be used for improving the methodology instead.

Funding: Funding for this proposal will be pursued through multiple avenues, including DSO, Water Resources and Planning Office, Research and Development, and regional offices, and is not necessarily intended or expected to rely only on WaterSMART funding.

What: This study would apply the proposed projected FHA (section 4) and Consequences (section 5.3) methodologies to multiple facilities to refine the description of these methodologies and provide more specific guidance on datasets, models, and methods to be used. This study would include five tasks:

1. Identifying the dams to be used in the prototype study.
2. Identifying hazards and consequences for those prototype locations.
3. Exploring hazards for the prototype locations.
4. Conduct climate informed hazard estimation and decision-making for prototype locations.
5. Documentation of prototype study and revision of methodology (updated guidance to be published to the WaterSMART website).

Potential prototyping sites are listed in table 4 and shown in figure 13, and proposed tasks are outlined in table 5.

Table 4.—List of potential prototype study sites

No.	Region	Dam	Basin (Hydrologic Unit Code)	Dam ownership	Included in Beyene (*pending*)
1	MB	Jamestown Dam	Missouri River (HUC: 10)	Reserved	
2	MB	Olympus Dam	Missouri River (HUC: 10)	Reserved	
3	MB	Willow Creek (MT) Dam	Missouri River (HUC: 10)	Reserved	
4	UCB	Nambe Falls Dam	Rio Grande (HUC: 13)	Transferred	
5	UCB	El Vado Dam	Rio Grande (HUC: 13)	Reserved	
6	UCB	Ridgeway Dam	Upper Colorado River (HUC: 14)	Reserved	Yes
7	UCB	Pineview Dam	Great Basin (HUC: 16)	Reserved	
8	LCB	C.C. Cragin Dam	Lower Colorado River (HUC: 15)	Transferred	
9	LCB	New Waddell Dam	Lower Colorado River (HUC: 15)	Reserved	
10–12	CPN	Boise River System	Columbia River (HUC:17)	Reserved	Yes
13	CPN	McKay Dam	Columbia River (HUC:17)	Reserved	Yes
14	CGB	Prosser Creek Dam	Great Basin (HUC: 16)	Reserved	Yes
15	CGB	Folsom Dam	Sacramento River (HUC: 18)	Reserved	
16	CGB	Shasta Dam	Sacramento River (HUC: 18)	Reserved	
17	CGB	Trinity Dam	Sacramento River (HUC: 18)	Reserved	Yes

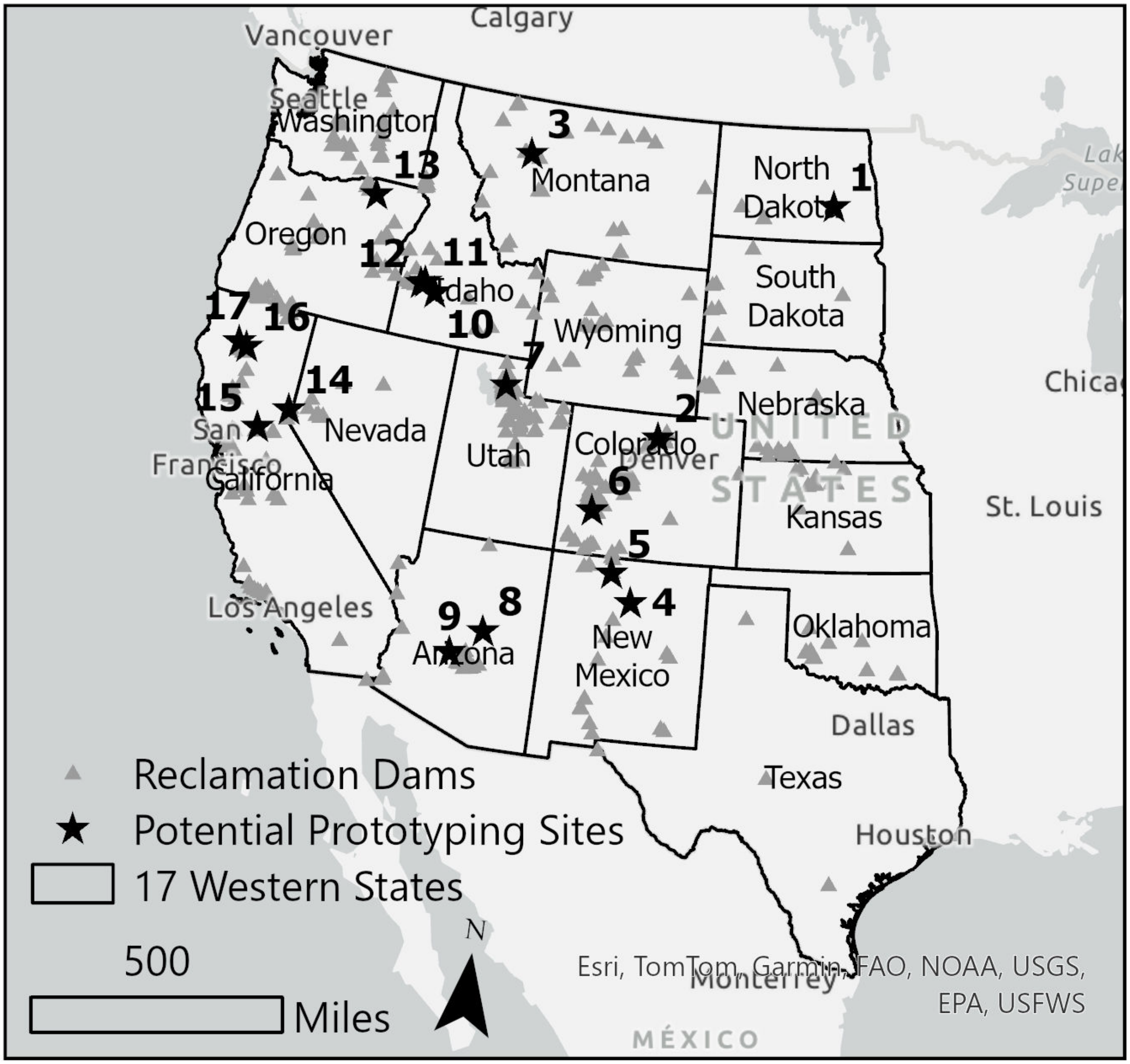


Figure 13.—Map showing locations of potential prototyping sites (stars) and all Reclamation dams (triangles) across the 17 Western States.[17]

[17] For numbers for potential prototyping sites see table 4.

Table 5.—Recommended tasks for implementing proposed flood hazard screening process

Task	Sub task	Description	Potential options
1 – Prototype Selection	1.1 - Climate Change Screening	Following steps in section 3.2.2	If the proposal in section 6.2 is funded and underway, these steps could rely on the finished product
	1.2 – Hydrologic Trends Screening	Following steps in section 3.2.1	
	1.3 - Risk Team Screening	Following steps in section 3.2.3	
	1.4 - Prototype Study Selection	Select 3–5 dams to be used in the prototype study; justify selection.	
2 – Identifying Hazards and Consequences	2.1 - Exploration of flood hazards	This task would include literature review and discussions with meteorology and hydrology personnel to properly identify flood hazards, as described in section 4.3.1.1	
	2.2 - Creation of system models	This task would include literature review and development of system models as described in section 4.3.1.2, potentially testing a range of different options and approaches	
	2.3 - Estimating projected consequences	This task would include literature review and continued analysis to compare different datasets for sensitivity for land use and flood plain roughness coefficients, inundation mapping, and PAR as described in section 5.3. Include collaboration with Economists to understand potential secondary impacts.	
3 – Hazard Exploration	3.1 - Explore Sensitivity	This task would include literature review and development of sensitivity runs as described in section 4.3.2.1, potentially testing a range of different options and approaches.	
	3.2 - Define Decision Threshold	This task would include discussions with the risk team to define any decision thresholds as described in section 4.3.2.2, potentially considering a range of different thresholds	

Task	Sub task	Description	Potential options
4 – Climate Informed Hazard Estimation	4.1 - Select and Analyze GCM Ensemble	This task would include literature review and selection of a GCM ensemble as described in section 4.3.3.1, potentially considering a range of different selection criteria	
	4.2 – Build Case for Decisions	This task would include discussions with the risk team to build a case for decision-making as described in section 4.3.3.2	
5 – Documentation, Dissemination, and Methodology Revision	5.1 – Update documentation	Based on the findings of Tasks 2–4, descriptions and details of the methodologies in this document would be refined and updated to more accurately represent the state of the methodology as informed by the prototype study	
	5.2 – Pursue opportunities to disseminate and further refine methodology	Pursue opportunities to publish findings and disseminate methodology within the community through professional conferences, potentially throughout the project timeline.	

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